Signal Processing: Image Communication 60 (2018) 107–115

Contents lists available at ScienceDirect

Signal Processing: Image Communication

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

Extracting sub-exposure images from a single capture through Fourier-based optical modulation

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ARTICLE INFO

Keywords:
Computational photography
Optical coding
Pixel-wise exposure control

ABSTRACT

Through pixel-wise optical coding of images during exposure time, it is possible to extract sub-exposure images from a single capture. Such a capability can be used for different purposes, including high-speed imaging, high-dynamic-range imaging and compressed sensing. In this paper, we demonstrate a sub-exposure image extraction method, where the exposure coding pattern is inspired from frequency division multiplexing idea of communication systems. The coding masks modulate sub-exposure images in such a way that they are placed in non-overlapping regions in Fourier domain. The sub-exposure image extraction process involves digital filtering of the captured signal with proper band-pass filters. The prototype imaging system incorporates a Liquid Crystal over Silicon (LCoS) based spatial light modulator synchronized with a camera for pixel-wise exposure coding.

1. Introduction

Coded aperture and coded exposure photography methods, which involve control of aperture shape and exposure pattern during exposure period, present new capabilities and advantages over traditional photography. In coded aperture photography, the aperture shape is designed to achieve certain goals. For example, the aperture shape can be designed to improve depth estimation accuracy as a part of depth-from-defocus technique [1], or to improve deblurring performance through adjusting the zero crossings of point spread function [2]. Coded aperture photography may involve capture of multiple images, where each image is captured with a different aperture shape, for instance, to acquire light field [3], or to improve depth estimation and deblurring performance [4]. Using coded aperture, it is possible to do lensless imaging as well [5,6].

In coded exposure photography, the exposure pattern is controlled during exposure period. The coding can be global, where all pixels are exposed together with a temporal pattern, or pixel-wise, where each pixel has its own exposure pattern. An example of global exposure coding is the flutter shutter technique [7], where the shutter is opened and closed according to a specific pattern during exposure period to enable better recovery from motion blur. The flutter shutter idea can also be used for high-speed imaging [8]. Pixel-wise exposure control presents more flexibility and wider range of applications compared to global exposure coding. An example of pixel-wise exposure control is presented in [9], where the goal is to spatially adapt the dynamic range of the captured image. Pixel-wise coded exposure imaging can also be used for focal stacking through moving the lens during the exposure period [10], and for high-dynamic-range video through per-pixel exposure offsets [11].

Pixel-wise exposure control is also used for high-speed imaging by extracting sub-exposure images from a single capture. In [12], pixels are exposed according to a regular non-overlapping pattern on the space–time exposure grid. Some spatial samples are skipped in one time period to take samples in another time period to improve temporal resolution. In other words, spatial resolution is traded off for temporal resolution. In [13], there is also a non-overlapping space–time exposure sampling pattern; however, unlike the global spatial–temporal resolution trade-off approach of [12], the samples are integrated in various ways to spatially adapt spatial and temporal resolutions according to the local motion. For fast moving regions, fine temporal sampling is preferred; for slow moving regions, fine spatial sampling is preferred. Instead of a regular exposure pattern, random patterns can also be used [14–16]. In [14], pixel-wise random sub-exposure masks are used during exposure period. The reconstruction algorithm utilizes the spatial correlation of natural images and the brightness constancy assumption in temporal domain to achieve high-speed imaging. In [15,16], the reconstruction algorithm is based on sparse dictionary learning. While learning-based approaches

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https://doi.org/10.1016/j.image.2017.09.012
Received 6 May 2017; Received in revised form 8 September 2017; Accepted 29 September 2017
Available online 14 October 2017
0923-5965/

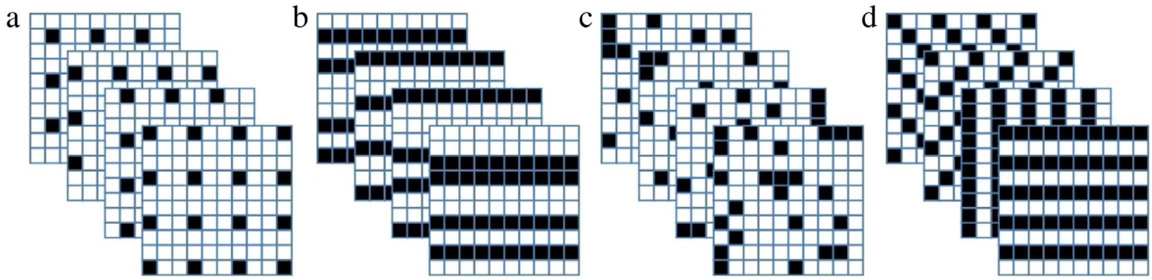

Fig. 1. Illustration of different exposure masks. (a) Non-overlapping uniform grid exposure [13], (b) Coded rolling shutter [17], (c) Pixel-wise random exposure [15], (d) Frequency division multiplexed imaging exposure [20].

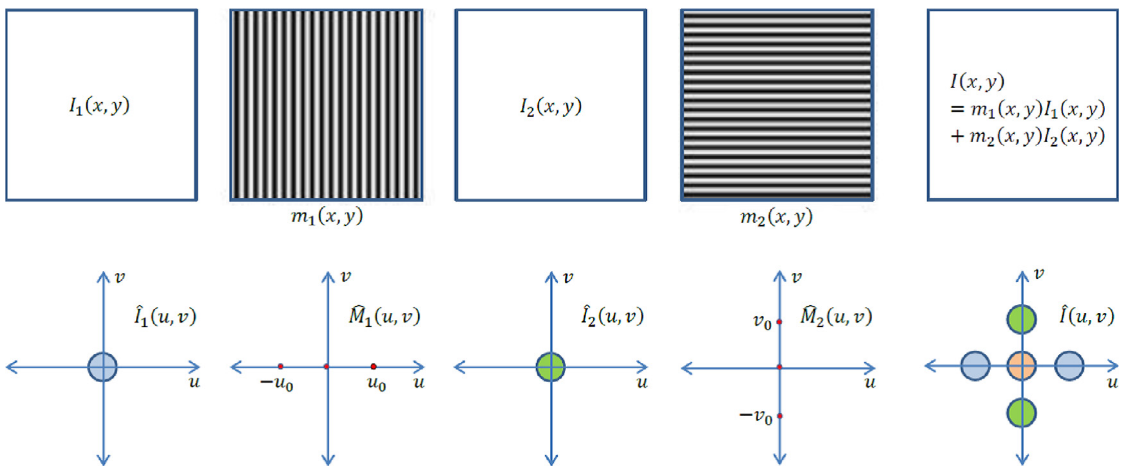

Fig. 2. Illustration of the FDMI idea with two images [20].

may yield outstanding performance, one drawback is that the dictionaries need to be re-trained each time a related parameter, such as target frame rate, is changed.

Alternative to arbitrary pixel-wise exposure patterns, it is also proposed to have row-wise control [17] and translated exposure mask [18,19]. Row-wise exposure pattern can be designed to achieve high-speed imaging, high-dynamic-range imaging, and adaptive auto exposure [17]. In [18], binary transmission masks are translated during exposure period for exposure coding; sub-exposure images are then reconstructed using an alternating projections algorithm. The same coding scheme is also used in [19], but a different image reconstruction approach is taken.

Pixel-wise exposure control can be implemented using regular image sensors with the help of additional optical elements. In [9], an LCD panel is placed in front of a camera to spatially control light attenuation. With such a system, pixel-wise exposure control is difficult since the LCD attenuator is optically defocused. In [21], an LCD panel is placed on the intermediate image plane, which allows better pixel-by-pixel exposure control. One disadvantage of using transmissive LCD panels is the low fill factor due to drive circuit elements between the liquid crystal elements. In [22], a DMD reflector is placed on the intermediate image plane. DMD reflectors have high fill factor and high contrast ratio, thus they can produce sharper and higher dynamic range images compared to LCD panels. One drawback of the DMD based design is that the micromirrors on a DMD device reflect light at two small angles, thus the DMD plane and the sensor plane must be properly inclined, resulting in "keystone" perspective distortion. That is, a square DMD pixel is imaged as a trapezoid shape on the sensor plane. As a result, pixel-to-pixel mapping between the DMD and the sensor is difficult. In [23], a reflective LCoS spatial light modulator (SLM) is used on the intermediate image plane. Because the drive circuits on an LCoS device is are on the back, high fill factor is possible as opposed to the transmissive LCD devices. Compared to a DMD, one-to-one pixel correspondence is easier with an LCoS SLM; however, the light efficiency is not as good as the DMD approach. In [18], a lithographically patterned chrome-on-quartz binary transmission mask is placed on the intermediate image plane, and moved during exposure period with a piezoelectric stage for optical coding. This approach is limited in terms of the exposure pattern that can be applied.

In this paper, we demonstrate a sub-exposure image extraction idea. The idea, which is called frequency division multiplexed imaging (FDMI), was presented by Gunturk and Feldman as a conference paper [20]. While the FDMI idea was demonstrated by merging two separate images with a patterned glass based and an LCD panel based modulation in [20], it was not demonstrated for sub-exposure image extraction. Here, we apply the FDMI idea to extract sub-exposure images using an optical setup incorporating an LCoS SLM synchronized with a camera for exposure coding.

In Section 2, we present the problem of extracting sub-exposure images through space–time exposure coding, and review the FDMI approach. In Section 3, we present the optical setup used in the experiments. In Section 4, we provide experimental results with several coded image captures. In Section 5, we conclude the paper with some future research directions.

2. Extracting sub-exposure images from a single capture

There are various exposure coding schemes designed for extracting sub-exposure images from a single capture. First, we would like to present a formulation of the coding process, and then review the FDMI idea.

2.1. Space–Time exposure coding

Space–time exposure coding of an image can be formulated using a spatio-temporal video signal $I(x, y, t)$, where (x, y) are the spatial