Computational ghost imaging with the sweeping algorithm

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Abstract. The idea of ghost imaging was firstly presented more than 25 years ago and since then many techniques have been proposed to improve image quality and simplify optical scheme. Nevertheless, the image reconstruction speed has always remained a serious problem to wide practical implementations. As a solution, a sweeping algorithm was proposed, which allowed to reduce the number of iterations to image resolution. However, this method has some serious limitations on objects shape. In this article we present a new technique, which combine a sweeping algorithm using alternating rows/columns and traditional pseudothermal ghost imaging using speckle structures.

1. Introduction
Ghost imaging (GI) is a special visualization technique where information about an unknown object is extracted from the intensity fluctuation correlation function of two detectors. In the classical pseudothermal GI [1], a laser beam hits a diffuse structure to form a speckle field, which later diverges on a beam-splitter into two arms. The object arm contains the object under study itself and a bucket detector, which register only total transmitted light intensity. The reference arm contains a matrix detector and register part of the speckle field, which never interacted with the object. Finally, by correlating measured intensities from bucket and matrix detectors an image of the object is restored.

This technique allows higher efficiency information extraction than traditional optical imaging and may be used in such applications as remote sensing [2], optical encryption [3] and microscopic imaging [4].

The computational method of GI (CGI) [5] is very similar to the classical one, but instead of the diffuse structure and beam-splitter a spatial light modulator (SLM) is used, which allows to create a “structured” speckle field and calculate the intensity distribution in the reference arm on a computer, which considerably simplify the optical scheme.

The main problem of the GI technique with speckle fields is numerous numbers of iterations needed to reconstruct the image. As a solution, a sweeping algorithm was presented [6], which allowed to reduce the number of iterations to the image resolution. This technique was called sweeping computational GI (SCGI). The essence of this method is that the SLM instead of forming speckle structure gradually alternate all-bright rows and columns. However, the quality of the reconstructed image is highly dependents on the shape of the object and as a result has serious limitations in practical field.

2. Method
To accelerate the image reconstruction speed and overcome the SCGI technique limitations we have purposed a new algorithm, which combines altering rows/columns and speckle structures. We have called it combined computational GI (CCGI).
Firstly, we reconstruct an image separately for rows $G_R$ and columns $G_C$ using intensity fluctuation correlation function

$$G(x, y) = \langle B \cdot I(x, y) \rangle - \langle B \rangle \cdot \langle I(x, y) \rangle$$  \hspace{1cm} (1)$$

where $B$ is the intensity on a bucket detector, $I(x, y)$ – spatial distribution of intensity in the object plane (speckle structure or altering rows/columns for instance), $\langle \cdot \rangle = \frac{1}{N} \sum_j$ – ensemble average over $N$ realizations. In our model intensity on a bucket detector is obtained by $B = \sum_{x+y} T(x, y) \cdot I(x, y)$, where $T(x, y)$ is the object mask.

Secondly, we select vertical $G_R^{(1)}$ and horizontal $G_C^{(1)}$ line from row and column images respectively by

$$G_R^{(1)}(x, 1) = G_R(x, j), \quad j \in [1, y]$$  \hspace{1cm} (2)$$

$$G_C^{(1)}(1, y) = G_C(i, y), \quad i \in [1, x]$$  \hspace{1cm} (3)$$

At last, we reconstruct the whole SCGI technique image using equation (4)

$$G^{(SCGI)}(x, y) = G_R^{(1)}(x, 1) \cdot G_C^{(1)}(1, y)$$  \hspace{1cm} (4)$$

After that, the second image $G^{(CCGI)}$ is reconstructed by traditional GI technique with speckle structure using the same intensity fluctuation correlation function in equation (1). In the end, the final image of CCGI technique is obtained by

$$G^{(CCGI)} = G^{(CCGI)} + G^{(SCGI)}$$  \hspace{1cm} (5)$$

Also, to compare the restored images from different GI techniques a signal-to-noise ratio (SNR) and contrast (C) were measured using equation (6) and (7)

$$SNR = 20 \cdot \log_{10} \left( \frac{A_s}{A_n} \right)$$  \hspace{1cm} (6)$$

$$C = \frac{\langle I_o \rangle - \langle I_b \rangle}{\langle I_o \rangle}$$  \hspace{1cm} (7)$$

where $A_{s,n}$ is the root-mean-square intensity of signal and noise and $\langle I_{o,b} \rangle$ is the average intensity of the object and background respectively.

3. Experiment
To confirm the results of the proposed CCGI technique on practice, an experimental setup was assembled, the optical scheme of which is shown in figure 1. The He-Ne laser with a central wavelength of 633 nm was used as a source, the illumination from which was directed to the beam expander (telescopic system) to increase the transverse radiation area. Next, the laser beam passed through the beam-splitter and then hit the SLM (HOLOEYE, LETO-3) with 1080x1920 addressable $6.4 \mu m \times 6.4 \mu m$ pixels, where it got phase modulation. The corresponding phase masks were obtained using the
Gerchberg–Saxton algorithm [7] from pre-created spatial intensity distribution masks. After the SLM, the beam was again directed to the beam-splitter, then further to the object and finally to the registration system. In the registration plane, instead of bucket detector, a multi-pixel camera (EVS, VAC-136) and a two-lens system was used to control the spatial distribution of intensity obtained at the object plane. It was also possible to directly focus light emission into the camera plane to simulate the bucket detector. The post-processing algorithm exactly reproduces the previously considered mathematical model, only now the intensity of the virtual bucket detector has been replaced by the total intensity of the camera used.

Figure 1. Experiment setup for CCGI technique.

4. Results
As an object, the capital letters of the abbreviation of our university were used, the size of the area of which was $5 \text{ mm} \times 5 \text{ mm}$. As mentioned earlier, the SCGI technique has strict limitations on the shape of the object and in most cases restores a distorted image. In this regard, we have presented a CCGI technique, a comparison of which with other methods is shown in figure 2. As can be seen from the results obtained, the SCGI technique is good at reconstructing only rectangular objects, while the rest are restored incompletely or have strong distortions. The images obtained using the CGI technique, where the number of iterations was 1000, recovered completely, but they have quite high level of background noise and may not be reconstructed with a smaller number of iterations. Thus, the proposed CCGI technique combined the advantages of the above methods and reduced their negative impact on the image restoration process. On the one hand, the CCGI were able to completely restore all forms of objects, in contrast to the SCGI, and on the other hand, the noise level turned out to be lower compared to the CGI.

Also, the dependence of SNR and contrast was investigated for the CGI and CCGI techniques depending on the number of iterations for letter O restored image. The results obtained are shown in figure 3 and 4. It can be seen that the difference in SNR for the two techniques remains practically unchanged with the CCGI exceeding CGI 1.5 times, but the difference in contrast decreases from 0.4 to 0.1 with an increase in the number of iterations. From this we can conclude that the proposed method is most effective with a small number of iterations.

5. Conclusion
In conclusion, we have presented a new GI technique that combines alternating rows/columns and speckle structures. The images obtained with its help are superior to the classical GI with speckle fields, but the greatest effect is obtained at a small number of iterations.
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Figure 2. Restored images of letters I, T, M and O by SCGI, CGI and CCGI techniques.

Figure 3. Dependence of SNR on the number of iterations for CCGI and CGI techniques for letter O restored image.

Figure 4. Dependence of contrast on the number of iterations for CCGI and CGI techniques for letter O restored image.

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