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A performance comparison among different super-resolution techniques ☆

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ABSTRACT

Improving image resolution by refining hardware is usually expensive and/or time consuming. A critical challenge is to optimally balance the trade-off among image resolution, Signal-to-Noise Ratio (SNR), and acquisition time. Super-resolution (SR), an off-line approach for improving image resolution, is free from these trade-offs. Numerous methodologies such as interpolation, frequency domain, regularization, and learning-based approaches have been developed for SR of natural images. In this paper we provide a survey of the existing SR techniques. Various approaches for obtaining a high resolution image from a single and/or multiple low resolution images are discussed. We also compare the performance of various SR methods in terms of Peak SNR (PSNR) and Structural Similarity (SSIM) index between the super-resolved image and the ground truth image. For each method, the computational time is also reported.

1. Introduction

The computerized image resolution enhancement began in 1984 when Tsai and Huang [1] introduced a mathematical method for combining multiple low resolution (LR) images to obtain a single high resolution (HR) image. While initially there was little interest in this technology, over time with much theoretical and practical improvement, the technique led to the development of many tools currently available and was used in different fields such as security surveillance,

Abbreviations: LR, low resolution; HR, high resolution; SNR, Signal-to-Noise Ratio; SR, super-resolution; PSNR, Peak-Signal-to-Noise Ratio; SSIM, Structural Similarity; MSE, Mean Square Error; EGI, Edge-Guided Interpolation; NEDI, New Edge-Directed Interpolation; GBA, Gradient-Based Adaptive; ASDS, Adaptive Sparse Domain Selection; DFT, Discrete Fourier Transform; DCT, Discrete Cosine Transform; DWT, Discrete Wavelet Transform; IBP, Iterative Back Projection; POCS, Projection Onto Convex Set; MAP, Maximum A-Posteriori; MRF, Markov Random Field; PDF, Probability Density Function; SAR, Simultaneous Autoregressive; CRF, Conditional Random Field; MLE, Maximum Likelihood Estimation; PCA, Principle Component Analysis; CSR, Centralized Sparse Representation.

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biomedical applications, remote sensing, object recognition (such as face, finger print, iris, vehicle number plate and text) and video conversion [2,3]. Resolution enhancement is one of the most rapidly growing areas of research in the field of image processing. The term resolution refers to the ability of an imaging instrument in revealing the fine details of an object. The resolution of an imaging device depends on the quality of its optics as well as its recording (sensor) and display components. The spatial resolution of an imaging instrument can be improved by modifying the hardware (sensor) in two ways. The first approach is to increase the pixel numbers. However, this approach has rather limited applications since it decreases the Signal-to-Noise Ratio (SNR) and increases the image acquisition time, and therefore, it is challenging to balance the trade-off between resolution, SNR, and acquisition time [4]. The second approach is to increase the chip size; however, a chip size necessary to capture a HR image would be very expensive [5]. An interesting alternative to both of the aforementioned approaches is to use the super-resolution (SR) techniques. SR is an off-line approach for improving the resolution of an image. SR techniques are broadly divided into multi-frame SR (classic approach) and single-frame SR. In multi-frame SR techniques a set of LR images acquired from the same scene are combined to reconstruct a single HR image. LR images can be taken by the same imaging instrument or with different instruments. The goal is to find the information missing in one LR image in other LR images. By doing so, the information contained in all LR images is pooled to obtain a HR image [5]. Several multi-frame SR techniques have been investigated in medical imaging [4]. In single frame SR technique, the missing high frequency information in the LR image during the acquisition step is estimated from a large number of training set images and added to the LR image [2].

In this paper, we present a survey of major SR techniques. Besides this, the MATLAB codes written and published by different groups of researchers were downloaded from their websites and the performance of various SR techniques were compared. The comparisons are made in terms of common image quality metrics such as peak SNR (PSNR) and Structural Similarity (SSIM) discussed in details in Section 5. We also report the execution time of the codes for each method. A number of review papers have also been published in this field [3,5–8]. While some of these papers provide a good overview of SR techniques, only [8] provides a comprehensive performance comparison in terms of image quality metrics. The survey paper [8] has provided the performance comparison in terms of objective quality metrics; however, it is limited to single-frame SR techniques. This paper is different from the previous review papers in that it provides performance comparisons of both single-frame and multi-frame SR techniques. The rest of the paper is organized as follows. Section 2 explains observation model that relates the HR image to the observed LR images. Several multi-frame SR techniques are described in Section 3. The single-frame SR techniques are described in Section 4. The image quality metrics are discussed in Section 5. Section 6 provides comprehensive performance comparisons of various SR techniques with natural images. A detailed discussion of the pros and cons of each technique is presented in Section 7, and the paper is concluded in this section.

2. Observation model

The observation model describes the way by which the observed LR images have been obtained. It models the parameters that degrade the original HR image to the observed LR images; therefore, it is also termed as forward model. A number of parameters contribute to the reduced image quality. These include: (a) the blur created either by defocus or motion of the camera; (b) sampling an object at a frequency less than the highest frequency contained in the object produces aliasing artifact on the image; (c) the inherent noise of natural images, as all the natural images contain some level of noise. These image degradation factors (i.e., blur, aliasing, and noise) can be incorporated into a mathematical model that relates the HR image to the observed LR image [5]. The schematic diagram of observation model is depicted in Fig. 1.

Mathematically, let X be an original image degraded by motion blur (M), camera blur (B), and decimation effect (D). Suppose the image contains white Gaussian noise of standard deviation (η). Therefore, the forward observation model that relates the HR image to the observed LR image is [9]:

$$y^k = DB^kM^kX + \eta^k; \qquad Y = HX + \eta \tag{1}$$

where k represents the number of LR images. A slightly different amount of blur and motion parameters are used to create different LR images. An example for creating simulated LR images from a HR natural image is described in Section 6. Once the

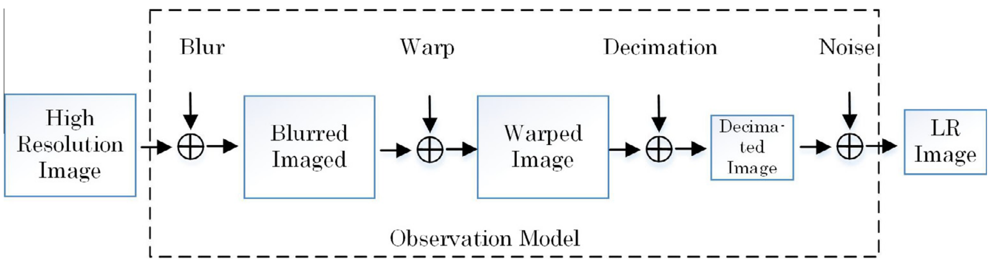

Fig. 1. The low resolution image is the blurred, warped, decimated and noisy version of the high resolution image created by the observation model.

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