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Infrared super-resolution imaging based on compressed sensing

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HIGHLIGHTS

- We raised an infrared super-resolution imaging method based on compressed sensing.
- Our method uses a Toeplitz matrix as the measurement matrix.
- The measurement matrix is realized by phase mask method.
- Our method is applicable to the super-resolution reconstruction of moving objects.

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ABSTRACT

The theoretical basis of traditional infrared super-resolution imaging method is Nyquist sampling theorem. The reconstruction premise is that the relative positions of the infrared objects in the low-resolution image sequences should keep fixed and the image restoration means is the inverse operation of ill-posed issues without fixed rules. The super-resolution reconstruction ability of the infrared image, algorithm's application area and stability of reconstruction algorithm are limited. To this end, we proposed super-resolution reconstruction method based on compressed sensing in this paper. In the method, we selected Toeplitz matrix as the measurement matrix and realized it by phase mask method. We researched complementary matching pursuit algorithm and selected it as the recovery algorithm. In order to adapt to the moving target and decrease imaging time, we take use of area infrared focal plane array to acquire multiple measurements at one time. Theoretically, the method breaks though Nyquist sampling theorem and can greatly improve the spatial resolution of the infrared image. The last image contrast and experiment data indicate that our method is effective in improving resolution of infrared images and is superior than some traditional super-resolution imaging method. The compressed sensing super-resolution method is expected to have a wide application prospect.

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1. Introduction

The infrared image super-resolution reconstruction has an important role in military, medical, industrial, aerospace and many other areas. In military, higher resolution of infrared images means greater capacity of identification, detecting and combating military targets. In medical, higher-resolution of infrared images can help to detect early lesions, and then carry out early intervention therapy. In industry, higher-resolution of infrared images are more meaningful to locate the power system fault location, and steelmaking furnace temperature distribution, and then facilitate the effective maintenance of the system. In aerospace, higher-resolution infrared image is conducive to the running state of the various components of the spacecraft. It has important guiding significance to the spacecraft attitude control and trait judgments. Continuously improving the spatial resolution of the infrared image has become more and more urgent basic needs of the people [1,2].

There are two main ways in traditional infrared super-resolution research. One is based on microscanning. For example, Fortin et al. [3], Awamoto et al. [4], Armstrong and Packard [5], Cabanski et al. [6] and our research team [7] all proposed microscanning super-resolution imaging method based on infrared optical system (or optical elements). However, there are some serious problems existing in microscanning technology. For example, image rotation occurs and image non-uniformity increases, which limit the performance of super-resolution reconstruction. In recent years, software super-resolution reconstruction method is developing rapidly. The method is composed of image registration and image restoration. Guizar-Sicairos et al. [8], Katsaggelos of Northwestern University all obtain a large number of results on the research of registration, interpolation and recovery algorithm. Although the super-resolution imaging methods have made a series of progress, there are still

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some defects. (1) The infrared image super-resolution reconstruction technology is restricted by the Nyquist sampling theorem. Restricted by Nyquist sampling theorem, the theoretical spatial resolution lifting capacity is low; (2) the super-resolution reconstruction methods which have excellent performance need some continuous image sequences to complete the reconstruction process. This requires that the objects should be stationary or the speed of the relative movement is low. These defects severely limit the further development of traditional super-resolution reconstruction method (see Fig. 1).

Donho, Candes, Tao put forward the concept of compressed sensing in 2006 [9]. Its core idea is that if signal y is sparse in an orthogonal space Ψ (i.e. the spatial transform coefficients S of signal y are almost zero in space Ψ), we sample the signal y by a sampling matrix Φ which is irrelevant with Ψ and get some sampling points. Then we can restore the original signal y with high probability. In this theory, under the condition of restoring signal y exactly, the number of sampling points is much smaller than that required by Nyquist sampling theorem [10–12]. Compressed sensing theory breakthrough Nyquist sampling theorem, and has the potential to play an important role in super-resolution reconstruction. In 2008, the Rice University reported the single-pixel camera system which adopted compressed sensing theory [13]. The imaging schematic diagram is shown in Fig. 4, in which the target scene is focused on the digital micromirror device (DMD) by the first lens. And then, the target scene is continuously reflected to the second lens by the rotation of the micromirrors on the DMD array. Through the converging action of the second lens, the scene target is mixed and converged to the photodiode, and one measurement completes. By use of multiple measurement results, original scene can be reconstructed. The sampling number of compressed sensing is only about 1% of that required by Nyquist Theorem.

The successful development of the single-pixel camera of Rice University provides a new way for infrared image super-resolution reconstruction. However, the single-pixel can only obtain one measurement value at one time. In order to recovery one frame super-resolution image, multiple imaging is necessary. Higher the resolution of the reconstruction image is, more measurement data are needed. So, it is also not adapt to moving objects as traditional super-resolution reconstruction method based on Nyquist sampling theorem. To resolve the problems mentioned above, we brought forward a panel detector compressed sensing-based super-resolution imaging method in this paper. The method uses the infrared focal plane array to detect measurement values, realizes measurement matrix by phase mask plate. This method not only broke through the Nyquist sampling theorem but also had the same ability of improving spatial resolution of stationary targets and moving target. The paper is organized as follows. Section 2 is the specific design of imaging method. Section 3 is about the design of measurement matrix. Recovery algorithm is discussed in Section 4. The experiment verification is in Section 5 and Section 6 give the conclusion of the paper.

2. Imaging design based on compressed sensing

The imaging design proposed in this paper is illustrated in Fig. 2. In Fig. 2 the phase mask plate is close to the lens L2. The infrared light emitted from infrared object P1 is focused on P2 by the convergence effects of lens L1. Through the phase modulation effect of phase mask plate, the infrared light from P1 dispersed in the entire receiving surface of the lens L2. Similarly, through the modulation effect of the phase mask plate, the other points of the infrared image also dispersed in the entire receiving surface of the lens L2. Thereby the infrared light emitted from infrared scene can confuse on the surface of lens L2. Lens L2 focuses the infrared light which has modulated by phase mask template on the infrared focal plane array (IRFPA) detection element. Each detection element obtains a measurement value, and so, all measurement values can be acquired at one time.

Supposing the array size of the IRFPA is 320×240 (frame rate is 25 Hz and pixel non-uniformity is 0.021%), 320×240 measurement data can be obtained after a single image. If our experiment results are the same with single-pixel camera of Rice University, that is, the sampling number of compressed sensing is only about 1% of that required by Nyquist theorem. Then, our method can recover the infrared image with the array size of 384,0000 (3200×2400, or 1600×1200 or others). The spatial resolution has been far more than the current commercial highest resolution of the thermal imager. Compared with the DMD program of Rice University single-pixel camera, the advantages of our program are: (1) our program can obtain multiple measurements at one-time which reduces system imaging time; (2) the theoretical maximum resolution that our program can recover is much larger than that of Rice University single-pixel camera; (3) to moving target, our program can obtain exact measurement values. Compared with the traditional super-resolution imaging method, our program can acquire all data needed by recovery algorithm through one-time measurement. This characteristic overcomes the restriction that targets should be stationary or moving slowly in traditional super-resolution reconstruction.

The theoretical analysis of our program is as follows.

For a spares signal f in some spare basis Ψ, estimation coefficient $\hat{\theta}$ can be obtained by solving minimization problem [14]:

$$\hat{\theta} = \arg\min ||\theta||_1, \quad g = \Phi\Psi\theta, \tag{1}$$

where $\|\theta_1\| = \sum_{i=1}^{N} |\theta_i|$, $g = \Phi f$ is measurement vector, Φ is measurement matrix, $\Phi\Psi$ is sensing matrix. By finding $\hat{\theta}$ which has the minimum 1_1 norm from coefficient vector θ, we can take use of $f = \Psi\hat{\theta}$ and then reconstruct original infrared image

In actual measurement process, we need take into account the influence on the imaging model by various errors. In this case, Eq. (1) should be changed to:

$$\hat{\theta} \arg\min \|\theta\|_1, \|g - \Phi\Psi\theta\|_2 \le \varepsilon, \tag{2}$$

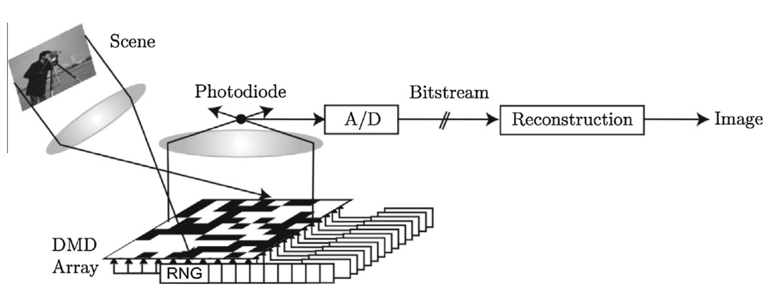

Fig. 1. Single-pixel camera imaging principle of Rice University.

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