Optics Communications 371 (2016) 105–111

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Compressive microscopic imaging with "positive–negative" light modulation

Wen-Kai Yu [a,*], Xu-Ri Yao [b], Xue-Feng Liu [b], Ruo-Ming Lan [c], Ling-An Wu [d], Guang-Jie Zhai [b], Qing Zhao [a]

[a] School of Physics, Beijing Institute of Technology, Beijing 100081, China
[b] Key Laboratory of Electronics and Information Technology for Space System, National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China
[c] School of Physics and Electronics, Shandong Normal University, Jinan 250014, China
[d] Laboratory of Optical Physics, Institute of Physics and Beijing National Laboratory for Condensed Matter Physics, Chinese Academy of Sciences, Beijing 100190, China

ARTICLE INFO

Article history:
Received 17 December 2015
Received in revised form
17 March 2016
Accepted 23 March 2016
Available online 29 March 2016

Keywords:
Imaging systems
Compressed sensing
Image reconstruction techniques
Medical and biological imaging
Modulation techniques
Microscopy

ABSTRACT

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 micromirror device (DMD). A magnified image of micron-sized objects illuminated by the microscope's own incandescent lamp has been successfully acquired. The image quality is improved by one more orders of magnitude compared with that obtained by conventional single-pixel imaging scheme with normal modulation using the same sampling rate, and moreover, the system is robust against the instability of light source and may be applied to very weak light condition. Its nature and the analysis of noise sources is discussed deeply. The realization of this technique represents a big step to the practical applications of compressive microscopic imaging in the fields of biology and materials science.

1. Introduction

Compressed sensing (CS) [1–3] brought a new era of signal processing and information theory. It asserts that a signal can be perfectly reconstructed from the linear noisy measurements with a sampling rate much lower than the Nyquist–Shannon limit, when the signal is sparse or compressive. Based on this idea, Baraniuk's group designed a prototype single-pixel camera (SPC) [4,5], which shifts the spatial information away from the array detector and onto a set of patterns, and replaces the spatially resolving detector with a bucket detector, solving operational problems involved in systems of raster scanning. This work has motivated an ongoing effort to implement SPC-based technologies, such as lidar [6], optical encryption [7], and newly, adaptive compressive imaging [8–10]. Besides, the SPC was also applied to microscopy [11–13]; in 2012, Studer et al. [12] tested their microscope scheme on a sample of fluorescent beads distributed sparsely. Then, Radwell et al. [13] presented a single-pixel microscope system to produce images of a simple silicon CMOS chip simultaneously in the visible and shortwave infrared. These SPC-based methods use a programmable digital micromirror device (DMD). The advance of DMD technique also initiates many new design approaches for Hadamard transform spectral imager [14], Fourier ptychographic microscopy [15,16], entanglement imaging [17], and entanglement light object tracking [18]. Since each micromirror on the DMD can only be oriented at $+12^\circ$ (corresponding to bright pixel 1) or -12° (dark pixel 0), the patterns used for the light modulation are generally non-negative and are 0–1 randomly distributed.

However, such random patterns whose entries are either 0 or 1 cannot achieve good performance [19,20] with respect to the restricted isometry property (RIP) [21,22] required for CS reconstructions. To reduce this limitation, we have recently proposed a novel technique that uses corresponding patterns in both reflections of the DMD known a priori to be complementary to dramatically improve the image quality [23]. We call this technique complementary compressive imaging. As an alternative to differential measurements in both reflections, a prototype single-arm compressive microscope with "positive–negative" (differential) modulation of the DMD is presented here, offering significant cost savings. We make a difference between each adjacent frames to generate a zero-mean sensing matrix, which is

* Corresponding author.
E-mail address: yuwenkai@bit.edu.cn (W.-K. Yu).

http://dx.doi.org/10.1016/j.optcom.2016.03.067
0030-4018/

equivalent to encode "positive–negative" patterns onto the DMD to realize the "positive–negative" modulation. Because it inherits the advantages of our previous method, it can not only image complex gray samples but also produce a very satisfactory image quality. Moreover, the system can overcome intensity instability of the light source and may be used in ultra-weak light conditions. Through the quantitative analysis of the noise, it is proved that the signal-to-noise ratio in the measurement process can also be significantly improved.

To our knowledge, Padgett's group has proposed similar compressive microscopic imaging scheme [13] which also uses the differential measurement between each frame and its inverse, and their earlier paper [24] said that such differential detection is more robust to external noise. However, they failed to provide the detailed description and analysis of noise sources, as well as direct comparison between positive–negative modulating and normal modulating. Besides, the system presented in their earlier paper used structured light illumination and was performed under bright field illumination, which is different from the one employed in this paper. Furthermore, although both papers from Padgett's group used compressed sensing theory, they all failed to explain why differential measurements could help increase the performance. In this paper, we will provide a new detailed explanation from RIP aspect. Furthermore, we have also proved that the complementary sampling protocol (where each frame is displayed twice, the second time inverted) is a special case of the differential measurement scheme (where the two adjacent frames are irrelevant), having a zero-mean in common. To our knowledge, differential ghost imaging (DGI) [25] is a very early differential imaging scheme, which can improve the signal-to-noise by subtracting the background noise item from the weighted average item of the conventional ghost imaging, but it is not a pairwise differential measurement like the one used here. Besides, most references [26–29] to differential imaging have been relative to our work. It can be said that our work is derived from the differential imaging. However, in this paper, the word "differential" refers to the manner that one pattern (or bucket value) minus its adjacent one, which is a little different from DGI's subtracting the background noise.

In the experiment, using an ordinary microscope's own illumination lamp and the differential modulation of the DMD, images of the mouthparts of a female mosquito have been reconstructed with far fewer measurements and a better performance in one more orders of magnitude than that of conventional compressive imaging with normal modulation.

2. Experimental setup and implementation

The experimental apparatus is illustrated in Fig. 1. The sample table is illuminated from overhead by an ordinary incandescent lamp (a noncoherent thermal source). The light from the object passes vertically down through the objective, and after reaching a flippable beam splitter it may be viewed directly through the eyepiece or transmitted by various mirrors and lenses to the DMD. A $10\times$ magnification is achievable with the objective, which has a numerical aperture of 0.25. The DMD that consists of 768×1024 micro-mirrors each with size $13.68 \times 13.68\ \mu m^2$ is switched between two positions oriented at $+12^\circ$ or -12° with respect to the plane of the DMD. The modulation frequency of the DMD can reach 32.5 kHz. A photomultiplier tube (PMT) (Hamamatsu H7468-20) is used as the bucket (single-pixel) detector for collecting the total light intensity reflected from the DMD. Our proof-of-principle single-pixel microscopic imaging experiment is performed under ultra-weak light condition where ordinary microscopy photography would be impossible. Generally, in biological microscopy, the object is a fluorescing sample like cells, tissues and beads, the light from which is extremely weak. Here the sample consists of the mouthparts of a female mosquito, about

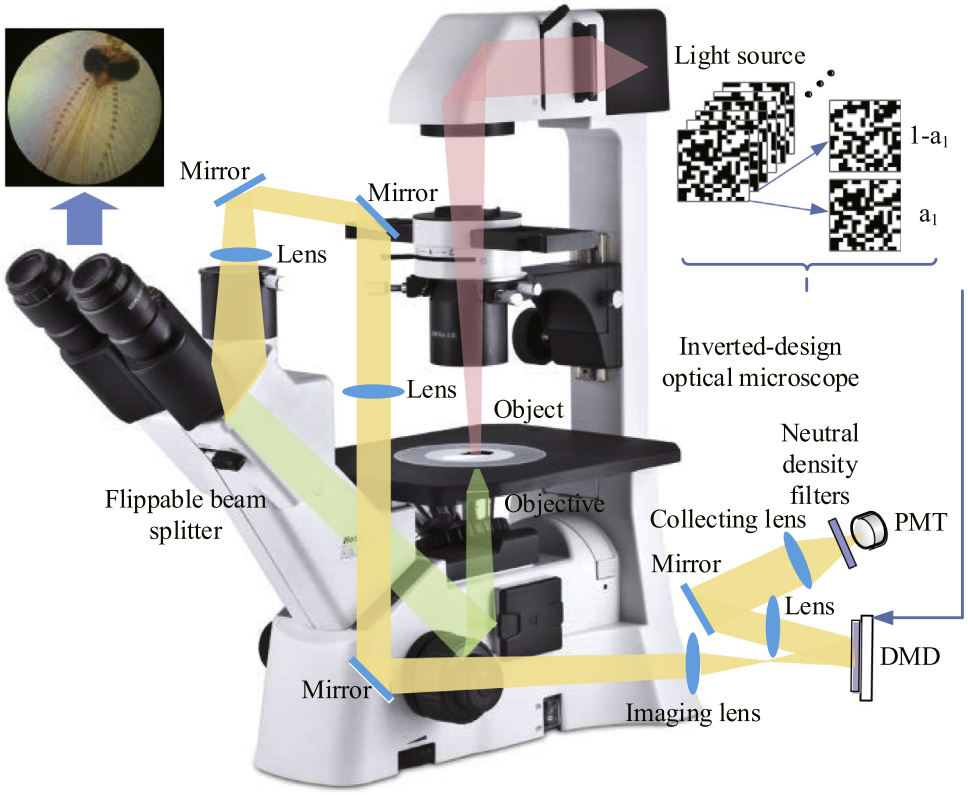

Fig. 1. Schematic of the experimental setup.