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Review

Image super-resolution: The techniques, applications, and future

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ABSTRACT

Super-resolution (SR) technique reconstructs a higher-resolution image or sequence from the observed LR images. As SR has been developed for more than three decades, both multi-frame and single-frame SR have significant applications in our daily life. This paper aims to provide a review of SR from the perspective of techniques and applications, and especially the main contributions in recent years. Regularized SR methods are most commonly employed in the last decade. Technical details are discussed in this article, including reconstruction models, parameter selection methods, optimization algorithms and acceleration strategies. Moreover, an exhaustive summary of the current applications using SR techniques has been presented. Lastly, the article discusses the current obstacles for future research.

Contents

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1. Introduction

Image spatial resolution refers to the capability of the sensor to observe or measure the smallest object, which depends upon the pixel size. As two-dimensional signal records, digital images with a higher resolution are always desirable in most applications. Imaging techniques have been rapidly developed in the last decades, and the resolution has reached a new level. The question is therefore: are image resolution enhancement techniques still required?

The fact is, although the high-definition displays in recent years have reached a new level (e.g., 1920*1080 for HDTV, 3840*2160 for some ultra HDTV, and 2048*1536 for some mobile devices), the need for resolution enhancement cannot be ignored in many applications [1]. For instance, to guarantee the long-term stable operation of the recording devices, as well as the appropriate frame rate for dynamic scenes, digital surveillance products tend to sacrifice resolution to some degree. A similar situation exists in the remote sensing field: there is always a tradeoff between the spatial, spectral, and temporal resolutions. As for medical imaging, within each imaging modality, specific physical laws are in control, defining the meaning of noise and the sensitivity of the imaging process. How to extract 3D models of the human structure with high-resolution images while reducing the level of radiation still remains a challenge [2,3].

Based on these facts, the current techniques cannot yet satisfy the demands. Resolution enhancement is therefore still necessary, especially in fields such as video surveillance, medical diagnosis, and remote sensing applications. Considering the high cost and the limitations of resolution enhancement through "hardware" techniques, especially for large-scale imaging devices, signal processing methods, which are known as super-resolution (SR), have become a potential way to obtain high-resolution (HR) images. With SR methods, we can go beyond the limit of the low-resolution (LR) observations, rather than improving the hardware devices.

SR is a technique which reconstructs a higher-resolution image or sequence from the observed LR images. Technically, SR can be categorized as multi-frame or single-frame based on the input LR information [4–8]. If multiple images of the same scene with subpixel misalignment can be acquired, the complementary information between them can be utilized to reconstruct a higher-resolution image or image sequence, as Fig. 1 shows. However, multiple LR images may sometimes not be available for the reconstruction, and thus we need to recover the HR image using the limited LR information, which is defined as single-frame SR [9–12].

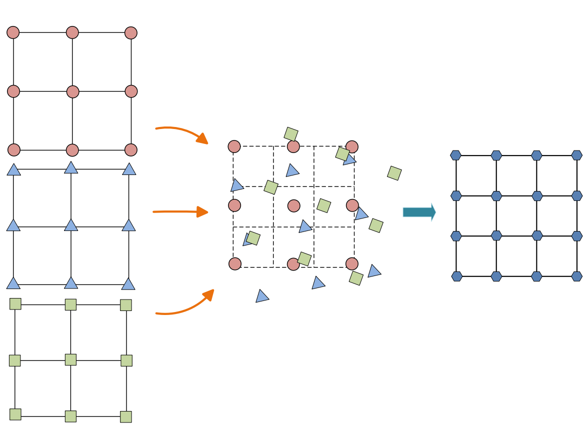

Fig. 1. The concept of multi-frame super-resolution. The grids on the left side represent the LR images of the same scene with sub-pixel alignment, thus the HR image (the grid on the right side) can be acquired by fusing the complementary information with SR methods.

Although SR techniques have been comprehensively summarized in several studies [4,6,8,13–15], this paper aims to provide a review from the perspective of techniques and applications, and especially the main contributions in recent decades. This paper provides a more detailed description of the most commonly employed regularized SR methods, including fidelity models, regularization models, parameter estimation methods, optimization algorithms, acceleration strategies, etc. Moreover, we present an exhaustive summary of the current applications using SR techniques, such as the recent Google Skybox satellite application [16] and unmanned aerial vehicle (UAV) surveillance sequences [17]. The current obstacles for the future research are also discussed.

2. Technical background

Nowadays, charge-coupled devices (CCDs) and complementary metal oxide semiconductors (CMOSs) are the most widely used image sensors [4,18]. To obtain an HR image, one of the solutions is to develop more advanced optical devices. As the spatial resolution is governed by the CCD array and optical lens, reducing the pixel size is one of the most direct approaches to increase the spatial resolution. However, as the pixel size decreases, the amount of available light also decreases, and the image quality becomes severely degraded by shot noise. Furthermore, nonrectangular pixel layouts, as in the hexagonal Fujifilm super CCD and the orthogonal-transfer CCD [18,19], have been used to increase the spatial sampling rate, as shown in Fig. 2. Other approaches include increasing the focal length or the chip size. However, a longer focal length will lead to an increase in the size and weight of cameras, while a larger chip size will result in an increase in capacitance. Therefore, both of these approaches are not considered to be effective due to the limitations of the sensors and the optics manufacturing technology [4]. Compared with CMOSs, CCDs have advantages in sensor sensitivity, imaging resolution, noise suppression and technology maturity [20]. However, considering the high cost of current CCD-based cameras, CMOS-based technologies have recently been investigated. For example, Scientific CMOS (sCMOS) sensors feature a higher resolution and high signal-to-noise ratio (SNR); however, the practical use of this technology remains a problem [21]. Overall, due to the limitations of hardware technology, it is still necessary to study SR algorithms to achieve the goal of resolution enhancement.

Based on the concept of SR, the first problem we need to discuss is the conditions to obtain an HR image from multiple LR observed images. In general, if there is supplementary information among the images, SR is feasible [22]. That is to say, the LR observations cannot be obtained from each other by a transformation or resampling process, thus they contain different information