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Modeling and image motion analysis of parallel complementary compressive sensing imaging system

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ABSTRACT

Based on the theory of compressive sensing, a parallel complementary compressive sensing imaging system is proposed, and the mathematical model of block parallel processing is established. Parametric analysis shows that the quality of the restored image increases with the increase of observed compression ratio and the decrease of the number of blocks, which is in conflict with total amount of data and time-consuming of algorithm, and needs to be considered comprehensively. According to the demand of space remote sensing system applied in push-broom mode, the image motion model of the system is established. The results show that the image motion has a severe effect on the quality of restored image, and increasingly responsive with the decrease of the number of blocks. when the orbital image motion parameter is constant, improving the frame rate of the detector and increasing the pixel size can obtain a smaller image motion ratio, thereby enhancing the image quality. But the application scope of the system for push-broom imaging is somewhat limited for its significantly degrade under low image motion ratio.

1. Introduction

From the perspective of signal decomposition and approximation theory, E.J. Candes, J. Romberg, T. Tao and D.L. Donoho proposed the theory of compressed sensing(CS) in 2006 [1–3]. In the framework of this theory, if a signal is sparse in a transform domain, the sampling process will no longer be limited by the Shannon–Nyquist sampling theorem, and the original signal can be recovered from far fewer samples [4–6]. This not only reduces the requirements for hardware sampling devices, and far fewer samples can also reduce the pressure on data storage and transmission, thereby improving resource utilization.

Based on the above advantages, the compressive sensing theory has been widely concerned in the fields of medical imaging, optical radar imaging, information image processing and wireless communication. The research of computational imaging technology in the field of space remote sensing mainly focuses on high resolution imaging and multi-spectral imaging based on CS theory [7,8]. In the application of CS theory, aperture coding [9–11], digital micro-mirror device(DMD) coding [12,13], random exposure coding [14] are mostly adopted in the system to realize the random coding observation of the target signal.

The single pixel camera based on DMD is a typical application of CS theory [15–17]. It uses photodiode instead of the image sensor to complete the image sampling function, which greatly reduces the cost and the complexity of the hardware design. However, when large-scale imaging is performed, the number of coding increases, resulting in a sharp increase in observation time. Meanwhile, large-scale matrix makes the operation time of reconstruction algorithm greatly increased. The combination of the above two makes the time cost of the system larger, which sacrifices the real-time performance of the system.

Solmaz Hajmohammadi presents a parallel algorithm for handling the recursion in bispectrum phase recovery [18]. The proposed massively parallel bispectrum algorithm relies on multiple block parallelization, which achieves a speed-up of 85.94 over its recursive sequential counterpart with no loss in image quality. Aswin C. Sankaranarayanan shows two specific prototypes that achieve megapixel resolution images at video-rate by the extensions of Single Pixel Camera(SPC) [19]. A highly parallel extension of the SPC based on a focal plane array is investigated by John P. Dumas [20]. Yao Zhao et al. proposed a super resolution imaging system based on parallel compressed sensing. The proposed method first measures the transmission matrix of the scattering sheet, and parallel means that charge-coupled device camera can obtain enough measurements at once instead of changing the patterns on the DMD repeatedly [21].

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B. Sun has demonstrated that a computational ghost imaging system can be readily made more robust to sources of noise, by rapid sequential projection of binary patterns and their inverse and demodulating the signals acquired from a single photodiode [22]. The sampling concept of complementary compressed sensing is proposed by Wen-Kai Yu, and applied in a telescope system with two photomultiplier tubes [23]. He also demonstrated a 3D compressive reflectivity imaging system with only a single-pixel detector and complementary intensity modulation performed by a DMD, which complies with the computer-generated random one-to-one complementary binary pattern pairs [24]. And an experiment on compressive microscopic imaging with single-pixel detector and single-arm has been performed on the basis of "positive–negative" (differential) light modulation of a digital DMD [25]. A new type of compressive spectroscopy technique employing a complementary sampling strategy is reported by Ruo-Ming Lan. In a single sequence of spectral compressive sampling, positive and negative measurements are performed, in which sensing matrices with a complementary relationship are used [26]. A.D. Rodríguez demonstrates an inverted microscope that utilizes a DMD for patterned illumination altogether with two single-pixel photo sensors for efficient light detection. The system works by sequential projection of a set of binary intensity patterns onto the sample that are codified onto a modified commercial DMD [27].

Based on the above considerations, a parallel complementary compressive sensing imaging system based on DMD is proposed in this paper. By means of two detectors sensing the light reflected in both outputs of the DMD, the measurement matrix of −1, 1 sequence is acquired without increasing the observation time, whose performance is generally better than 0, 1 sequence. Moreover, multi-block parallel coding is carried out with an array detector instead of a single pixel, which reduce the observation time and the operation time. But compared to the traditional compressive sensing system, an additional detector is added, and the subsequent driving and processing circuits are also increased, so the cost of hardware is somewhat increased.

On the basis of this system, the mathematical model of block parallel processing is established. Parameters such as number of blocks and observed compression ratio are analyzed and discussed. Then, the image motion model in the field of remote sensing imaging is established, and the performance degradation of the restored image due to image motion is quantitatively analyzed and discussed.

2. Composition of the imaging system

The schematic diagram of parallel complementary compressive sensing imaging system is shown in Fig. 1, which consists mainly of front-end lens system, DMD, matching lens system 1 and 2, and detector 1 and 2. The DMD is used as a compression encoder in the system. Each micro-mirror in DMD has 0 and 1 working states, of which 0 corresponds to the deflection of −12 degrees, and 1 corresponds to the deflection of +12 degrees. When the target scene is incident on the DMD through the front-end lens system, a part of the light is reflected by the micro-mirror in the 0 state along the direction 1, and reaches the detector 1 through the matching lens system 1. Another part of the light is reflected by the micro-mirror in the 1 state along the direction 2, and reaches the detector 2 through the matching lens system 2. The matching lens system mainly realizes the matching relationship between the micro-mirror size of DMD and the pixel size of detector.

Compared with the single-pixel imaging system, this imaging system uses an array detector instead of the photodiode as the image information receiver. At the same time, two detectors are used to collect the light reflection information of DMD under two states. Therefore, the imaging system has two significant advantages.

Firstly, with the array detector used, the target scene can be divided into blocks according to the scale of the detector pixels, that is, each encoding is performed in parallel for multiple image blocks. Since the amount of information of each sub-image block is greatly reduced with respect to the entire image, the number of parallel encoding times is greatly reduced, which thus reduces the observation time of encoding process.

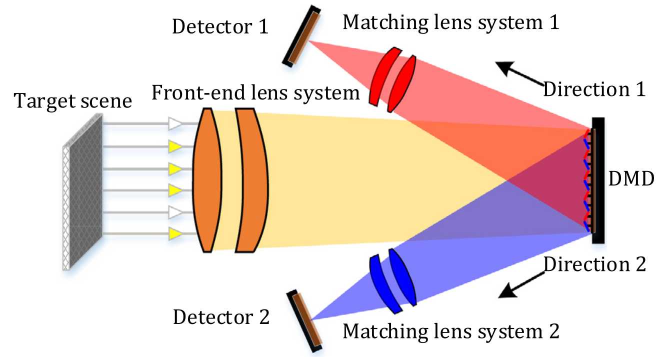

Fig. 1. The schematic diagram of parallel complementary compressive sensing imaging system.

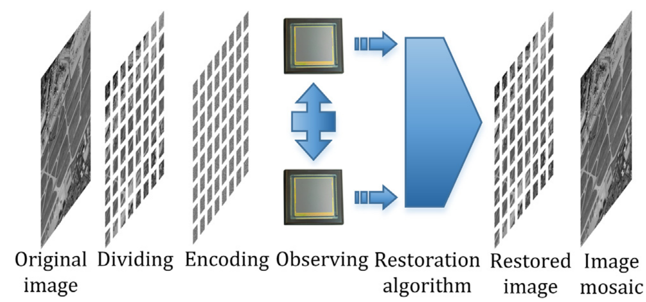

Fig. 2. The workflow of parallel complementary compressive sensing imaging system.

Secondly, two array image detectors are used to receive the light reflection information of the two states of micro-mirror in the DMD respectively. By subtracting the data collected by each detector from each other, an observation information can be obtained, thereby the measurement matrix formed is a sequence of −1 and 1. Compared with the 0, 1 sequence, this method can obtain more image information, which resulting in a better reconstructed image with the same number of observations. Or from another point of view, this system can consume less observation time with the same reconstructed image quality.

The above description is only a qualitative analysis of the system. In the following, the mathematical model of the system will be built, and quantitative analysis and discussion of specific parameters will be carried out.

3. Blocking and parallel processing method

3.1. Model establishment

The workflow of the imaging system is shown in Fig. 2. Compared with the traditional compressive sensing imaging system, the target scene is divided into several blocks first, and each sub-image block is simultaneously encoded in parallel by DMD. Then two array detectors are used to receive the encoded image information, wherein each detector pixel corresponds to a sub-block. Based on the collected image information, the reconstruction of each sub-image block is completed by the image restoration algorithm, and finally the block images are spliced into the desired target scene. The number of encoding is the number of frames captured by the detector.

The algorithm theory of compressive sensing imaging system is derived from the sparse characteristics of natural images under the