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Three-Dimensional Photon Counting Optical Encryption With Enhanced Visual Quality and Security Level

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ABSTRACT In this paper, we propose three-dimensional (3D) photon counting double random phase encryption (DRPE) with enhanced visual quality and security level. Conventional 3D photon counting DRPE can quickly encrypt the data by using the 4f optical system and random phase masks with enhanced security because the 3D photon counting technique is used. 3D photon counting DRPE extracts photons from the encrypted data by using statistical methods such as the Poisson random process, and the visual quality of the decrypted data can be enhanced through the 3D reconstruction process. However, it still has a problem to visualize the data when we extract extremely a few photons. To improve the security and the visual quality of the decrypted data, we propose the random amplitude reconstruction process in the encryption stage. Our proposed method reconstructs the amplitude of the encrypted data at a random depth. Thus, the shifting pixel value and depth information can be another important key for decryption through the random process. Therefore, it can effectively decrypt data securely, and the visual quality of the decrypted data can be enhanced. Finally, through the random reconstruction process in the decryption stage, our proposed method can simultaneously enhance the security and visual quality. To verify our proposed method, we carry out the simulation and optical experiment.

INDEX TERMS Double random phase encryption, information security, photon counting, statistical optics, three-dimensional reconstruction, volumetric computational reconstruction.

I. INTRODUCTION

Recently, the development of the e-commerce market and smartphone applications have led people to preserve their data as an image. However, the security of this personal data is very weak because of various hacking technologies. Therefore, encryption for personal data has been essential. Double random phase encryption (DRPE) [1]–[6], an optical encryption, can enhance the security level of the data by using two random phase masks and 4f optical imaging system.

In DRPE, the data can be encrypted securely and quickly by the optical system. DRPE uses two different random phase masks for encryption in 4f optical imaging system. Then, the data can be decrypted by using the complex conjugate of the second random phase mask (i.e., decryption key). Thus, DRPE has an improved security level and high-speed processing. However, when attackers can have the decryption key, it is easy to reveal the data. Therefore, to enhance the security level of DRPE, photon counting [7]–[11] has been applied to DRPE.

Photon counting DRPE [12]–[14] detects a few photons from the encrypted data by DRPE. Thus, it can have a stronger security level than the conventional DRPE due to the lack of information for the encrypted data. However, in the decryption process, even if the decryption key is known, it is not easy to decrypt the data visibly. Therefore, three-dimensional (3D) photon counting DRPE has been used. [15]–[20]

In 3D photon counting DRPE, integral imaging [21]–[25] which records elemental images from the data by lens array or camera array is applied to visualize the data. Especially, it is more effective for photon counting DRPE because it can enhance the visual quality of the decrypted data by

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statistical estimation methods. In addition, it can reconstruct the decrypted data with a certain reconstruction depth which can be another key information for decryption. However, when severely a few photons are extracted from the encrypted data, 3D DRPE may not visualize the decrypted data since each encrypted elemental image may lose a lot of encrypted data information. Therefore, a method that can improve both the visualization and the security level of the decrypted data in 3D photon counting DRPE is required.

In this paper, we propose a new 3D photon counting DRPE with enhanced visual quality and security level. Our proposed technique can generate new elemental images from the encrypted elemental images by volumetric computational reconstruction (VCR) [21]–[25]. It means that our technique can increase the number of photons in each elemental image. Thus, our proposed method can enhance the visual quality of the decrypted data. In addition, since the reconstruction depths are required to generate a new elemental image in the encryption process and reconstruct the decrypted data respectively, the security level also can be improved. To verify the performance of our proposed method, we implement the computer simulation and optical experiment. Furthermore, to show the feasibility of our proposed method, we analyze the visual quality of the decrypted data by calculating correlation peak, peak signal to noise ratio (PSNR), and peak sidelobe ratio (PSR) as the performance metric.

II. 3D PHOTON COUNTING DRPE

A. DOUBLE RANDOM PHASE ENCRYPTION

Double random phase encryption (DRPE) is one of the popular optical encryption methods. It can simply encrypt the data by using two random phase masks in 4f optical imaging system. Fig. 1 illustrates the schematic of the encryption and decryption processes of DRPE.

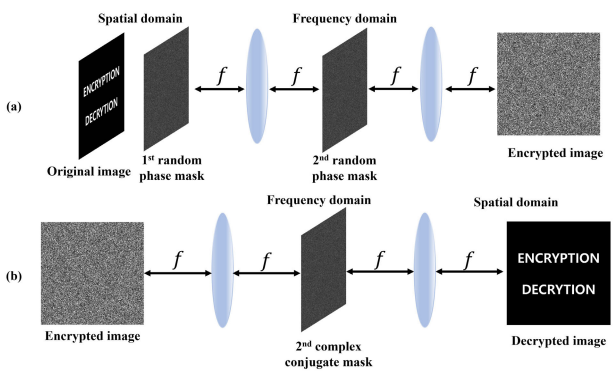

FIGURE 1. Double Random phase encryption. (a) encryption process and (b) decryption process.

In encryption process, two random phase masks can be divided into spatial domain $n(x)$ and frequency domain $n(\mu)$, respectively. Through these two random phase masks, the encrypted image can be generated as the following:

$$E(x) = F^{-1}\left\{F[f(x)exp\left\{i2\pi n(x)\right\}]exp[i2\pi n(\mu)]\right\} \quad (1)$$

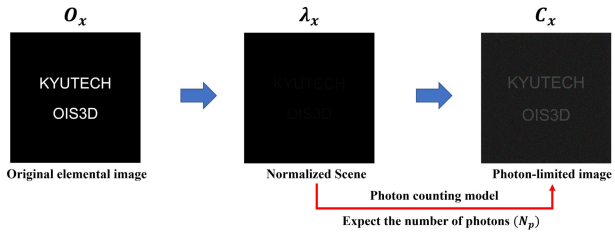

FIGURE 2. Computational photon counting model.

where $f(x)$ is the primary data, F is the Fourier transform and F^{-1} represents the inverse Fourier transform. In the encryption process, the primary data is multiplied by the first random phase mask $exp[i2\pi n(x)]$ in the spatial domain, and then, it is multiplied by the second random phase mask $exp[i2\pi n(\mu)]$ in frequency domain. Finally, the encrypted data ($E(x)$) can be generated. Since this encrypted data ($E(x)$) in (1) is complex value, it can be rewritten by its amplitude and phase terms as:

$$E(x) = |E(x)|exp[i\phi(x)] \quad (2)$$

where $\phi(x)$ is the phase information of the encrypted data. In decryption process, the complex conjugate of the second random phase mask can be used as decryption key.

$$D(x) = |F^{-1}[F\left\{E(x)\right\}exp\left\{-i2\pi n(\mu)\right\}]| \quad (3)$$

Finally, the decrypted data $D(x)$ can be obtained. However, when attackers have this decryption key, the primary data can be revealed easily. Therefore, to improve the security level, photon counting has been applied to DRPE [12]–[14].

B. PHOTON COUNTING DRPE

In general, photon counting imaging [7]–[9] has been used for detecting photons from the dark scene. Photons are rarely detected in the unit space and time under this condition. Therefore, photon counting imaging can be modelled by Poisson distribution [7]–[9], and it can estimate the scene by using statistical methods such as maximum likelihood estimation (MLE) [15], [16] or Bayesian approaches [17], [18]. To generate the photon-limited image with computational method, the normalized scene can be used. Fig. 2 illustrates the computational photon counting model, and this model can be expressed as follows.

$$\lambda(x) = \frac{O(x)}{\sum_{x=1}^{N_x} O(x)} \quad (4)$$

$$C(x)|\lambda(x) \sim Poisson[N_p\lambda(x)] \quad (5)$$

where N_p is the expected number of photons, $O(x)$ is the original image, $\lambda(x)$ is the normalized irradiance of the original image, N_x is the number of pixels for the original image, and $C(x)$ is the photon-limited image by computational photon counting imaging. Through the Poisson random process, the photon-limited image can be generated. Moreover, the photon counting model can be utilized to encrypt the data securely. Since photon counting model can detect

a few photons from the encrypted data, it can have more effective security and compression. Finally, the encrypted photon-limited data can be defined as follows:

$$|E_p(x)| = \frac{|E(x)|}{\sum_{x=1}^{N_x} |E(x)|} \tag{6}$$

$$|C_p(x)||E_p(x)| \sim Poisson[N_p|E_p(x)|] \tag{7}$$

The normalized amplitude of the encrypted data $|E_p(x)|$ can be generated from the amplitude of the encrypted data $|E(x)|$. To compress and improve the security of information effectively, the photon counting model has been used by (7). The photon-limited encrypted data $|C_p(x)|$ can be obtained through the Poisson random process. To decrypt the primary data, the same decryption key (i.e., complex conjugate of the second random phase mask) and phase term of the encrypted data can be used as:

$$D_p(x) = |F^{-1}[F\{C_p(x)\}exp\{-i2\pi n(\mu)\}]| \tag{8}$$

where $C_p(x) = |C_p(x)|exp(\phi_{C_p}(x))$. Finally, the decrypted data $D_p(x)$ can be obtained. However, it may not be visualized since it has only a few photons. Therefore, to enhance the visual quality and security level of the decrypted data, integral imaging has been used to photon counting DRPE [12]–[14].

C. 3D PHOTON COUNTING DRPE

Integral imaging can provide the full parallax and continuous viewing points for 3D image without any coherent light source such as a laser and special viewing glasses. Since it is simple and cost effective, it is one of the popular 3D scene reconstruction techniques. In integral imaging, multiple 2D elemental images with different perspectives can be recorded through the lens array or camera array. The 3D scene can be generated through the lens array in optical reconstruction process as shown in Fig. 3.

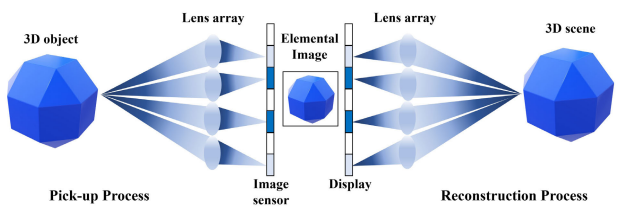

FIGURE 3. Integral imaging system.

To reconstruct the 3D scene virtually, VCR has been used. Elemental images are back-projected through their corresponding virtual pinholes. Then, these images are overlapped according to the shifting pixel value. To enhance the visual quality of the decrypted primary data, the decrypted photon-limited data is used with VCR, as depicted in Fig. 4. According to the reconstruction depth, the shifting pixel value and the 3D reconstructed image can be defined as following:

$$s_x = \frac{N_x pf}{c_x z_r} \tag{9}$$

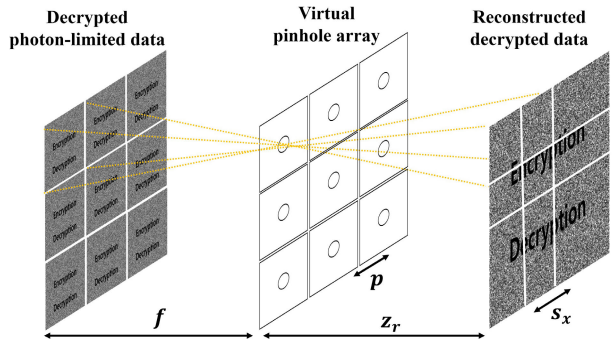

FIGURE 4. Volumetric computational reconstruction.

$$R_c(x, z_r) = \frac{1}{N_p O(x, z_r)} \sum_{k=1}^{K} D_p(x + s_x(k-1)) \tag{10}$$

where s_x is the shifting pixel value for reconstruction, p is the distance between pinholes, f is the focal length of the camera lens, c_x is the sensor size, and $O(x, z_r)$ is the overlapping matrix at the reconstruction depth, z_r. Finally, the 3D reconstructed decrypted data $R_c(x, z_r)$ can be obtained. Using VCR with photon counting DRPE [15]–[20], the visual quality can be enhanced due to overlapping of the decrypted photon-limited data. In addition, the depth information can be another decryption key because the accurate depth information of VCR is required to identify the decrypted data. When depth information is wrong, the decrypted data may not be obtained. However, when severely a few photons are used in this technique, it cannot visualize the scene well. Thus, to enhance the visual quality, the sufficient number of photons is needed. In addition, since it uses the decrypted data as the elemental image, it is vulnerable to security. Therefore, we require a new reconstruction technique that can visualize the scene effectively and securely. The next section presents our proposed method, which can visualize the decrypted data with enhanced visual quality and security level by using a few photons.

III. ENHANCED VISUAL QUALITY AND SECURITY USING AMPLITUDE RECONSTRUCTION

A. ENCRYPTION AND DECRYPTION PROCESS

The single photon counting encryption technique [10]–[13] can encrypt the data using various technique such as ptychography, phase deformation and so on. However, when the single image has only a few estimated photons, it cannot visualize the data well. Therefore, the receiver needs a metric such as Peak to correlation energy (PCE) of the data for recognition. If the data contains a few photons, it is hard to recognize the valid data using PCE. To enhance the PCE and visualize the data, most researches use integral imaging technique. Integral imaging can increase the number of the photons through the reconstruction process. However, the conventional method still cannot visualize the decrypted data under the extremely photon-starved conditions. To improve the security level and visual quality of

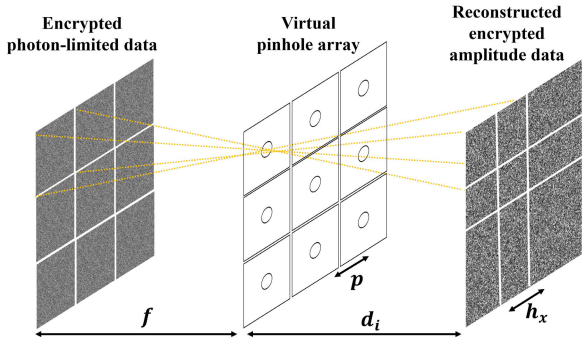

FIGURE 5. Amplitude term reconstruction in encryption process.

the decrypted data simultaneously, our proposed method uses integral imaging technique not only for the visualization but also for encryption. Our proposed method reconstructs the images on the virtual space with random depth information to encrypt the data securely. It reconstructs the amplitude data randomly from the encrypted photon-limited data as depicted in Fig. 5, and (11) and (12).

$$h_x = \frac{N_x p f}{c_x d_i} \tag{11}$$

$$|R_a(x, d_i)| = \frac{1}{N_p O(x, d_i)} \sum_{k=1}^{K} |E_p(x + h_x(k-1))| \tag{12}$$

where $|R_a(x, d_i)|$ is the reconstructed amplitude of the encrypted data at the random reconstruction depth, d_i. Through the computational reconstruction process with random reconstruction depth, the shifting pixel value for reconstruction, h_x can be changed randomly. The randomly selected depth information (d_i) and the corresponding shifting pixel value (h_x) can be used as the key information for the encryption process to reconstruct the decrypted data with enhanced visual quality. To generate new encrypted amplitude data, the reconstructed amplitude $|R_a(x, d_i)|$ is cropped by the corresponding shifting pixel value (h_x). In conventional 3D photon counting DRPE, VCR has been only used for decryption. In contrast, our proposed method uses VCR to increase the amplitude information of the encrypted data and enhance security. As the amplitude information increases, it can enhance the number of photons and generate high-quality decrypted data. Moreover, it can preserve the data securely by the virtual reconstruction process with the additional security key. To decrypt the data accurately, it should be located at the same position with the complex conjugate of the second random phase mask according to the shifting pixel value and depth information. New encrypted amplitude elemental data can be defined as the following:

$$E_{a,k}(x) = |R_a(x + h_x(k-1)| \quad for\ k = 1, 2, ..K \tag{13}$$

where $E_{a,k}(x)$ is the cropped amplitude data from the reconstructed data, $|R_a(x, d_i)|$. Now, the decryption process can be carried out by using complex conjugate of the second random

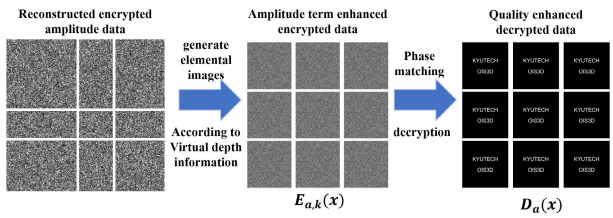

FIGURE 6. Amplitude term reconstruction in decryption process.

phase mask as the following:

$$D_a(x) = |F^{-1}[F\{E_a(x)exp[i\phi(x)]\}exp\{-i2\pi n(\mu)\}]| \tag{14}$$

In decryption process, if users have wrong information of virtual reconstruction depth and the shifting pixel value, the primary data is not visible because the location of the phase and amplitude information is not the same as each other. Thus, the phase and amplitude location matching processes are needed according to the depth information. When the matching process works properly, it can decrypt the data well. In addition, the amplitude data is enhanced through the reconstruction process. Therefore, the decrypted data by our proposed method can provide the better image quality compared with conventional method. Finally, the decrypted data can be utilized as elemental images to generate the 3D information of the decrypted data.

B. RECONSTRUCTION PROCESS

To decrypt the primary data at a certain reconstruction depth by our proposed method, VCR can be used as shown in Fig. 7 and (15).

$$R_f(x, z_r) = \frac{1}{O(x, z_r)} \sum_{k=1}^{K} D_a(x + s_x(k-1)) \tag{15}$$

3D decrypted primary data $R_f(x, z_r)$ can be obtained using a certain depth information. Our proposed method uses twice reconstruction processes to enhance visual quality and security. Especially, the virtual reconstruction process can enhance the amplitude information and provide the high quality of the image when we decrypt the data even under photon-starved conditions. In addition, it can preserve the data simply

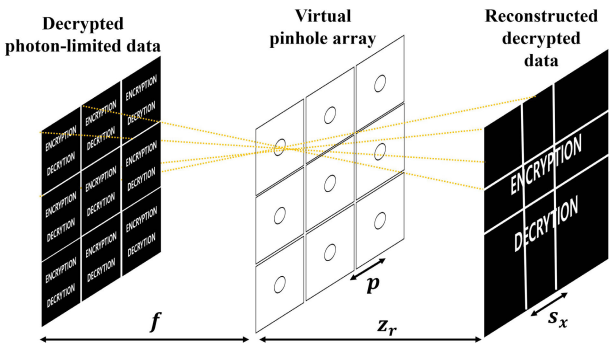

FIGURE 7. Information reconstruction in decryption process.

and securely through the random depth security key information without any phase deformation. Finally, our proposed method shows better performance in data security and visualization compared with the conventional method. To verify the performance of our proposed method, we present the computer simulation and optical experiments in the next section. Moreover, to prove 3D image quality by our proposed method, we use various image quality metrics such as correlation and peak signal to noise ratio (PSNR).

IV. EXPERIMENTAL RESULTS

A. SIMULATION RESULTS

Figure 8 represents the simulation setup. In simulation, we use 5(H) × 5(V) camera array for capturing elemental images which have 800(H) × 800(V) pixels. The focal length of camera lens is 50mm and the pitch between cameras is 2mm. The plain text objects are located in front of camera array with different depths.

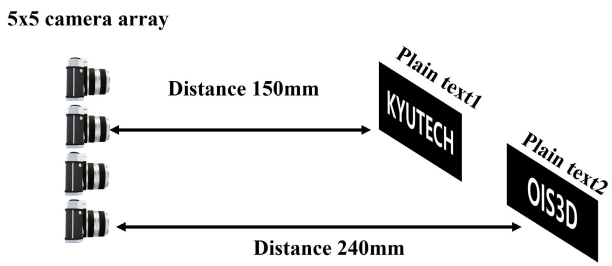

FIGURE 8. Simulation setup.

For comparison of the visual quality, various number of photons from 1,000 (0.0015625 photons/pixel) to 19,000 (0.0296875 photons/pixel) have been used. Figure 9 shows the elemental image of each method, respectively.

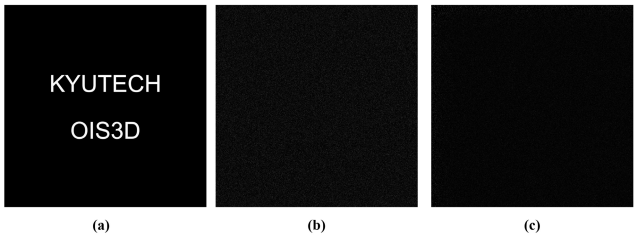

FIGURE 9. Primary data and encrypted data. (a) primary data, (b) encrypted data by conventional method, and (c) encrypted data by proposed method, where 7,000 (0.0109375 photons/pixel) expected photons are used in each encrypted data.

We cannot recognize the primary data by both conventional and our proposed encryption processes. However, the conventional method can be attacked easily when attackers know the decryption key. On the other hand, since our proposed method reconstructs the amplitude information at the randomly selected depth by using VCR, it is hard to disclose the data even attackers know the decryption key. In addition, through the reconstruction process, our method can increase the primary data information. Finally, the visual quality of the decrypted data can be enhanced. To verify the decryption performance of our proposed method, these encrypted data has been used. Figure 10 shows the reconstructed decrypted plain text1 data.

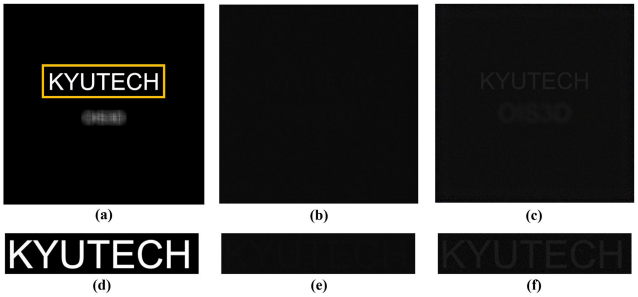

FIGURE 10. Reconstructed decrypted data at 150mm. (a) reconstructed primary data, (b) conventional reconstructed decrypted data, (c) proposed reconstructed decrypted data, (d) enlarged image from reconstructed primary data, (e) enlarged image from conventional reconstructed decrypted data, and (f) enlarged image from proposed reconstructed decrypted data, where 7,000 (0.0109375 photons/pixel) expected photons are used.

Using a few photons (0.0109375 photons/pixel), conventional method cannot visualize the information. Since the information of primary data is not sufficient, it is difficult to decrypt the information correctly. In contrast, our proposed method shows the word exactly under the same condition. Through the amplitude reconstruction process, the sufficient information can be obtained. Therefore, it can visualize information well. To verify the visual quality of the primary data at another depth, we show the result image which focused on plain text2 in Fig. 11.

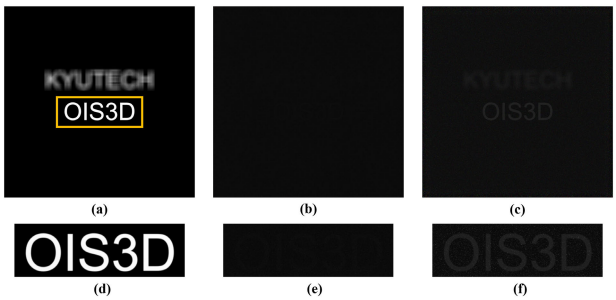

FIGURE 11. Reconstructed decrypted data at 240mm. (a) reconstructed primary data, (b) conventional reconstructed decrypted data, (c) proposed reconstructed decrypted data, (d) enlarged image from reconstructed primary data, (e) enlarged image from conventional reconstructed decrypted data, and (f) enlarged image from proposed reconstructed decrypted data, where 7,000 (0.0109375 photons/pixel) expected photons are used.

The conventional method still cannot visualize the second text. However, our proposed method shows high visual quality compared with the conventional method. To evaluate the visual quality of the decrypted data, we use various performance metrics such as correlation, peak signal to noise ratio (PSNR) and peak sidelobe ratio (PSR).

Figure 12 shows the visual quality analysis result. Our proposed method shows the higher peak than conventional

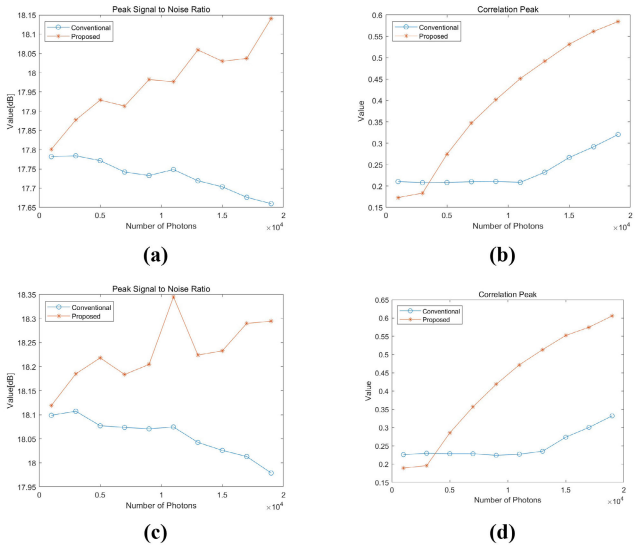

FIGURE 12. Visual quality analysis graph. (a) Peak Signal to Noise Ratio at 150mm, (b) Correlation peak at 150mm, (c) Peak Signal to Noise Ratio at 240mm, and (d) Correlation peak at 240mm.

method in various metrics. As estimated photons increase, the PSNR result by conventional method shows downward-right graph. It refers that the noise from the data may decrease the image quality. However, our proposed method can visualize the data accurately through the amplitude virtual reconstruction. Therefore, PSNR value increases according to the estimated photons growth. In addition, the conventional method shows the same value until the estimated 12,000 photons in the data. It refers that the conventional method cannot visualize the image well under photon-starved conditions. On the other hand, our proposed method can visualize the image using only 6,000 estimated photons in the data. It refers that our proposed method can decrypt the correct information using a few photons. To verify the accuracy of the information, we calculate the PSR as shown in Fig. 13.

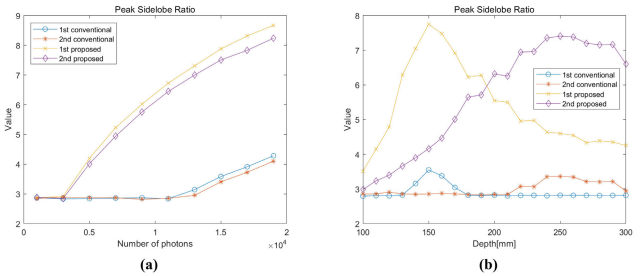

FIGURE 13. Peak Sidelobe Ratio via (a) number of photons and (b) various depths.

According to Fig. 13 (a), conventional method cannot visualize the primary data until we use the 10,000 (0.015625 photons/pixel) expected photons. However, our proposed method can visualize the data after 3,000 (0.0046875 photons/pixel) photons. In addition, the PSR value increases gradually, when more expected photons are used. This is because, as the expected photons increase, the amplitude of reconstructed data also can increase. Therefore, our proposed method can decrypt the primary data accurately. Figure 13 (b) shows the PSR value via various reconstruction depths, respectively. The conventional method has the PSR peak value under around 4 throughout all reconstruction depths. On the other hand, our method has the highest peak value at 150mm and 240mm. It means that our method can decrypt the primary data exactly at the depth of plain text objects. To verify that our proposed method is superior in all situations, we implement optical experiments.

B. OPTICAL EXPERIMENT RESULTS

Figure 14 shows our optical experimental setup. In the optical experiment, we use 5(H) × 5(V) camera array and each elemental image has 600(H) × 400(V) pixels. The pitch between cameras is 2mm and the focal length of the camera lens is 50mm. The two objects are located at different distances in front of the camera array.

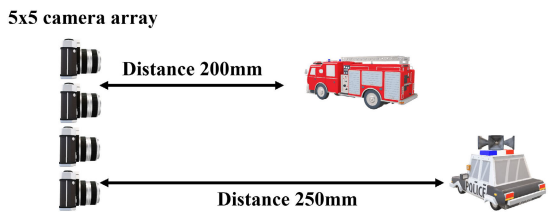

FIGURE 14. Optical experimental setup.

To show the feasibility of our method with various number of photons, 1,000 (0.004167 photons/pixel) to 10,000 (0.04167 photons/pixel) expected photons are used. Figure 15 shows the encrypted data by conventional method and our proposed method.

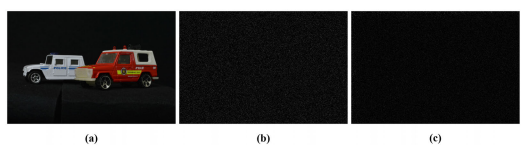

FIGURE 15. Primary data and encrypted data. (a) primary data, (b) encrypted data by conventional method, and (c) encrypted data by our proposed method, where 10,000 (0.04167 photons/pixel) expected photons are used.

In Fig. 15 (b) and (c), both methods can encrypt the data well. Besides, our proposed method uses the random amplitude reconstruction process. Through the reconstruction, the depth information can be a decryption key. Therefore, our proposed method can enhance the security level compared with conventional method. Using these data, our method can decrypt the primary data and reconstruct the 3D primary data.

Figure 16 shows the reconstructed data at 200mm. The conventional method can visualize the shape of cars slightly as shown in Figs. 16 (b) and (e). However, it cannot visualize

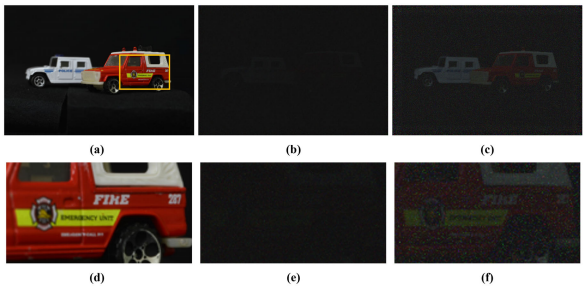

FIGURE 16. Reconstructed decrypted data at 200mm. (a) reconstructed primary data, (b) conventional reconstructed decrypted data, (c) proposed reconstructed decrypted data, (d) enlarged image from reconstructed primary data, (e) enlarged image from conventional reconstructed decrypted data, and (f) enlarged image from proposed reconstructed decrypted data, where 10,000 (0.04167 photons/pixel) expected photons are used.

the object in detail. On the other hand, our proposed method can visualize the detail of the object and the characters on the car is readable as shown in Figs. 16 (c) and (f).

In Fig. 17, we reconstruct the second object at 240mm. The conventional method cannot visualize the primary data well even if 10,000 (0.04167 photons/pixel) expected photons are used as shown in Figs. 17 (b) and (e). In contrast, proposed method can visualize the primary data under the same condition. We can recognize the word on the car as shown in Figs. 17 (c) and (f). To verify the visual quality of the decrypted data by our proposed method, we use the same performance metrics as the simulation.

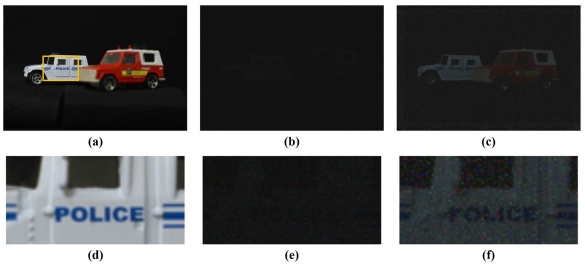

FIGURE 17. Reconstructed decrypted data at 240mm. (a) reconstructed primary data, (b) conventional reconstructed decrypted data, (c) proposed reconstructed decrypted data, (d) enlarged image from reconstructed primary data, (e) enlarged image from conventional reconstructed decrypted data, and (f) enlarged image from proposed reconstructed decrypted data, where 10,000 (0.04167 photons/pixel) expected photons are used.

Figure 18 represents the PSNR and correlation results. Through the Figs. 18 (a) and (c), our proposed method shows the highest PSNR value compared to the conventional method. Moreover, our proposed method shows almost twice higher correlation peak value than conventional method as shown in Figs. 18 (b) and (d). It is noticed that our method can enhance the visual quality of the decrypted data. To verify the accuracy of the decrypted data, we calculate the PSR as shown in Fig. 19.

In Fig. 19 (a), the conventional method shows the flat graph even if the number of photons increases. It is noticed

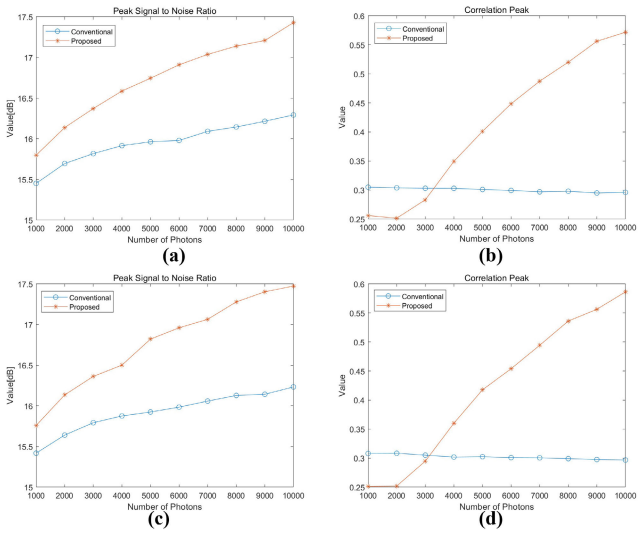

FIGURE 18. Visual quality analysis graph. (a) Peak Signal to Noise Ratio at 200mm, (b) Correlation peak at 200mm, (c) Peak Signal to Noise Ratio at 240mm, and (d) Correlation peak at 240mm.

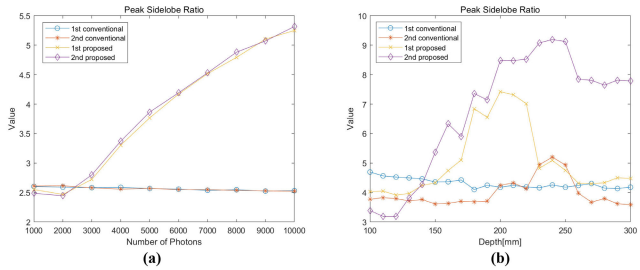

FIGURE 19. Peak Sidelobe Ratio via (a) number of photons and (b) various depths.

that the conventional method may not visualize the primary data accurately when we use a few photons. In contrast, PSR value by our proposed method increases steeply after 3,000 (0.0125 photons/pixel) expected photons. In addition, as shown in Fig. 19 (b), our proposed method shows the exact high peak where the object is located. This can be referred as our proposed method can visualize primary data correctly at the object distance. As a result, through the experiments, our proposed method can enhance the security and the visual quality of the primary data through the reconstruction process. Especially, when we use a few photons to encrypt the primary data, the conventional method cannot visualize the data accurately but our method can visualize the data.

V. CONCLUSION

In this paper, we have presented the secure data encryption and decryption system using 3D photon counting DRPE. The conventional 3D photon counting DRPE may not visualize the primary data accurately when we use a few photons for encryption. Since a few photons are used for more secure encryption process, it is difficult to visualize the data in detail. To improve the security level and the visual quality

simultaneously, our proposed method uses the amplitude information reconstruction process for encrypting data securely. In addition, through the amplitude reconstruction, the visual quality of the primary data can be enhanced. Therefore, our proposed method can be effective way to authenticate the information safety and visualize the primary data accurately. We believe that our proposed method can be used for many industrial fields such as e-commerce market and simple identification system in the future.

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