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# Study on ghost imaging via compressive sensing for a reflected object

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ABSTRACT

The computational ghost imaging for a reflected object was realized by a spatial light modulator and a coaxial imaging system. The resolution of the reconstructed imaging was improved by the compressive sampling algorithm, and the noise caused by the limited aperture of the lens was minimized by the fuzzy-removing algorithm. After the theory analysis and simulation, the experiment system was set up to verify validity of the algorithm. From the experiment, we can conclude that the reconstructed image of reflected object by compression sensing correlation calculation became clearer with the increase of calculation times. The image obtained by fuzzy-removing algorithm was much clearer than that obtained by none fuzzy-removing algorithm with the same measurement times. Because the noise introduced by the aperture of lens decreased as the increase of the diameter of the lens, the visibility of the reconstructed image increased. The resolution of reconstructed imaging can reach several tens micron order by the compressive sampling and fuzzy-removing algorithm. This method expanded the application of the compressive ghost imaging in the remote sensing, and decreased the complexity of the imaging system in the space platform.



## 1. Introduction

In recent years, ghost imaging has become a new type imaging technology with high resolution [1–17]. Ghost imaging can realize non-locally imaging, whose images do not appear on the light path containing object. Shapiro [2] and Bromberg [3] have succeeded in ghost imaging with a single detector by presetting the light field of the reference arm and a spatial light modulator, which was called computational ghost imaging. On that basis, paper [16] has applied compressive sensing algorithm to computational ghost imaging, which enhanced the resolution of ghost image furthermore. Papers [14,15] have applied computational ghost imaging to remote sensing, and researched on ghost imaging for a reflected object. Papers above just studied on the resolution and SNR of ghost image for a reflected object, however, their optical imaging system by active illuminating have some disadvantages, such as disalignment between the sending axis of illuminating beam and receiving axis, larger errors, and limited application field. This paper used a transmission spatial light modulator and an imaging system to realize the computational ghost imaging for a reflected object in a coaxial system. The structure of the imaging system was compact. At the same time, it increased the system precision of the computational ghost imaging for a reflected object. The visibility and signal to noise of ghost imaging via compressive sensing for a reflected object increased by using the fuzzy-removing algorithm of the imaging system and compressive sensing algorithm. This method expanded the application of the computational ghost imaging in the remote sensing, and decreased the complexity of the imaging system in the space platform.

## 2. Computational ghost imaging for a reflected object with amplitude modulation by a SLM

A spatial light modulator can change the amplitude or intensity, phase, polarization state and wavelength of light in space under the control of electric driven signal or other signals with time. Computational ghost imaging for a reflected object based on SLM amplitude modulation used the monochrome coherent source to illuminate the object. Then we modulated the amplitude of the image (the amplitude of the image was modulate) at the surface of SLM that was the conjugate surface of the object, the total modulated light intensity was detected by the bucket detector, the image of the object can be reconstructed by correlated calculation with the recorded SLM modulating signal.

Such as Fig. 1, a coherent source $S(')$ illuminated the object $t(x_1,y_1)$, the reflected light arrived at the surface of the lens by a Fresnel diffraction, then reached the conjugate surface by another

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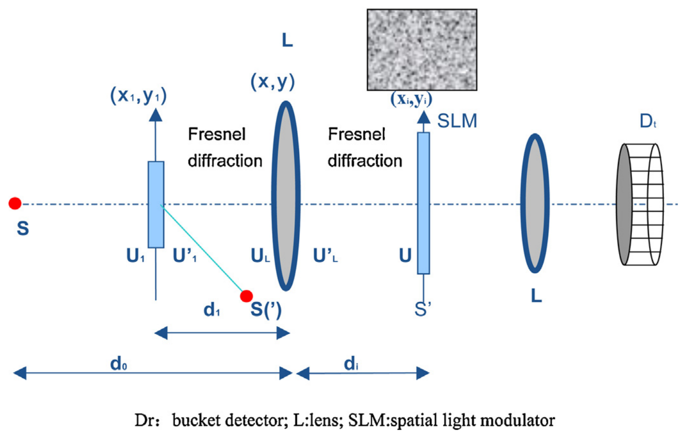


**Fig. 1.** The theory figure of the computational ghost imaging for a reflected object with amplitude modulation by a SLM.

Fresnel diffraction after an Fourier transformation. The imaging formula was as follows:

$$U(x_i,y_i)=\frac{a_0}{\lambda^2(d_i-d_0)(-d_1)d_i}\int_{-\infty}^{\infty}\int \exp\left(-jk\frac{x^2+y^2}{2f}\right)\times$$
$$\exp\left\{jk\frac{[(x_i-x)^2+(y_i-y)^2]}{2d_i}\right\}\times \quad (1)$$
$$\left[\int_{-\infty}^{\infty}\int t(x_1,y_1)\exp\left[jk\frac{x_1^2+y_1^2}{2(d_1-d_0)}\right]\exp\left\{jk\frac{[(x-x_1)^2+(y-y_1)^2]}{2(-d_1)}\right\}dx_1dy_1\right]dxdy$$

$d_0$ denotes the distance between the light source and lens, and $d_1$ and $d_i$ refer to object distance and image distance respectively. $S$ is the symmetric center of $S(')$. When the $d_i$ was belonged to $(1/d_i)-(1/d_1)=1/f$, the surface $U$ is the conjugate surface of the object plane, where the image of diffraction screen can be got. Put spatial light modulator at the place of image, and conducted amplitude modulation then collected light intensity with a bucket detector, we can get the image of object by correlated calculation with a recorded SLM modulating signal. For convenient calculation, we chose the object distance and image distance to be $2f$ respectively, the image on the conjugate surface was inversed image and had the same size as the object. The correlation calculation formula of a reflected object was as follows:

$$B_r=\int dxdyI_r(x,y)T(x,y)$$

$$G(x,y)=\frac{1}{N}\sum_{r=1}^{N}(B_r-\langle B\rangle)(I_r-\langle I\rangle) \quad (2)$$

$\langle\bullet\rangle=\frac{1}{N}\sum_{r=1}^{N}(\bullet_r)$, $B_r$ is the total light intensity of bucket detector, $T(x,y)$ is the image of a reflected object, $I_r(x,y)$ is the amplitude modulation signal of the SLM.

## 3. Ghost imaging via compressive sensing for a reflected object

Compressive sensing theory [10–13] is a new theory of signal sampling and processing. Compressive sensing algorithm can reconstruct the original signal with less amount of sampling which was smaller than the required one by Nyquist sampling theory. The formula of ghost imaging via compressive sensing algorithm was as follows:

$$T_{cs}=T;\quad \min\left\|T(x,y)\right\|_{L_1}$$

$$B_r=\int dxdyI_r(x,y)T(x,y);\forall r=1,\cdots,N \quad (3)$$

$T_{cs}$ denotes the image function of a reflected object. $N$ denotes the times of measurement, which is smaller than the number of the pixels of a reflected object. Make the matrix of the image of a reflected object be the required sparse matrix. Use the $N$ random independent distribution observation matrix to form a new matrix and make the new matrix be the observation operator matrix. Use the $N$ measured value $B_r$ to constitute a new matrix and make the new matrix be the measured value. Then the image of a reflected object can be got with the minimal $L1$-norm.

Because the imaging system was limited by the aperture of lens, the image was the convolution of the object and the point spread function, and the point spread function was the Fourier transformation of the function of the aperture of lens $P(x,y)$, so the results of the formulas of (2) and (3) were the ideal images of the reflected object. Due to the limitation of the aperture of lens in the $2f$–$2f$ optical system, noise has been raised, using compressive sensing algorithm could not get high resolution reconstructed image. This paper used a fuzzy-removing algorithm to reduce the noise caused by the aperture of lens. The solving step was as follows. Make the convolution of the object in spatial domain and the point spread function to be a linear transforming course, then we can induce the real image of a reflected object that did not limit by the aperture of lens. The transformation course was shown in the formula of (4):

$$T=KT' \quad (4)$$

$T'$ denotes the object matrix, $T$ denotes the image matrix, $K$ is the fuzzy-removing matrix. The formula of (3) can be changed to be:

$$T_{cs}=T';\quad \min\left\|T'(x,y)\right\|_{L_1}$$

$$B_r=\int dxdyI_r(x,y)K(x,y)T'(x,y);\quad \forall r=1,\cdots,N \quad (5)$$

Fuzzy-removing matrix can be obtained by translating the point spread function. Convolute every dot in object plane with point spread function in sequence, a set of 2 D scheme of point spread function can be obtained. The 2 D scheme matrix of point spread function was made to be lines according to the row, which were the corresponding lines of Matrix $K$. The formula of (5) represents a real image of the reflected object that did not limited by the aperture of lens and fuzzy-removed.

## 4. Theory simulation of ghost imaging via compressive sensing for a reflected object

This paper used compression sensing algorithm to obtain real images and used the numerical simulation method to obtain SLM modulation signals. The simulation was conducted with MATLAB, the steps were as follows. The designed object $T'$ with a space domain was placed on the object plane of a $2f-2f$ imaging system. Assuming that in the imaging course, from object to the SLM surface was a linear invariant space process, and lens in the imaging system was an ideal thin lens, the point spread function was obtained by the optical design software of Zemax. The object and point spread function were convoluted to get the image of the reflected object, which was on the SLM plane. Each pixel on the image of the object was modulated by simulation signals. In the