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A novel approach for enhancing very dark image sequences

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ABSTRACT

We propose the methods, involving a denoiser and a tone mapper, that especially enhance very dark image sequences having an extremely small signal-to-noise ratio (SNR). The proposed denoiser and tone mapper, respectively, boosts the very small SNR and enlarges the extremely low dynamic range: they jointly form a conceptual framework to do the enhancement. We explicitly show that the conceptual framework adheres to a theoretical biological model of visual systems in nocturnal animals. The developed denoiser utilizes adaptive spatial–temporal filtering and effectively succeeds in reducing high noise and motion blur artifacts while preserving image details. The devised tone mapping method carries out different transformations for low and high intensity pixels by employing a single function which meanwhile takes into account the local contrast of each pixel, supporting a spatially and temporally consistent tone adjustment per frame. The conceptual framework and a customized post-process lead to a novel technique that is demonstrated to accomplish a satisfactory enhancement of very dark videos, and produce high quality restored image sequences – outperforming the recent state-of-the-art results. Finally, the proposed adaptive spatial–temporal filter and the post-processing procedure can be combined and adapted for normal-light image sequences to deal well with remarkably heavy noise.

1. Introduction

With the development of video capture devices, digital videos have become widespread. Specifically, very dark image sequences, taken in particularly poor light conditions, not only occur under amateurish situations, but also commonly emerge in many industrial applications such as surveillance. Hence the enhancement of very dark image sequences plays a critical role in a lot of real-world tasks. In fact, image/video enhancement itself is one of the most appealing topics in digital image processing [1].

However, few algorithms particularly for enhancing very dark image sequences have been successfully developed so far [2,3]: this may be most likely due to the challenging complexity of the problem itself. In this paper, we develop methods for enhancing very low-light image sequences to make previously unacceptable footage perceivable.

1.1. The proposed technique

We utilize a conceptual framework jointly involving two processing components, a new adaptive spatial–temporal filter and a novel tone mapping approach, to simultaneously combat the two bad issues, the *very small SNR*

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and the *extremely low dynamic range*, for enhancing very low light-level videos. To exploit the spatial–temporal correlation of a video, noise reducing and tone mapping are algorithmically operationalized in a temporal sequence to construct the enhancement framework. Notably the conceptual framework is in accordance with a theoretical biological model of visual systems in nocturnal animals [4], as to be shown in Sections 4.5.2 and 5.1.1.

Due to its conceptual simplicity but competitive ability of denoising and preserving image details, the recent static 3D Non-Local Means (NLM) [5,6] is selected to be adapted as the basis of the new spatial–temporal filter. Actually the proposed filter leads to a novel and computationally lighter NLM method. The new advanced tone mapping method is driven by the contrast increment, significantly enlarging the dynamic range of very dark videos. Also, a static 3D NLM and a Yaroslavsky neighborhood filter [7] are customized for deriving a post-process to encourage the eventual output to have better color and detail appearance. Finally the proposed technique, which comprises the enhancement framework and the post-process, converts the extremely dark videos into more perceivable ones. The results achieved by our newly proposed technique show an improvement upon those by the state-of-the-art methods [2,3].

In addition, the proposed filter and the post-process can be merged to construct a novel filtering scheme to handle heavy noise for normal light-level video. For the post-processing procedure, we also propose a new method in which a linear function is utilized to approximately model an image patch to set the important parameter of static 3D NLM. The novel filtering scheme results in a better denoising performance and also in a more efficient process, running 20 times faster than the original 3D NLM. This filtering scheme can handle real-world noisy videos well.

This paper is an extension of our preliminary work [8], but here we propose three improvements. Firstly, we argue, based on utilizing the spatial–temporal correlation as a tight bond, that in effect the conceptual framework is formed by uniting a denoiser and a tone mapper, for enhancing very dark image sequences. And, the framework we use has theoretical soundness in the sense that it conforms to a theoretical biological model of visual systems in nocturnal animals. Secondly, for the proposed tone operator we introduce a new contrast driven correction method that does the intensity mapping somewhat more sharply to yield better visual perception for some very dark videos. Thirdly, the selection of the filter parameter for static 3D NLM using a linear function based approximation method is promising. More importantly, we believe that it opens new possibilities for improving the well-known NLM.

1.2. The paper organization

The remainder of this paper is as follows. In next section, related work is reviewed. The conceptual framework for enhancing very low light-level videos is described in Section 3. The proposed spatial–temporal denoising filter is detailed in Section 4. The created tone mapper especially for low dynamic range images is presented in Section 5. The post-processing procedure is described in Section 6. The adaptation of our dark video technique for denoising normal light-level videos with high level of noise is depicted in Section 7. The experimental results are demonstrated in Section 8. Finally Section 9 concludes the paper, and some future work is also discussed.

2. Related work

2.1. Enhancement methods addressing very dark videos

Enhancing very dark image sequences sets a big challenging problem due to their poor dynamic range and high noise level. And not so surprisingly, few reported attempts have been targeted specifically on very-low-light video enhancement: recently two closely related methods [2,3] have achieved very encouraging results. There is another slightly relevant algorithm [9] relying on straightforward filtering steps for simple hardware implementation: it is only aimed at handling somewhat dim – but not very dark – videos.

As discussed in the conceptual framework we use (Section 1.1), the approach for enhancing very dark videos does always have the noise reducing and tone mapping constituents (see also [2,3] as examples).

The filter presented by Bennett and McMillan [2] uses temporal filtering only as long as there are no moving scene elements, and changes to the mixture of temporal and spatial filterings if the motion in the scene exists. Both the temporal and spatial filterings are based on the bilateral filter [10]. The tone mapper introduced by [2] for low dynamic range images is inspired from [11] and [12]. The bilateral filter is also used to separate the input image into large scale features and details. Two different versions of tone mapping function are performed respectively for the large scale image features and image details. Bennett and McMillan's approach can produce very good results. The main difference between the denoising filter deployed in [2] and our filter is the strategy of how to utilize the spatial and temporal filters. The denoising filter of [2] favors temporal filtering over spatial filtering, whenever possible. Our approach configures spatial and temporal filters adaptively and dynamically based on the comparison between video motion and image anisotropy: this is beneficial to the preservation of motion and image edges.

In the work by Malm et al. [3], a 3D structure tensor is developed and used in the kernel of the structure-adaptive anisotropic filter [13,14] for denoising, and a contrast limited histogram equalization algorithm [15] is done for tone mapping. It is the clever use of the structure tensor that gets Malm et al.'s method to restore image edges and details very well. Contrary to the symmetric 3D filter support used by [3], we employ the separation of spatial and temporal dimensions in the proposed spatial–temporal filter so that our new filter can better protect spatial and temporal discontinuities from smearing.