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A distortion-free contrast enhancement technique based on a perceptual fusion scheme

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ABSTRACT

Contrast enhancement, in a broad sense, is a process whereby some characteristics of an image signal are highlighted. Techniques for image contrast enhancement improve the visibility of image details but may generate some undesirable artifacts such as noise amplification, ringing and overshooting. As a consequence, developing distortion-free methods for image enhancement is of great interest. In this paper, we propose a perceptual fusion technique to improve the performance of some existing contrast enhancement methods in terms of noise amplification. Multi-resolution fusion using the Laplacian pyramid decomposition is performed to account for the multi-channel characteristics of the human visual system (HVS). The results show the efficiency of the proposed method in enhancing details while preventing noise amplification.

1. Introduction

The quality of the captured image can often be degraded due to imperfections in imaging devices, noise in the environment and insufficient lightning conditions. Due to some of these limitations in image transmission and acquisition systems, image enhancement techniques play an important role in imaging applications. Contrast enhancement methods improve image detail visibility by suitable increase in contrast for improved visual interpretation or for better representation for further image processing tasks such as recognition, analysis, segmentation and detection. Many approaches for image contrast enhancement have been proposed in literature. A survey of contrast enhancement techniques can be found in [1]. In general, the contrast enhancement techniques can be divided into two broad categories: direct and indirect methods [2,3]. Indirect methods involve an improvement in image contrast without defining any specific function for contrast. These techniques improve the global contrast but usually fail to enhance local image details. Contrast stretching using linear and non-linear functions [4,5], and histogram based techniques [6–10] are some examples of indirect enhancement techniques. Direct methods, on the other hand, enhance the details by defining a specific function for contrast. These methods improve contrast by modifying local contrast measure, usually some edge based information or information related to local statistics of the image [11,12]. Although, these local enhancement techniques overcome some of the drawbacks of the global approaches, they often produce certain undesirable effects such as noise amplification, overshooting and color mismatch. Therefore, an interesting issue in image enhancement is to develop techniques for distortion-free contrast enhancement. One solution to deal with noise amplification in contrast enhancement is to reduce the noise prior to enhancement. Nevertheless, conventional noise reduction techniques suppress noise but tend to blur image details. As a result of these limitations, combined sharpening and de-noising methods are developed to improve the contrast of the image while reducing the noise level. Some adaptations of the conventional un-sharp masking techniques (UM) to perform simultaneous sharpening and noise suppression were proposed in [13,14]. In [15,16], the authors address the problem of ringing artifacts for the un-sharp masking technique. Although ringing artifacts are reduced, noise amplification problem still remains. Chang et al. [17], propose a technique which produces enhanced images with reduced overshoot effect and noise amplification. However, the method is iterative and requires the user to assign parameters to design a contrast gain function. Cherifi et al. apply a steerable pyramid filtering based approach to enhance the mid-frequency components by using a selective non-linear function [18]. This avoids increasing noise in low and high frequency bands. The results show an improvement in the noise performance as well as reduced edge ringing artifacts for the enhanced images.

In contrast to the already existing techniques, we propose a fusion based strategy to overcome the problem of noise amplification which manifests itself as a side effect of the enhancement process. Image

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fusion is a well explored area in image processing with applications in remote sensing, medical imaging as well as security and surveillance, to name a few. Image fusion algorithms combine two or more images into a composite image by retaining some of its most useful features. Recently, image fusion techniques were applied in the area of image enhancement. In [19,20] multi-scale fusion approach is applied for de-hazing/de-fogging. A contrast enhancement technique based on multi-resolution (MR) fusion is proposed to suppress the saturation and over-enhancement artifacts [21]. To the best of our knowledge this is the first attempt to address the effectiveness of a fusion approach to overcome the problem of noise amplification in enhancement techniques.

Our method is based on a novel perceptual fusion framework which employs information about the selectivity property of the HVS (to different frequencies) and some characteristics of contrast enhanced images such as the noise and edge artifacts. It is applied to the output of some existing contrast enhancement techniques to prevent noise amplification, thereby improving their overall perceptual performance. Our method, unlike the one proposed in [18] can be applied to the output of any enhancement technique and thus improve its performance in terms of noise and edge ringing artifacts.

Image quality assessment for the contrast enhanced images is a rather difficult task. Quality of contrast enhanced images is evaluated using quantitative measures as well as visual inspection. Visually the enhanced images are evaluated based on image details visibility, the appearance of color, visibility of noise, edge artifacts and other perceptual features. Objective measures of contrast are also used to analyze the quality of enhanced images. We validate the performance of the proposed method objectively as well as by visual inspection. The results are evaluated objectively by analyzing the rotationally averaged energy spectrum [22].

The paper is structured as follows. In Section 2, the theoretical and mathematical fundamentals are presented. The results are discussed in Section 3. Finally, we conclude and present some perspectives for the future.

2. Fusion based methodology

While the knowledge on the HVS is far from complete, current models for visual information processing are sophisticated enough and can be used to design and improve image processing techniques. Perceptual approaches based on some characteristics of the human visual system are very promising in imaging applications such as objective image quality assessment, image compression and image enhancement. These techniques take in to account some spatial and spatio-temporal properties of human vision system. A well-known application of the human contrast sensitivity can be observed in JPEG compression (Joint photographic expert group) where the quantization of the discrete cosine transform (DCT) coefficients is based on a contrast sensitivity function (CSF) based quantization matrix. The aim of the method developed here is to reduce noise amplification and ringing artifacts (amplified during the enhancement process) from contrast enhanced images using perceptual information about the visibility of noise and the selectivity (property) of the HVS to different frequency bands.

The HVS exhibits varying sensitivity to different spatial frequencies. It is keener to discern some frequency components while it is less sensitive to some spatial frequencies (spatial variations which are too high or too weak). A model for the contrast sensitivity function was proposed by Mannos and Sakrison [23]. The contrast sensitivity function is a model of the contrast sensitivity of the HVS as a function of the spatial frequency in the visual stimuli. The contrast sensitivity function proposed in [23] is given by:

$$A(f)=2.6(0.0192+0.114f)e^{-(0.114f)^{1.1}} \tag{1}$$

Where f represents the spatial frequency of the visual stimulus. Thus, the HVS is more sensitive to medium frequencies and the sensitivity drops as spatial frequency increases. Moreover, we also note that high frequency noise is more visible in low frequency background and less visible in high frequency background. Similarly, overshoot effect may appear around high frequency signal components, such as edges, when applying contrast enhancement. Based on the observations above, we propose a multi-resolution based framework to avoid noise amplification and overshoot artifacts from the contrast enhanced images while preserving the detail enhancement performance of these techniques.

Generally, Fusion is performed to achieve certain objectives. The choice of fusion methodology and fusion rule is primarily dictated by the objectives and application of image fusion. In a generic multi-resolution based fusion technique, different fusion rules (which depend upon the application at hand) are applied to form a composite pyramid. The fused image can then be obtained from this composite MR representation by applying an inverse transformation.

For our application, we wish to construct a composite image such that all important details in the enhanced image are retained while noise and artifacts such as over/under shooting and edge ringing artifacts are not amplified. We can achieve this by integrating/combining the low and high frequency information of the original image (image before enhancement as it is less affected by noise amplification and artifacts) with the mid-frequency information extracted from the enhanced images. Indeed, the detail/contrast enhancement performance of these methods is preserved (as the mid-frequency information of the enhanced images is preserved) while avoiding noise amplification and artifacts.

To fuse the images according to the objectives presented above, we need to represent them such that the images are well localized in both space and spatial frequency. Image pyramid representation is such a flexible and convenient multi-resolution representation where the components are well localized in the space and spatial frequency domains. It provides a decomposition of the image into a set of band pass copies and mirrors the multiple scales of processing in the HVS. We select Laplacian pyramid decomposition (among the various MR decomposition techniques such as the discrete wavelet transform) as it results in similar performance at reduced computational complexity.

The proposed fusion scheme is summarized in Fig. 1. The original and enhanced images are decomposed first using the Laplacain pyramid decomposition. The high and low frequency nodes of the composite pyramid are constructed from the corresponding nodes (of the Laplacian pyramid decomposition) of the original image as these are less affected by noise and edge artifacts. Similarly, the medium frequency nodes of the composite pyramid take contribution from the corresponding nodes of enhanced image as the important detail information (achieved by the contrast enhancement operation) is present in these nodes. Thus, a composite pyramid is constructed by selecting low and high frequency nodes from Laplacian decomposition of the original and the medium frequency nodes from the pyramid representation of the enhanced images. Each level l of the fused Laplacain pyramid $LF_l(i,j)$ is obtained by the following fusion rule.

$$LF_l(i,j)=\begin{cases}\frac{LA_l(i,j)+LO_l(i,j)}{2}, & l=0\\ LA_l(i,j), & 1\le l\le N-3\\ LO_l(i,j), & otherwise\end{cases} \tag{2}$$

$LA(i,j)$, $LO(i,j)$ and $LF(i,j)$represent the Laplacian pyramid decomposition of the enhanced, original and fused images, respectively. N is the decomposition level or the analysis depth and $0\le l\le N-1$. It is not possible to accurately estimate the optimal number of decomposition levels. The value of N depends upon the observation distance and the spatial extent of the objects. In general, larger the spatial extent of the objects in the image, more the number of decomposition levels. For the purpose of our simulations, we set the number of decompositions to 5. The composite image is then obtained simply by expanding and

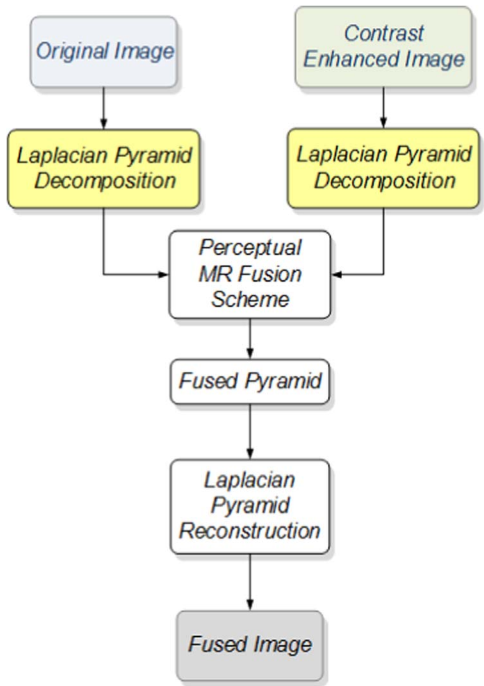

Fig. 1. Block Diagram of the Fusion Methodology.

adding the levels of $LF(i, j)$.

2.1. Evaluation of contrast enhancement

In the recent years, there have been considerable efforts to develop image quality assessment (IQA) methods [24]. Generally, the IQA analysis is treated as an estimation of image distortion. However, little work has been done to evaluate the quality of the contrast enhanced images. Indeed, the contrast evaluation problem is different from the classical IQA paradigm. Unlike the IQA analysis, the original image before enhancement is taken as the distorted image and the comparison is performed with the enhanced image. In the literature, we can find some simple measures which were proposed to evaluate the quality of the contrast enhanced images [21,25–29]. However, there is still no measure that correlates well with the HVS and the perceptual quality of the enhanced images. Some of the popular and widely used measures to evaluate the quality of contrast enhanced images are: the measure of enhancement (EME) [27], Edge Content [21], Absolute mean brightness error (AMBE) [25] and contrast [30]. These measures, however are not suitable for noisy images as they tend to over or under estimate the image quality for noisy images. In [31], the author performed a critical analysis of some existing contrast enhancement measures. They demonstrated the inefficiency of existing measures in capturing the undesirable effects such as ringing, noise amplification and other edge related artifacts. Therefore, after careful consideration, we decided to assess the result of our method objectively by analyzing the radial energy spectrum of the images before and after enhancement. As mentioned, the aim of our method is to improve the contrast but prevent noise amplification and artifacts (in low and high frequency part of the image) that might result from the traditional enhancement methods. Therefore, it is logical to analyze the rotationally averaged energy spectrum which helps us analyze the energy in the low, mid and high frequency bands of the images.

The average radial energy of an image can be computed by the analysis of the Fourier spectrum with respect to the radial and angular frequencies. The centered discrete Fourier transform $F(u, v)$, of an image $f(x, y)$ is defined as:

$$F(u, v)=\frac{1}{XY}\sum_{x=0}^{X-1}\sum_{y=0}^{Y-1}f(x, y)(-1)^{x+y} \quad \times\exp\left[-2j\pi\left(\frac{ux}{X}+\frac{vy}{Y}\right)\right] \tag{3}$$

where X, Y represent the image size and (u, v) are the spatial frequencies. Then, the corresponding energy spectrum is given by:

$$|F(u, v)|=\sqrt{R^2(u, v) + I^2(u, v)} \tag{4}$$

$R(u, v)$ and $I(u, v)$ being the real and imaginary parts of $F(u, v)$, respectively. We can use Eq. (4) to calculate the energy spectrum in polar coordinates, $w = \sqrt{u^2 + v^2}$ is the radial frequency and θ the angular frequency. The average radial energy spectrum $E(w)$ for a given radial frequency w is defined by:

$$E(w)=\frac{1}{M}\sum_{j=1}^{M}|F(w, \theta_j)| where \theta_j=\frac{j\pi}{M} \tag{5}$$

Where $F(w,\theta_j)$ is the Fourier spectrum in polar coordinates and M is the angular sampling rate.

Fig. 2. (a) Noisy image (generated by adding white Gaussian noise with zero mean and standard deviation of 0.01, Image enhanced with (b) ELCE (c) Proposed method.

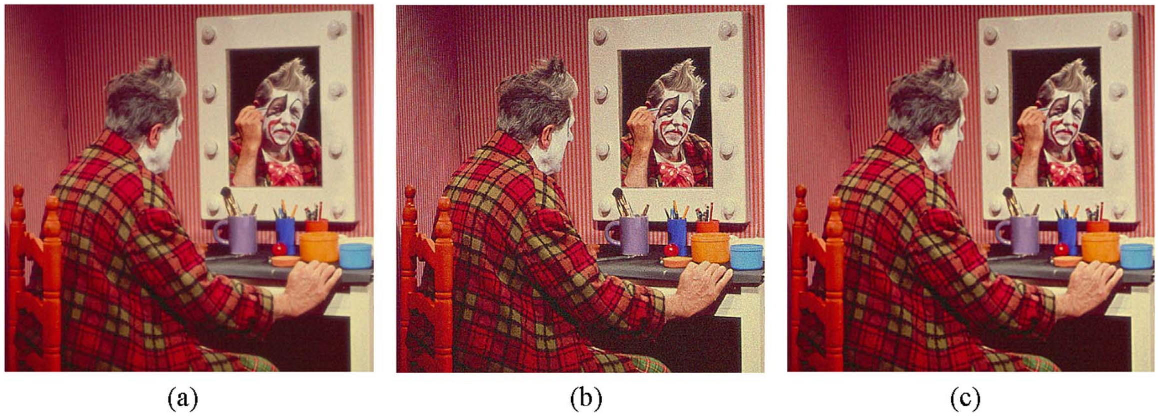

Fig. 3. (a) Noisy image (generated by adding white Gaussian noise with zero mean and standard deviation of 0.01, Image enhanced with (b) Un-sharpening (c) Proposed method.

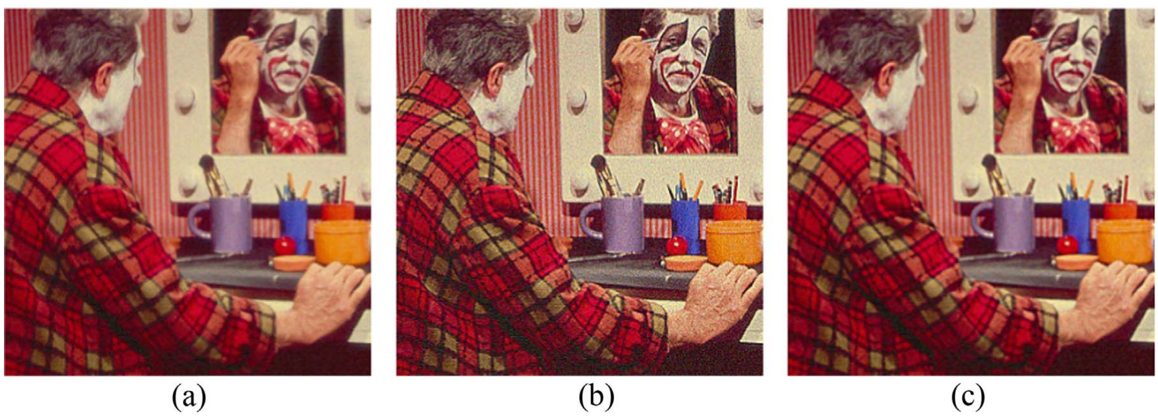

Fig. 4. Zoomed images corresponding to Fig. 3, Zoomed (a) Noisy image (generated by adding white Gaussian noise with zero mean and standard deviation of 0.01, Image enhanced with (b) Un-sharpening (c) Proposed method.

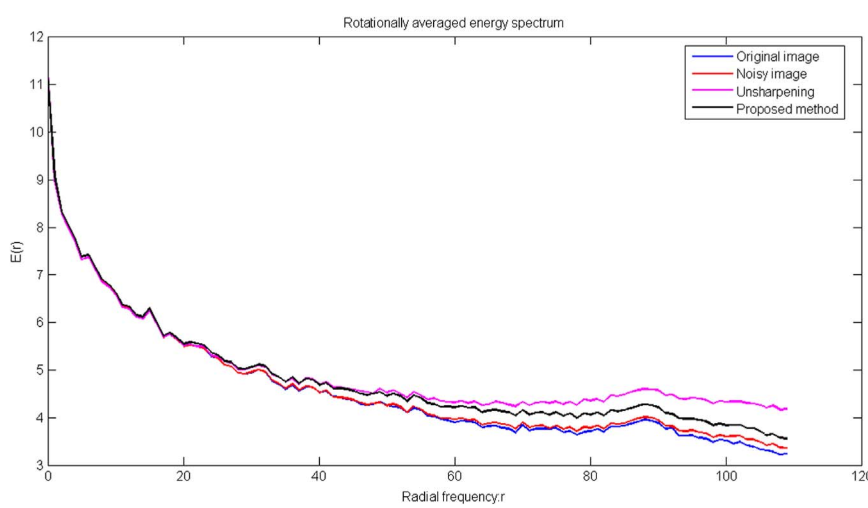

Fig. 5. Radial frequency spectrum for the images of Fig. 3.

3. Experiments and analysis

In this section, we present the simulation results for the proposed fusion technique. It is worth mentioning that this method can be applied to the output of any contrast enhancement technique with poor noise sensitivity. The aim is to propose a strategy to reduce the effects of noise amplification from some conventional and computationally simple contrast enhancement methods with poor noise sensitivity. We test our method by applying it to some classical enhancement techniques. We limit the analysis to classical methods as we want to demonstrate that the performance of some traditional methods (which are inefficient when used alone) can be improved by applying our proposed fusion based technique. For simulation and analysis, we therefore choose two simple conventional methods, the controlled un-sharp masking method proposed in [32] and the edge based local contrast enhancement techniques (ELCE) [12]. The UM and ELCE techniques effectively improve the image contrast and sharpness. However, the presence of linear high pass filter such as Laplacian operator in UM and ELCE methods, respectively, makes the system sensitive to noise and results in distortions (amplification of noise and

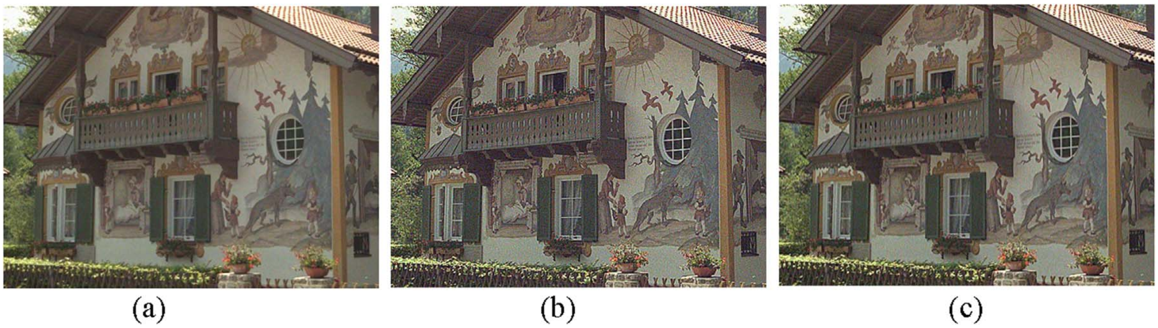

Fig. 6. Performance Comparison (a) Image corrupted with non-uniformly distributed noise, Images enhanced using (b) Un-sharpening (c) Proposed method.

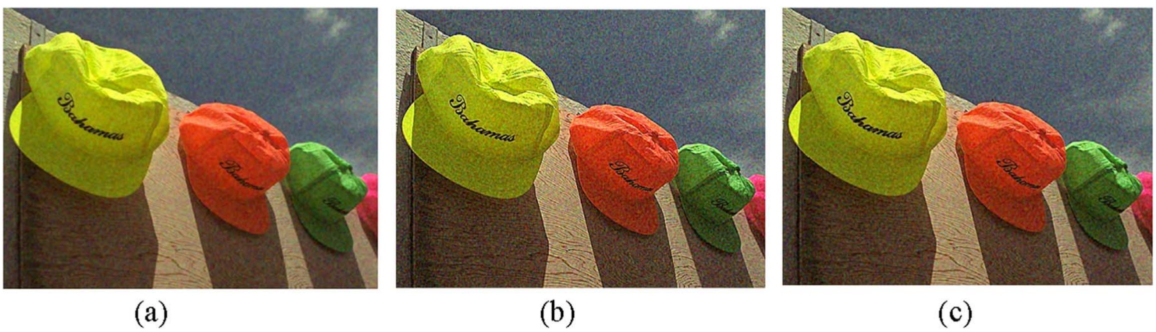

Fig. 7. (a) Image corrupted with spatially correlated noise, Images enhanced using (b) Un-sharpening (c) Proposed method.

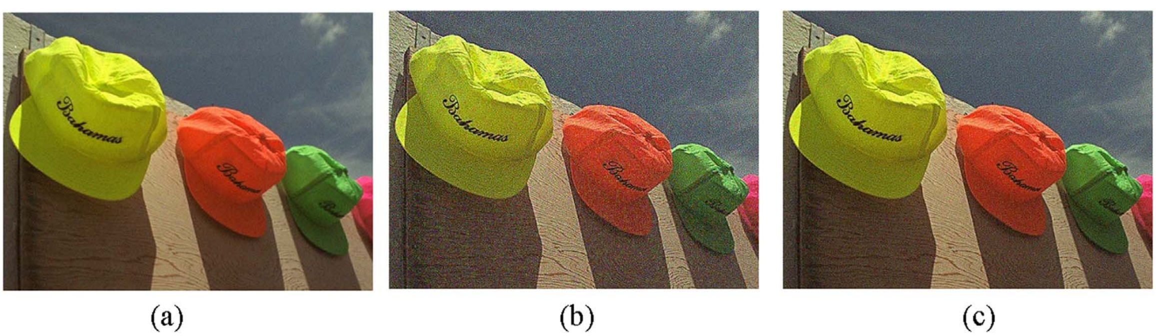

Fig. 8. Performance Comparison (a) Image corrupted with high frequency noise, Images enhanced using (b) Un-sharpening (c) Proposed method.

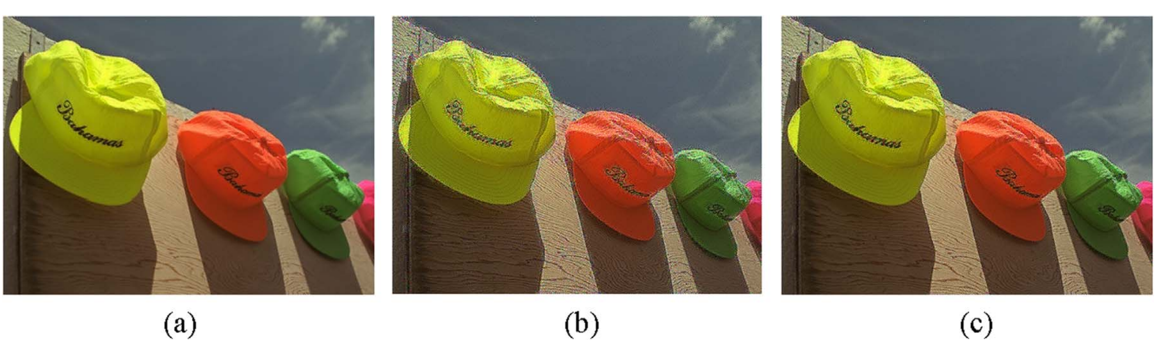

Fig. 9. Performance Comparison (a) Image corrupted with masked noise, Images enhanced using (b) Un-sharpening (c) Proposed method.

edge related artifacts) even for slightly noisy images. The applicability of these methods is limited due to the amplification of noise and edge related artifacts. For completeness, we first briefly recall the UM and ELCE contrast enhancement techniques in the following sections.

3.1. Un-sharpening method

The un-sharpening technique is based on improving the visual appearance of the image by emphasizing the high frequency content. For this, a high pass filtered and scaled version of the image is added to the original image. For an image I, the smoothed version of the image is obtained by using a low pass filter as given below:

$$I_{smooth}(x, y) = I(x, y) * h(x, y) \tag{6}$$

Here, $h(x, y)$ is the impulse response of the filter. The enhanced image $I_{um}(x, y)$ is then obtained from the original image as:

$$I_{um}(x, y) = I_{smooth}(x, y) + \alpha[I(x, y) - I_{smooth}(x, y)] \tag{7}$$

Where α is a scaling factor which controls the amount of sharpening.

This method is often applied in different applications due to its simplicity. However, it is very sensitive to noise and can produce distortions such as noise and overshooting, even for slightly noisy images. There have been various efforts to improve the noise sensitivity of the un-sharp masking technique [33–36]. We select the un-sharpening technique to show the effectiveness of our fusion based methodology.

3.2. Local edge based contrast enhancement

The local edge based contrast enhancement method is based on the measurement of local contrast [12]. For an image I, the local contrast in a window $w \times w$ centered at the pixel location (x, y) is given by the following expression:

$$C_{xy} = \frac{|I_{xy} - \overline{E_{xy}}|}{|I_{xy} + \overline{E_{xy}}|} \tag{8}$$

and

$$\overline{E_{xy}} = \frac{\sum_{(x,y)\epsilon w_{xy}} I_{xy}\varphi_{xy}}{\sum_{(x,y)\epsilon w_{xy}} \varphi_{xy}} \tag{9}$$

$\overline{E_{xy}}$ being the mean edge gray value and φ_{xy} represents the edge value of the pixel (x, y). The edge value of a pixel can be computed by applying any gradient operator (such as Prewitt or Sobel operator). The image contrast is enhanced by applying any increasing function bounded to [0,1] to the local contrast C_{xy}.

$$C'_{xy} = T(C_{xy});\ 0 \le C'_{xy} \le 1 \tag{10}$$

The ELCE enhancement technique is based on human visual perception. But it is susceptible to ringing and other edge distortions.

3.3. Experimental results

To test the performance of the proposed technique, we apply it to noisy test images. The images are often corrupted by additive Gaussian noise (modeled as white Gaussian noise) during acquisition because of poor illumination conditions, high temperatures etc. Noise can also be non-uniformly distributed between the different color components [37]. Moreover, in some instances, additive noise cannot be treated as spatially uncorrelated (white). This type of noise is present in images captured using the modern digital cameras. Apart from these, masked and high frequency noise are some other noise distortions that are typical for some imaging operations such as lossy image compression [38]. We present the results of our method for images corrupted with additive white Gaussian noise, non-uniformly distributed, spatially correlated, masked and high frequency noise.

Figs. 2 and 3 illustrate the results of the proposed method in preventing noise amplification and other edge artifacts for ELCE and un-sharpening techniques. To test the noise robustness performance of our method some noisy test images are generated by adding white Gaussian noise (Figs. 2a and 3a). Figs. 2b and 3b show the images enhanced by ELCE and UM techniques, respectively. It can be noticed that ELCE and un-sharpening techniques amplify noise and tend to produce over shooting. Visual analysis of the processed images (Figs. 2c and 3c) shows that the proposed method prevents noise amplification from the images obtained by enhancement using the ELCE and un-sharpening techniques while retaining their local and global contrast. For better visualization of the noise and edge ringing artifacts, the images in Fig. 3 are zoomed for comparison and shown in Fig. 4.

To objectively assess the noise performance of the proposed method we observe the radial energy spectrum of the images in Fig. 3. We can see from Fig. 5 that the radial frequency spectrum consists of three parts (low, mid and high energy). The low energy part of the output spectrum remains unchanged (similar to that of the original image) as imposed by the proposed method. Energy for the mid-frequency remains the same as that of the enhanced image (image enhanced using un-sharp masking in this example) while it attenuates and approaches that of the original image for the high frequency band (Fig. 5). For better visualization we plot only the low and mid frequency part of the spectrum and observe that the spectrum of the proposed method approaches that of the original image for the high frequency band.

We also analyze the performance of our method by testing it for images corrupted with non-uniformly distributed (between different color components) noise, spatially correlated, masked and high frequency noise. We select noisy images from the TID2013 database [39] which are relevant to our problem. The TID2013 database contains 25 reference and 3000 distorted images and seventeen different types of distortions.

Figs. 6–9 present the comparison of performance of the proposed method for different types of noise (i.e. non-uniformly distributed, spatially correlated, masked and high frequency noise). It can be observed that the proposed method (results displayed in Figs. 6c, 7c, 8c, 9c) improves the noise amplification problem for the un-sharpening technique (results presented in Figs. 6c, 7c, 8c, 9c) for the different types of noise displayed in Figs. (6a, 7a, 8a, 9a).

We notice that by applying MR perceptual fusion technique, we enhance image details visibility and at the same time avoid amplifying noise in low and high frequency. Thus, the proposed fusion based method for noise reduction preserves the most important information of the enhanced images corresponding to mid-frequency range while successfully avoiding the annoying noise and edge artifacts by fusing it with the original image.

4. Conclusions

We propose a multi-resolution based fusion methodology to prevent noise in some conventional image enhancement techniques. The results of the proposed approach show the efficiency of the technique in retaining subtle details without amplifying noise and overshoot or halo effects. The computational complexity of the proposed method is not substantially increased due to the efficient implementation of the pyramid based decomposition methods. The output of some computationally simple (old methods) can thus be fused in an effective way to produce images with improved visibility of image details without artifacts and noise amplification. The method proposed in our paper can also be extended to improve other image enhancement techniques such as de-noising, de-blocking and de-ringing.

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