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Optical aberration correction for simple lenses via sparse representation

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ABSTRACT

Simple lenses with spherical surfaces are lightweight, inexpensive, highly flexible, and can be easily processed. However, they suffer from optical aberrations that lead to limitations in high-quality photography. In this study, we propose a set of computational photography techniques based on sparse signal representation to remove optical aberrations, thereby allowing the recovery of images captured through a single-lens camera. The primary advantage of the proposed method is that many prior point spread functions calibrated at different depths are successfully used for restoring visual images in a short time, which can be generally applied to nonblind deconvolution methods for solving the problem of the excessive processing time caused by the number of point spread functions. The optical software CODE V is applied for examining the reliability of the proposed method by simulation. The simulation results reveal that the suggested method outperforms the traditional methods. Moreover, the performance of a single-lens camera is significantly enhanced both qualitatively and perceptually. Particularly, the prior information obtained by CODE V can be used for processing the real images of a single-lens camera, which provides an alternative approach to conveniently and accurately obtain point spread functions of single-lens cameras.

1. Introduction

Simple lenses with spherical surfaces are lightweight, inexpensive, easy to process, yet highly flexible optical equipment that can be used for numerous applications such as single-lens cameras. However, simple lenses with spherical surfaces suffer from optical aberrations that can seriously reduce image quality. Therefore, they cannot be directly used in high-resolution and high-quality photography. To enhance the performance of such imaging systems, different types of optical methods are used for optimization and compensating for aberrations such as increasing the number of lenses and using aspheric surfaces. Even though these methods significantly enhance the performance of optical imaging systems, they have high cost, structure complexity, volume, and weight problems.

Photography has attracted the attention of researchers who have been studying imaging sensors for a long time, not only to decrease the requirements of the hardware but also to enhance the performance of simple imaging systems. Recently, photography was transformed by computational photography that combines digital image processing with imaging systems for image restoration [1]. The basic methods of image restoration can be classified into two categories: blind deconvolution method [2–4] and nonblind deconvolution approach [5–8] depending on whether the point spread function (PSF) is known. Over the years, many deconvolution approaches have been developed, varying considerably in their speed and sophistication. Blind deconvolution algorithms can obtain superior images by employing the features of degraded images to estimate PSFs. However, the minimum of the resulting cost function does not correspond to a true sharp solution. This is particularly true if there is no evident enhancement in the degraded images when the optical aberrations are substantial. In contrast, nonblind deconvolution algorithms can significantly enhance the quality of images using the calibrated PSFs of imaging systems. These prior PSFs are typically measured at a single depth, thereby leading to inadequate results or even failures when the objects are outside the calibration plane. Although nonblind deconvolution performed by calibrating PSFs at different depths is the best method for recovering images, it requires complex calibrations for estimating PSFs to guarantee the accuracy. Moreover, the deblurring images obtained are time consuming. The calibration problem can be solved by allocating sufficient time for calibrations during the preparation step. However, all the prior PSFs must be used for the recovery of the images, which is unsuitable for a realistic implementation.

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Fig. 1. Single-lens camera developed by authors. Effective focal length (EFL) is 35 mm, f/2.4.

Recently, Schuler proposed a nonblind deconvolution method to correct the aberrations in optical imaging systems by encoding the errors of imaging systems on a reference plane [9]. The performance of photographic single lenses was significantly improved. However, as described by Schuler, the PSF is only measured on a single calibration plane, which indicates that this method remains conventional in its nature. Further, the images used for recovery must correspond to the field of view of the reference plane; otherwise, the deblurred images will not be effectively enhanced owing to the large matching error and lack of prior PSFs. Heide suggested a robust deconvolution algorithm with a cross-channel gradient prior that enforces sparsity of hue changes across the image [10]. Although this method enhances the image quality of single-lens cameras remarkably, the shortcomings of the nonblind deconvolution methods remain. The quality of recovered images can decrease or even become unacceptable because of a defocus and object distance variance. Li designed a single-lens camera and obtained acceptable images by combining the advantages of both nonblind deconvolution methods and blind deconvolution approaches [11]. However, this method also experiences the same problems as the previous.

For image recovery, we considered other technologies that can effectively solve the shortcomings of the conventional nonblind deconvolution methods. Sparse signal representations [12–15] were considerably successful in achieving superior-image resolutions for several years. For example, many image priors can be used for learning two overcomplete dictionaries D_h and D_l, D_h for high-resolution image patches, and D_l for low-resolution patches. Each high-resolution and low-resolution image patch pair is trained to exhibit the same sparse representations. In the application, the sparse representation of a low-resolution image patch in terms of D_l can be used for determining the corresponding high-resolution image patch from D_h rapidly and accurately. Moreover, the prior PSFs can be trained to dictionaries in this manner. Therefore, it is realistic to expect that a considerable number of prior PSFs can be used for the rapid and accurate recovery of images using nonblind deconvolution methods.

Inspired by this idea, we propose a set of computational photography techniques based on sparse signal representation to correct optical aberrations. Moreover, we demonstrate the proposed methods by recovering the images obtained by a single-lens camera, as indicated in Fig. 1. Further, optical software CODE V is applied for examining the reliability of the proposed method using a simulation.

In this study, the PSF of each degraded image is first accurately calibrated using a high-quality image corresponding to the degraded image, denoted as k_k. Algorithms based on hyper-Laplacian prior [16] are used for estimating the PSF of the same scene, denoted as k_{uk}. Many PSFs of prior images are obtained using this approach. Then, PSFs k_{uk} are used for training a coupled dictionary of sparse representations. Then, the PSF of a single test image is estimated to be the same as k_{uk}, denoted as k_y. PSF k_y is sparsely represented by the coupled dictionary to obtain the most relative prior PSF k_{uk}. The PSF k_k that corresponds to the dictionary PSF k_{uk} is used for deblurring [17] the test image. Finally, a blind deconvolution method [16] is applied for reducing the algorithmic noise and matching error to acquire a sharp image. The diagram of the proposed method is displayed in Fig. 2.

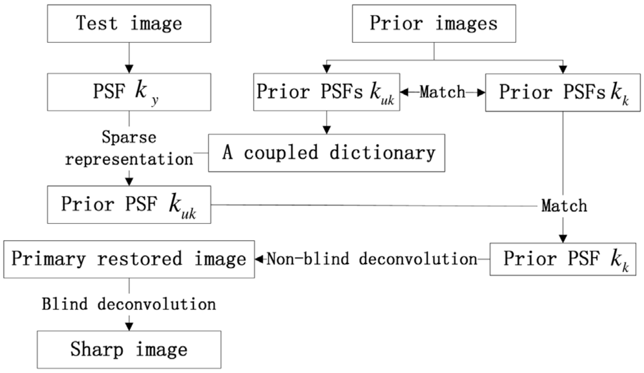

Fig. 2. Diagram of proposed method.

The remainder of this paper is organized as follows. Section 2 provides the details of the theory and method. In Section 3, the performance of the proposed method is verified using numerical tests and experiments. The conclusions are presented in Section 4. To provide a convenient and clear approach to restore the recovered images using the proposed method, we present an comprehensively detailed description of our research that includes knowledge of imaging sensors, applied optics, and digital image processing.

2. Deblurring model

In this section, we analyze the deblurring model. Image deblurring is a longstanding method that attempts to recover a sharp image from its blurred observation. The blurred image is modeled as the convolution of the sharp image with a PSF as

$$y = k \otimes x + n. \tag{1}$$

Here, y is the blurred image, x is the sharp image, k is the PSF, $\otimes$ is the 2D convolution operator, and n is the noise operator. In this study, the unknown sharp image x is recovered by $y = k \otimes x$. The overall process of the proposed approach is introduced in Algorithm 1.

Undoubtedly, degraded images can be effectively restored using prior PSFs corresponding to their own calibration planes, which is the most important advantage of nonblind deconvolution methods. For the process of recovering images, the primary idea of Algorithm 1 is to solve the problem of excessive processing time caused by the number of PSFs rather than outperform the performance of nonblind deconvolution methods. That is, the runtime of nonblind deconvolution can be significantly reduced using the proposed method when more than one prior PSF is used for restoring images. In practical applications, nonblind deconvolution methods can be suitably used for the recovery of images.

Note that every calibrated PSF has a limited depth of field because the optical aberrations vary in a nonlinear and complicated manner