A New Single Pixel Imaging System Based on Paired Rotary Diffraction Plates

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Abstract: We present a new single-pixel imaging system based on a paired rotary diffractive plates. Compared with tradition imaging system, our designed single-pixel imaging system contains simple structure and lower computational complexity. Theoretical simulation results show the single-pixel imaging system has the feasibility of thermal object imaging at wavelength $\lambda=10.6\mu m$, therefore which can be applied for SF$_6$ gas imaging.

1. Introduction

Traditional single-pixel imaging recognition is mainly used in ghost imaging [1]. In the 1980s, Klyshko proposed a ghost imaging scheme based on entanglement. Until 1995 Shi Yanhua et al firstly realized ghost imaging and ghost interference through entangled photon pairs. It was once believed that only entangled light could achieve ghost imaging, but in 2002 Bennink at Rochester University used pulsed laser to achieve the "ghost" imaging of the classical light source [2]. Soon afterwards Shi Yanhua et al realized the "ghost" imaging of the classical thermal light source, which formally opens the application door of "ghost" imaging in military and life.

One of the single-pixel imaging applications is as the cheap detector for gas imaging system. Traditionally gas imaging systems contain amount of infrared radiation detectors, which cause a greater cost [3]. Recently, a single pixel imaging camera for short wavelength infrared region was developed to detect methane gas leak [4]. A digital micromirror device (DMD) is used to pattern the laser output with a sequence of Hadamard masks (256 mask patterns, corresponding to an image resolution of 16x16). However, DMD is not the idea space light modulator for long-wave infrared application due to diffraction effect [5]. In this paper, a new single-pixel detection system at wavelength of 10.6 um is proposed to construct a imaging system for SF$_6$ gas. Different from traditional imaging system based on a change of reference and sampling components, our single-pixel detection system is a rotated double-plate diffractive structure. Preliminary theoretical simulation has been done to demonstrate the feasibility of new principle for single-pixel imaging, the simulation results show that the calculating error can be limited less than 8%.
2. Theoretical model and structural design

2.1 Structural design and details

Figure 1 demonstrates the whole structure of single-pixel imaging system, including light source information, optical platform, single-pixel detector, processor and controller. The optical platform is constructed by four parts. Part 1 and 2 are the same optical rectangular frames to fix two similar rotary platforms (part 3 and 4). Two platforms have four apertures in total signed as C1, C2, C3, C4, and which are placed at the same optical axis with the light source and single-pixel detector. Besides, two diffraction plates are placed in the apertures C2 and C4, which have different holes-distribution as shown in Fig. 3 and possess non-uniform diffraction characteristics.

![Fig. 1. Schematic diagram of the whole structure of single-pixel imaging system](image)

In Fig. 2, we illustrate the framework of a paired rotary diffractive plates. The rotary plates are signed as T1 and T2, besides S and V represent light source and single pixel detector, respectively. When the light emitted by the source S passes through the plates T1 and T2 in turns, two different diffraction effect will occur, finally the transmitted light is detected by the single pixel detector V. According to the detected results and model algorithm, the original distribution information of light intensity can be obtained.

![Fig. 2. Framework of the paired rotary diffractive plates](image)

Figure 3 shows the detailed structure of those two plates. Point A is the centre of the plate and the centre is not punched, the remained five points are five punched holes to make light go through from the plates. For this model, we select following parameters: $D = 15 \mu m$, $l = 165 \mu m$, $f_0^1 = 2 cm$, $f_1^2 = 1.55 mm$. The weight is set as $\varphi_p = 0.6$. $D$ is diameter of circular hole, $l$ is distance between adjacent rings on $T_1$ and $T_2$, $f_0^1$ is distance between $T_1$ and $T_2$, $f_1^2$ is distance between $T_2$ and the single pixel detector $V$. 

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2.2 Implementation Methods

When no.1 hole’s original value has been calculated successfully, T2 begins to rotate to align T1’s no.2 hole with T1’s no.2 hole so that no.2 hole’s original light signal value of this fixed radius can be calculated. Repeat the above operation to obtain no.3, no.4 and no.5 hole’s original values of this fixed radius. As 5 hole’s original light signal values has been obtained, T1 rotates and repeat the above operation to calculate the next radius’ data.

2.3 Model Establishing

According to the theory of circular aperture diffraction, the light intensity $I_p$ at point $p$ of circular aperture diffraction at the display screen can be expressed as [6]:

$$I_p = I_0 \left(\frac{J_1(2m)}{m}\right)^2, \quad m = \frac{\pi D \rho}{2f}$$

(1)

Where $I_0$ is the intensity of incident light, $D$ is the diameter of circular aperture, $\rho$ is the distance from the point $p$ at display screen to the maximum point of diffraction, and $f$ is the distance from the circular aperture diffraction plane to the target display screen.

According to Fig. 4, light will be diffracted by plates T1 and T2, the final formula is as follows:

$$I_i(i) = \sum_j \left(\frac{J_1(2m_i^1(j))}{m_i^1(j)}\right)^2 I_0(j), \quad m_i^0(j) = \frac{\pi D \rho_i(j)}{2f}$$

(2)

$$C_k = \sum_i \left(\frac{J_1(2m_i^2(i))}{m_i^2(i)}\right)^2 I_i(i), \quad m_i^2(i) = \frac{\pi D \rho_i(i)}{2f}$$

(3)

Here, $I_i(i)$ is the intensity value of the $i$ point on the $T_2$ plate after the diffraction of $T_1$, $C_k$ is the intensity value of the light, which is from $T_1$ diffracted into the $T_2$ plate, secondly diffracted into the single-pixel detector from $T_2$ when measuring the five points of the no. $k$ radius.

Through mathematical discretization and error analysis, light intensity can be restored by weight method. The diffraction effect of light passing through a circular aperture can be controlled by controlling parameters $D, f$ and $\rho$, so that in the final detection value $C_k$, it can be known that one of the approximate proportions is the value of light diffraction from the aligned point, and by choosing the above parameters, the proportions which can let us get good results can reach more than 60%(this proportions’ related value can be detected). The diffraction light is mainly generated by the alignment points but not the other non-alignment points. The diffraction caused by T1 and T2 corresponds to the weight $\tau_p$ and $\tau_{p'}$, respectively. When the point $p$ is aligned, we can get:

$$I_0(p) = a_1(p) \cdot a_0(j) \cdot \tau_p \sigma_i C_k$$

(4)
Here \( i = p \), \( a_i(p) = \sum_j \left[ \frac{J_1(2m_1^j(j))}{m_0^j(j)} \right]^2 \), \( a_0(i) = \left[ \frac{J_1(2m_1^i(i))}{m_1^i(i)} \right]^2 \). The incident light intensity of point \( p \) can be restored. Through making \( \varphi_p = \tau_p \sigma_p \), we can get the reduction value of the alignment point as follows:

\[
I_0(p) = a_i(p) \cdot a_0(p) \cdot \varphi_p C_k
\]

(5)

3. Results
Taking the simulation test of 10.6 um(Infrared absorption peak) infrared light source as an example, the parameters of ciculaare selected as follows: The intensity of incident light is set as \( I_0 = (100, 30, 50, 1, 70) \) to present the distribution of the intensity. After 5 times calculation of one radius’ holes, the detected value is \( C = (164.8036, 49.4411, 82.4018, 1.6480, 115.3625) \), after calculating, the final data is \( I_0^p = (101.0374, 30.3112, 49.8059, 1.0102, 70.7362) \). The error is near 1% through comparing \( I_0 \) and \( I_0^p \), which reveals that the detected values are almost the same as the intensity of incident light, as shown in figure 4.

![Image](a) Original data  (b) calculated data

Fig. 4. Linear numerical simulation diagram

According to the linear idea, each linear point in the image is simulated and each linear restored value is spliced into an image at the end. The two-dimensional picture can be restored by combining the linear points. The restoration of the image is not a direct rotational restoration, but divided into several linear points, and finally the restored results are spliced into one image. In Fig. 5, we present the original and calculated pictures. The results show that the degree of restoration between the calculated image and the original image is high. But the original image points are too dense and large, so less than 8% of the error accumulation makes the restored image deviate in some details. In addition, when calculating the reduction by computer, the default value is used to reserve three digits behind the decimal point, and the digits behind are omitted which increases the reduction error.

![Image](a) Original picture  (b) calculated picture

Fig. 5. Two-Dimensional Image Simulation Chart of Subregional Linear Restoration

For an image, the rotation simulation test is carried out directly. The test method is to use the idea of rotation and polar coordinates to directly simulate and test a circular highlight map without subarea. In this simulation, considering that there are only five layers of perforated rings, the simulated image is a smaller five-layer thermal image, and the results after restoration are within the expected range, as shown in figure 6. However, careful observation reveals that there are slight differences in edge details between the restored image and the original image, the reason is similar with the above simulation.
4. Discussion and conclusions

A new single-pixel imaging model based on paired diffractive plates is established. A set of fixed parameters $D$, $f$, $\rho$ and weight are selected, which have good effect on infrared image restoration at wavelength of 10.6 $\mu$m, but there are shortcomings: the results are successful but the points’ number are insufficient.

In conclusion, the double rotation of weights can solve the complicated problem of data acquisition in ghost imaging, and can be applied to $SF_6$ gas imaging sensing and recognition. Besides, the cost can be reduced significantly and the results are reasonable. But there are still further investigations to be made theoretically and experimentally.

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Reference

[1] Liu H C, Zhang S. Computational ghost imaging of hot objects in long-wave infrared range. Applied Physics Letters, 2017, 111(3): 031110.

[2] Bennink R S, Bentley S J, Boyd R W, et al. Quantum and classical coincidence imaging. Physical review letters, 2004, 92(3): 033601.

[3] Gibson G M, Sun B, Edgar M P, et al. Real-time imaging of methane gas leaks using a single-pixel camera. Optics express, 2017, 25(4): 2998-3005.

[4] Han Q, Wang J, Zhang J, et al. Diffraction analysis for digital micromirror device scene projectors in the long-wave infrared. Optical Engineering, 2016, 55(8): 085105.

[5] Vandenrijt J F, Thizy C, Georges M P, et al. Long-wave infrared digital holography for the qualification of large space reflectors. International Conference on Space Optics—ICSO 2012. International Society for Optics and Photonics, 2017, 10564: 1056403.

[6] Dunham R W. Diffraction by a Circular Aperture. JOSA, 1964, 54(9): 1102-1105.