Optics Communications ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Optics Communications

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

Separating reflective and fluorescent components for dynamic scenes

Xiangyang Ji [a,b,*], Changlong Miao [a], Yongbing Zhang [a], Xing Lin [b], Qionghai Dai [a,b]

[a] Graduate School at Shenzhen, Tsinghua University, Shenzhen, 518055, China
[b] Department of Automation, Tsinghua University, Beijing, 100084, China

ARTICLE INFO

Keywords:
Fluorescence
Reflectance
Computational hyperspectral imaging
Compressive sensing

ABSTRACT

Separating reflective and fluorescent components by hyperspectral (HS) imaging is significant in many applications. This paper designs an imaging system, where both HS reflective images and HS fluorescent images could be obtained from the same scene, even scenes within moving objects. The system consists of a high-frequency-spectra light source and a spatially–spectrally encoded camera. During the capture phase, the light source illuminates the scene with two high-frequency lighting patterns complemented in the spectral domain by turns, then encoded camera captures a image pair accordingly. During the reconstruction phase, sparsity of the natural reflective and fluorescent HS images is utilized to recover reflective and fluorescent spectra from encoded image pair. Benefited from double-shot imaging system, dynamic scene could also be handled. The method is tested in various datasets(including synthetic and real data), and the results demonstrate that the system could achieve high-resolution hyperspectral reflectance and fluorescence recovery with high-accuracy for dynamic scenes, which can be applied for spectral relighting of real scenes.

1. Introduction

Fluorescent surfaces are widely existing in about 20% of natural scenes [1], including gems, corals, writing paper and clothes, which is a significant proportion of scenes that have to be considered. In contrast to a reflective substance that reflects light at the same wavelength as illumination, the fluorescent substance usually emits light at longer wavelengths by absorbing illumination at certain wavelengths. The additional fluorescent spectrum information can facilitate some important applications [2,3]. Since a target scene may contain both reflective and fluorescent objects, and fluorescent items exhibit both reflectance and fluorescence, reflective–fluorescent spectra is challenging to un-mix.

Many hyperspectral imaging approaches have been proposed to recover high-resolution 3D HS images from a single 2D image, which has a distinct advantage for dynamic scenes, compressive HS imaging approaches [4–6] have been actively investigated in the past few years. However, conventional HS imaging methods do not consider fluorescent phenomena. Consequently, these approaches cannot separate between reflective and fluorescent spectra [7,8], which limits their applications for scenes containing fluorescent objects.

Recently, researchers are seeking to capture both reflective and fluorescent components for a static scene. Independent component analysis [9] is used to roughly separate the two components by assuming that the two components captured in an image are statistically independent, but it does not recover the spectral distributions. In addition, methods for HS imaging of reflective and fluorescent components have also been proposed, such as bispectral scanning [10,11] or spectral scanning under different illumination [12,13]. However, these existing approaches require extensively temporal scanning which limits their applications in dynamic scenes.

To address this problem, we design a method to simultaneously recover reflective and fluorescent hyper-spectra for dynamic scene. For this purpose, the proposed approach employed high-frequency illuminations in the spectral domain and coupled the reflective–fluorescent spectra into a complementary image pair with a spatially–spectrally encoded compressive HS camera. During reconstruction, we proposed a robust sparse representation method, where the over-complete reflectance and fluorescence dictionaries are learned offline. In order to recover the reflective and fluorescent HS images from the coded projection pair, we analyze the spectral light transport model for reflectance and fluorescence, and propose a robust sparse reconstruction approach to separately recover the high-resolution reflective and fluorescent HS images with high accuracy.

The contributions of this work are summarized as follows:

(1) We propose an approach that can simultaneously reconstruct HS reflectance and fluorescence images for dynamic scenes. The proposed approach is a general framework that can be applied to any compressive HS imaging methods for reflective and fluorescent separation flexibly.

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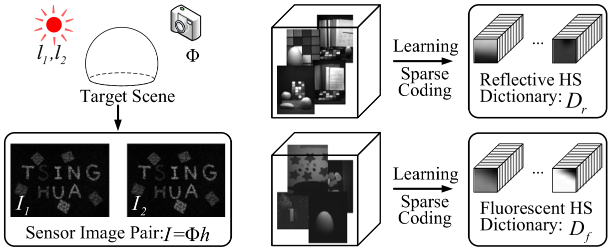
* Correspondence to: Main building No. 711A, Tsinghua University, Beijing, 100084, China.
E-mail address: xyji@tsinghua.edu.cn (X. Ji).

http://dx.doi.org/10.1016/j.optcom.2017.05.075
Received 6 April 2017; Received in revised form 20 May 2017; Accepted 28 May 2017

Please cite this article in press as: X. Ji, et al., Separating reflective and fluorescent components for dynamic scenes, Optics Communications (2017), http://dx.doi.org/10.1016/j.optcom.2017.05.075.



(a) Complementary spatial–spectral encoded HS sampling
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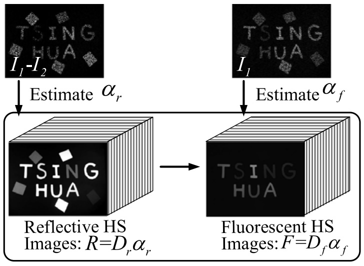
(b) Over-complete HS dictionaries learning (Offline).



(c) Separate HS images reconstruction .

Fig. 1. Overview of our approach. (a) Capturing a spatially–spectrally encoded image pair with complementary high-frequency illumination. (b) Learning over-complete reflective and fluorescent HS Dictionaries. (c) Recovering of reflective and fluorescent hyper-spectra separately.

(2) By learning the sparse representation of natural reflective and fluorescent HS images, and analyzing the spectral light transport model of reflectance and fluorescence under our coded illuminations, we derive the elegantly sparse reconstruction algorithm to separately reconstruct the reflective and fluorescent HS images from the compressive measurements.

(3) We build a prototype system that composed of a programmable coded HS light source and a spatial–spectral encoded compressive HS camera, and validate the effectiveness of our approach by simultaneously recovering high-resolution HS reflectance and fluorescence videos with high-accuracy from the data captured by our system.

2. Related work

In this section, we briefly review two related topics: (1) hyperspectral imaging, (2) fluorescent spectrum recovery.

Hyperspectral imaging has always been an active area of research over the past decades. Spectral analysis and imaging contribute to many applications, such as microscopy [14], remote sensing [15] and biomedical optics [16]. Generally, hyperspectral imaging can be divided into multiple exposures based and snaptshot based approaches. The former approaches involve a temporal sequential scanning of a spectral dimension [17,18]. A spatial variant color filter [18] and tunable spectral filter [17] can be placed in front of the camera to capture separating spectral data. Besides, the active illumination approach based on a linear spectral reflectance model [8] is also proposed. The snapshot approaches can deal with dynamic scenes by capturing the full 3D datacube in a single image. Capturing the HS images within a snapshot usually sacrifices spatial resolution by projecting the 3D data cube onto different regions of a 2D sensor plane [19]. However, by exploring the sparsity constraint of 3D datacube, coded aperture snapshot spectral imager (CASSI) [20], dual-coded hyperspectral imager (DCSI) [5] and spatial–spectral encoded compressive hyperspectral imager (SSCSI) [4] surmount the compromise between spatial resolution and spectral resolution via compressive computational reconstruction.

Fluorescent surfaces are present in 20% of randomly constructed scenes [1]. The additional fluorescent spectrum information can facilitate some important applications [2,3]. Besides, reflective and fluorescent components have different response properties to the incident light. When a surface is illuminated at a particular wavelength, the reflective component has the same wavelength to the incident light, but the fluorescent component is produced by absorbing incident light at certain wavelengths and emitting at longer wavelengths, phenomenon known as Stokes shift [21]. With this difference, some methods based on bispectral scanning have been proposed to obtain complete spectral distribution [10], which are time-consuming. Independent component analysis [9] can be adopted for roughly separating the two components, but it does not capture spectral distributions. Spectral scanning under either three ordinary illuminations [22] or two high-frequency light in the spectral domain [12] greatly reduces capturing procedure. However, because of the use of scanning spectrometer, above methods are still not applicable for dynamic scenes.

To address the problems mentioned above, we propose an approach that can recover reflective and fluorescent components of dynamic scenes. For the applications, we demonstrate the highly accurate spectral relighting [23] in this paper. Fig. 1 shows the overview of the proposed architecture, including complementary spatially–spectrally encoded HS sampling, over-complete HS dictionaries learning and sparse reflective–fluorescent hyper-spectra reconstruction.

3. Reflective and fluorescent spectra

3.1. General formalization

We first model the spectral property of reflective and fluorescent materials and then give a general formalization representation of surface spectral property.

For a reflective surface, let $r(\mathbf{x},\lambda)$ denote the 3D HS reflectance with $\mathbf{x} = (x, y)$ being the 2D spatial coordinates and λ being the spectral dimension, then the observed radiance can be represented as

$$h_r(\mathbf{x},\lambda) = l(\lambda)r(\mathbf{x},\lambda), \tag{1}$$

where $l(\lambda)$ is the spectrum of the incident light.

In contrast, the pure fluorescent surface absorbs incident light at certain wavelengths and emits at longer wavelengths. The formulation of radiance under this is

$$h_f(\mathbf{x},\lambda) = \left(\int l(\lambda_i)a(\mathbf{x},\lambda_i)d\lambda_i\right) f(\mathbf{x},\lambda) = k(\mathbf{x})f(\mathbf{x},\lambda), \tag{2}$$

where $a(\mathbf{x},\lambda_i)$ and $f(\mathbf{x},\lambda)$ represent the fluorescent absorption and emission spectra, and $k(\mathbf{x}) = \int l(\lambda_i)a(\mathbf{x},\lambda_i)d\lambda_i$ denotes the scale factor. By assuming the fluorescent absorption and emission have no intersection in spectra, which proves to be most cases in reality [12], the emitted spectral profile is the same for a specific fluorescent material. Consequently, the spectra of a reflective–fluorescent scene is the mixing of the two components, which can be formulated as

$$h(\mathbf{x},\lambda) = h_r(\mathbf{x},\lambda) + h_f(\mathbf{x},\lambda) = l(\lambda)r(\mathbf{x},\lambda) + k(\mathbf{x})f(\mathbf{x},\lambda). \tag{3}$$

3.2. Representations in terms of sparsity

We explore the sparsity constraint on the natural 3D HS reflective and fluorescent Images. It has been proved that learning an over-complete dictionary rather than using a predetermined basis (such as DCT or Wavelet) can achieve better sparse representations, and hence can improve the reconstruction quality [24]. We propose to learn the 3D over-complete reflective and fluorescent HS dictionaries ($\mathbf{D}_r \in \mathbb{R}^{n\times q}$ and $\mathbf{D}_f \in \mathbb{R}^{n\times q}$) as the sparse basis of HS reflectance and fluorescence

$$\begin{cases} \mathbf{r} = \mathbf{D}_r\boldsymbol{\alpha}_r \\ \mathbf{f} = \mathbf{D}_f\boldsymbol{\alpha}_f, \end{cases} \tag{4}$$

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