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Super-resolution reconstruction of astronomical images using time-scale adaptive normalized convolution

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Abstract In this work, we describe a new multiframe Super-Resolution (SR) framework based on time-scale adaptive Normalized Convolution (NC), and apply it to astronomical images. The method mainly uses the conceptual basis of NC where each neighborhood of a signal is expressed in terms of the corresponding subspace expanded by the chosen polynomial basis function. Instead of the conventional NC, the introduced spatially adaptive filtering kernel is utilized as the applicability function of shape-adaptive NC, which fits the local image structure information including shape and orientation. This makes it possible to obtain image patches with the same modality, which are collected for polynomial expansion to maximize the signal-to-noise ratio and suppress aliasing artifacts across lines and edges. The robust signal certainty takes the confidence value at each point into account before a local polynomial expansion to minimize the influence of outliers. Finally, the temporal scale applicability is considered to omit accurate motion estimation since it is easy to result in annoying registration errors in real astronomical applications. Excellent SR reconstruction capability of the time-scale adaptive NC is demonstrated through fundamental experiments on both synthetic images and real astronomical images when compared with other SR reconstruction methods.

1. Introduction

The engineering community that firstly encountered with image reconstruction and restoration was the space program in the 1950s.[1] The first sets of astronomical images captured from the Earth and the planets were of unimaginable resolution due to technical difficulties, such as diffraction blur, optical aberrations, noise, etc. These difficulties resulted in decimated, aliased extraterrestrial observations of an

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astronomical scene, and a multi-image-based Super-Resolution (SR) technique was introduced to retrieve as much additional information as possible from such degraded sequential astronomical images and reconstruct one High-Resolution (HR) astronomical image. Super-resolving observed Low-Resolution (LR) astronomical images has been proven to increase high-frequency components and remove degradations derived from ground-based optical astronomy imaging systems. There have been a considerable amount of image reconstruction and restoration techniques that achieve SR directing toward optical astronomy, especially since the discovery of the spherical aberration problem in the Hubble Space Telescope in 1990.[2] Molina et al.[3] provided a review of image restoration in astronomy and then proposed a Bayesian modeling and inference method to remove noise and blur in astronomical images. Starck et al.[4] described two novel multiscale approaches based on ridgelet and curvelet transforms instead of the wavelet transform, which present high directional sensitivity and can better show elongated details hidden in astronomical images. Wu and Barba[5] proposed an iterative optimization algorithm to restore star field images by using the minimum mean square error criteria and the maximum varimax criteria.

The classical multiframe SR reconstruction comprises three basic procedures: LR image acquisition, image registration, and HR image construction. Fig. 1 describes a common image formation model concerned with an HR image to decimated, aliased observations with motion between a scene and a camera. From Fig. 1, we can understand how LR observations are generated from detector limited imaging systems. The basic idea behind SR is that sampling diversity provided by the complementary information contained in multiple LR observations can be utilized to combat undersampling, making the ill-posed upsampling process better constrained. Therefore, SR reconstruction can be implemented by aligning LR images with subpixel shifts to reconstruct them on a new and greater image grid, achieving the inverse process of the observation model.

SR reconstruction was primarily presented by Tsai and Huang[6] in 1984, analyzing the basic characteristic of Fourier transform. Numerous novel SR reconstruction methods have emerged over the last two decades[7,8], which can be divided into two main types, i.e., spatial domain and frequency domain based methods. The formulation for SR reconstruction in Ref. 6 assumed an idealistic observation model with known parameters, upon which many improvements have existed to deal with more complex situations. Kim et al.[9] developed Ref. 6 by incorporating the motion blur and aliasing effect into a recursive procedure based on the weighted least square theory. They provided a further improvement in Ref. 10 by introducing a recursive total least squares algorithm. Tom et al.[11] presented a new approach that solves restoration and motion estimation sub-problems simultaneously using the Expectation-Maximization (EM) algorithm. Frequency domain based methods have the merit of high calculation efficiency, but can only deal with limited image degradation models and restricted image priors from the reconstruction process. Later works on SR reconstruction have focused more on the spatial domain, providing its adaptability to handle different types of image observation models. Typical approaches include Iterative Back Projection (IBP),[12] maximum likelihood (ML),[13] Maximum A Posteriori (MAP),[14] and Projection Onto Convex Sets (POCS),[15] which improve the disadvantages of frequency domain based methods with more computationally intensive operations.

In the conventional multiframe SR reconstruction, image registration is critical for the performance of HR image reconstruction. A promising approach used recently is the non-parametric approach, which omits accurate motion estimation. Protter et al.[16] incorporated the denoising NonLocal-Means (NLM) algorithm with an accurate-motion-estimation-free property into SR reconstruction. Later, they further extended the NLM algorithm and proposed a probabilistic and crude motion estimation to achieve SR without a need for image registration in Ref. [17] Takeda et al.[18] presented an iterative 3-D framework for SR reconstruction by applying a 3-D steering kernel,[19] which is based on the local Taylor series of its spatiotemporal neighborhood, containing information about the local motion across time. However, the NLM algorithm can lead to produce noticeable aliasing, and the iterative 3-D framework based method requires multiple iterations and complex computations.

In this paper, we present a novel multiframe SR framework independent of accurate motion estimation, called time-scale adaptive normalized convolution, and apply it to astronomical images. The proposed SR algorithm is inspired from Normalized Convolution (NC)[20] where the polynomial basis function is utilized to express a weighted neighborhood of a target position for local signal modeling. Furthermore, signal certainty and spatially adaptive filtering are introduced to minimize the influence of outliers and adapt the underlying image structure, leading to robust and adaptive NC. Finally, temporal scale applicability is incorporated to the SR framework which aims to omit accurate motion estimation during SR reconstruction.

The structure of the paper is as follows. Section 2 reviews the concept of a robust and adaptive NC method along with its SR reconstruction results. Section 3 presents a time-scale adaptive NC method for SR reconstruction and its major advantages compared against other SR approaches. Experimental results are shown in Section 4, and Section 5 concludes.

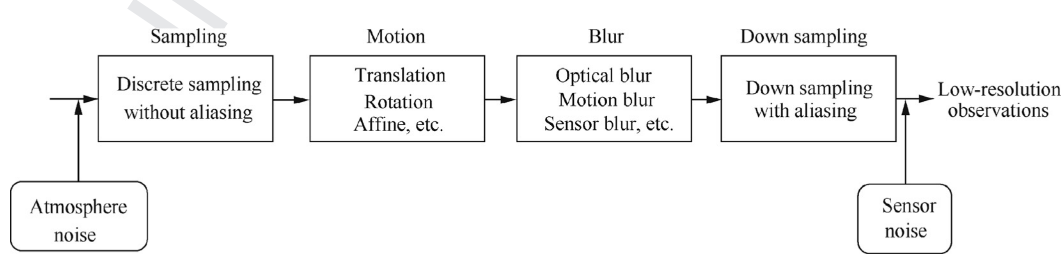

Fig. 1 A common image formation model.

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