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Analysis of the features and reconstruction of a high resolution infrared image based on a multi-aperture imaging system

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ABSTRACT

Infrared images of good quality are strictly important for such applications as targets detection, tracking and identifying. Traditional single aperture infrared imaging system brings in some defects for its imaging scheme. Multi-aperture imaging system shows promising characteristic of improving image quality and reducing size of optical instruments. We reconstruct a high resolution infrared image from the low resolution sub-images collected by the compact multi-aperture imaging system. A novel reconstruction method called pixels closely arrange (PCA) is proposed based on analyzing the compound eye imaging process, and this method is verified in a simulated 3D infrared scene to capture sub-images. An evaluation of the reconstructed image quality is presented to discuss the significant factors that affect the final result. Experimental results show that the PCA method can be efficiently applied to the multi-aperture infrared imaging system as long as the structure of the micro-lens array is specifically designed to be adaptive to the infrared focal plane array (IFPA).

1. Introduction

As the compact multiple apertures imaging system rapidly develops in recent years [1–3], the size of multi-aperture imaging device becomes very small and the quality of the reconstructed image has been greatly improved. Since the structure of the multi-aperture imaging system is inspired by the compound eye of arthropods, one of the most popular imitated compound eye structures is generally composed of a set of micro lens placed in front of an focal plane array (FPA), and a typical structure of this kind is named TOMBO (thin observation module by bound optics) [1]. At present, TOMBO system is extended to measure multi-dimensional objects [4] and high speed multiple spectral construction [5]. Infrared imager structure is more complex than the other systems which leads to a larger file size. Meanwhile, the resolution of infrared images captured by a single lens is usually not good. Hence, compound eye system is introduced [6,7], and super resolution methods are applied to synthesize a single high resolution (HR) image from a collection of low resolution (LR) sub-images. Therefore, it is important to study the post-processing of LR sub-images.

The origin methods to retrieve the HR image are image sampling and back-projection [1]. Other methods proposed by researchers are wavelets and related multi-resolution [8,9], minimum variance algorithm [6], which is designed to solve the image reconstruction optimization problem for the image that varies the least in the gradient. Super-resolution method was also implemented to synthesize the HR image [10], and an analysis of the image quality was made on the compound eye imaging system by considering MTF of the system [11,12]. So far as reported in an infrared multi-aperture imaging system a least gradient reconstruction algorithm was used to retrieve the HR image [13]. The above mentioned methods were all based on the digital signal processing or image processing techniques, and the optical features were overlooked. Although there have been some discussions about how the infrared sensor characteristics affect the reconstruction result [14], infrared compound eye system features were not analyzed. In this work, we propose a new method called pixels closely arrange (PCA) to improve the image resolution in a direct and novel way. The PCA method is simple, it is inspired by the multi-aperture imaging process which is a different way form the others. The structure of this paper is the following, we first analyze the imaging process of the infrared multi-aperture and derive the relation between the FPA pixel unit and the micro-lens array's structural parameters. Then we conclude that better parameterized structure of the micro-lens array plays an important role in the improvement of the reconstruction result. By strictly designing, we can gain a dramatic improvement in the quality of an infrared image in Section 4. Finally PCA is implemented in a simulated infrared 3D scene and experiments are done to verify the efficiency of PCA.

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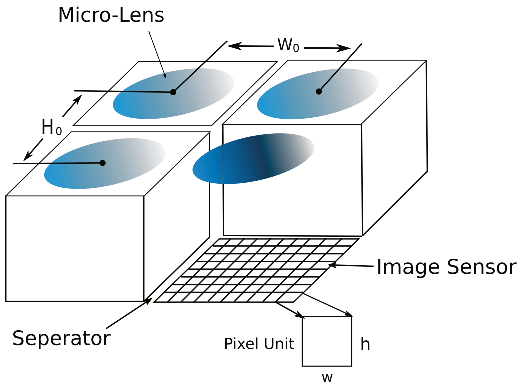

Fig. 1. Typical compound eye imaging system architecture.

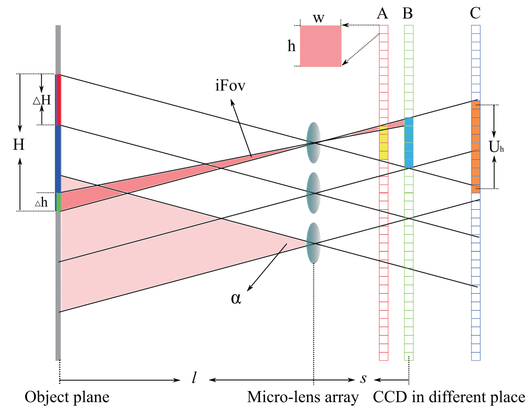

Fig. 3. Analysis of the multi-channel imaging architecture's imaging process.

2. Imaging system analysis

Over the past few years, the compound eye imaging system has been considered to have strongest potential in developing new systems that are compact size, but capable of producing fine images. Taking advantage of the typical compound eye system architecture, for example a TOMBO system as shown in Fig. 1 assuming each aperture a diffraction limited operation, we design the multi-aperture imaging system with the followed parameters in detail, as W_0 and H_0 indicate the distance between two micro lens in horizontal and vertical direction respectively, and w, h are used to describe the size of image sensor pixel unit. These parameters will all be analyzed and discussed in our simulation of the imaging system within an infrared scene.

It is well known that an infrared imaging system is usually considered to have a focus at infinity. Hence, in a multi-aperture infrared imaging system, each aperture should form a full image of the target instead of taking partial photos. Fig. 2 shows the process of capturing an LR infrared sub-image: the radiance of the target (a tank) together with the background through the atmosphere is finally captured by each single lens, then it is propagated onto the infrared focal plane array (IFPA) respectively. During this process digital processing is conducted to the captured image array, at which time the high resolution algorithm is applied. It is also one of the important factors affecting the quality of the final reconstruction result. Most HR reconstruction algorithms focus on the post-processing of the digital signals [2,9], we would like to focus on the imaging process.

For the infrared imaging process, the structural parameters we use to control the multi-aperture imaging system flexibly are list in the following. For the micro-lens array, we consider its horizontal and vertical lens number, size of its single lens, the interval between two adjacent lens and the field of view (FOV) of a single lens (or its focal length). Ideally four parameters are identical for all the micro lens in the multi-aperture imaging architecture. And for the infrared imaging sensor, we also consider its horizontal and vertical pixel units number, size of each pixel and the nonuniform noise effect, which can be together used to describe the basic structure of a sensor array. Here the pixel is treated as a square, which

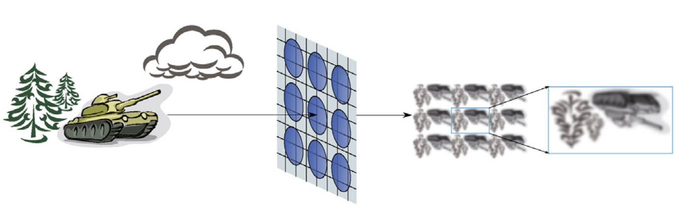

Fig. 2. Infrared image captured by multi-channel image system.

leads to the same instantaneous field of view both horizontally and vertically.

So far, the main parameters have been considered to construct the infrared multi-aperture imaging system. For the purpose of evaluating the reconstruction image quality, we will test several combinations of the parameters. In connection with all the structural parameters illustrated above, the multi-aperture imaging process can be objectively described as shown in Fig. 3.

In Fig. 3, we illustrate the relation between object plane and the micro-lens array with the IFPA, such as a CCD sensor array. In the traditional multi-aperture image system, the FPA is usually assumed to be placed at the focal length point, while in practice image quality of the captured image array changes with the different place where the sensor array is located, such as A, B and C shown in Fig. 3. In this paper, we consider the infrared CCD placed at the plane conjugated to the object plane, which can be obtained from *Gaussian formula*. We can see from Fig. 3 that the field of view α and the object distance l dictate the single image size both on the image plane and the relatively object plane, symbolized by H and U_h, respectively, where U_h can be equivalently regarded as the number of responsive pixels on the FPA. w and h indicate the size of the single sensor unit. Since the pixels on the FPA are all with the same size $w \times h$, we can derive $\triangle h$ the range of each pixel projected onto the object plane according to the IFOV $iFov$ and object distance l by Eq. (1).

$$\triangle h = l \cdot iFov = l \cdot \frac{\alpha}{U_h}. \tag{1}$$

From the view of the information captured on the FPA, we can evaluate the captured image quality by the quantity of information it contains, which also directly affects the definition of the image. Hence, reconstructing a HR image can be regarded as a procedure of increasing the information extracted from the object space as much as possible, which forms one of the basic principles in this paper. Therefore, sampling much more information through each micro-lens from the object space proves to be the core task of the HR reconstruction algorithm. Hence, the key parameter of the multi-aperture imaging system is the interval between each adjacent micro-lens, denoted by $\triangle H$ in Fig. 3. We can clearly see that $\triangle H$ is also the interval between unit images on the object plane captured by adjacent micro-lens. Then we find the way to enrich the information projected onto the FPA through each micro-lens. By restricting the interval of the adjacent micro-lens (namely W_0 and H_0 in Fig. 1) to be less than $\triangle h$, for example, we tested $\triangle H = (1/n) \cdot \triangle h$, $n = 1, \ldots, 5$, each micro-lens aperture can collect different information from the object space, which can be interpreted as sub-pixel level information on the FPA. This means that each pixel has a complementary information of the object space.