Image Enhancement Using the Log-ratio Approach

G. Deng and L. W. Cahill

Department of Electronic Engineering, La Trobe University
Bundoora Victoria 3083 Australia

Abstract

In this paper, we present a new image enhancement algorithm for interactively modifying the contrast and the sharpness of an image. The proposed algorithm aims at solving two basic problems associated with typical image enhancement technique: the enhanced image is usually out of the gray level range of an image, and there are conflicting requirements for image sharpening and noise reduction. A vector space based approach, the Log-ratio approach, is employed to solve the first problem and a multiscale approach is used for the second problem. The proposed algorithm has been used successfully to enhance medical images.

1: Introduction

Image enhancement is the processing of images to improve their appearance to human viewers or to enhance the performance of other image processing systems [1]. Typical contrast enhancement techniques are histogram modification and linear contrast stretching using piecewise linear functions [1]. Recently, adaptive histogram equalisation techniques have been developed for enhancing medical images [2]. Techniques for enhancing the sharpness of an image are based on linear or nonlinear high pass filtering or unsharp masking [1]. In this paper, our study will be focused on techniques that permit an interactive modification of the contrast and sharpness of an image. Two such techniques that have been widely used are Lee's algorithm [3] and the homomorphic filter [1].

Let $F(x,y)$ be the pixel brightness of an image, Lee's algorithm can be expressed as:

$$F'(x,y) = \gamma A(x,y) + \beta + \eta[F(x,y) - A(x,y)], \qquad (1)$$

where $A(x,y)$ is the arithmetic mean value of the brightness of a $(n \times n)$ window that is centered on the pixel position (x,y). The parameters γ and β control the contrast, while η controls the sharpness. Lee's algorithm can be regarded as a more general form of the unsharp masking technique.

The homomorphic filter proposed by Oppenheim, *et al.* [1] can simultaneously compress the dynamic range and enhance the sharpness of an image. It can be shown that the processing between the logarithm and the exponential operations actually uses the unsharp masking technique as expressed in Lee's algorithm.

There are two basic problems associated with these techniques. The first problem is associated with the digital image representation that the gray level is in the range of [0, M), where M equals 256 for an 8-bit image. Using these techniques, the gray level of the resultant image is often out of range. Therefore, the result needs to be rescaled by a linear or nonlinear (hard limiting) rescaling process. The linear rescaling process has a shortcoming in that it cancels out the linear contrast enhancement of Lee's algorithm. It has been shown that the rescaling process is not efficient and often results in information loss [4].

The Log-ratio approach [4] was originally proposed to overcome the same problem in image restoration. It is based on vector space theory. Since vector addition and scalar multiplication operations defined in a vector space are closed, then it is mathematically sound to define a vector space for images to overcome the out-of-range problem. An image vector space is defined by means of a homomorphism that maps the image vector space into the real number space. The Log-ratio is one of the mapping functions that satisfied a set of predefined conditions [4].

Another problem is the conflicting requirements inherent in image enhancement: sharpening the image whilst simultaneously reducing noise. One method of approaching this problem is to use adaptive filtering [5] which incorporates edge detection and pattern recognition techniques to "distinguish" the useful features from noise in an image. The definition of feature plays a crucial part in determining the success of this method. Another method is to use multiscale image processing [6,7].

Using multiscale processing technique, an image is first decomposed into a series of images in different scales (levels of spatial resolution). Images in each scale are processed independently. They are then recombined to obtain the final image. The multiscale processing technique is attractive because it provides the possibility of reducing the computational cost of image processing. Moreover, it permits the development of new image enhancement algorithms that can to some extent meet the conflicting requirements of image sharpening and noise

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suppression. This is based on the observation that important features such as the boundaries of the objects in an image have components in both the coarse and fine scale, while noise and fine textures have components only in the fine scale.

In this paper, we propose a Log-ratio based image enhancement algorithm to solve the "out-of-range" problem. This algorithm is further extended to multiscale processing to solve the noise enhancement problem. In section 2, the Log-ratio approach is briefly described and the nonlinearity of its operations is illustrated. The new image enhancement algorithm is presented in section 3, while simulation results and a comparison of the new algorithm with other techniques are presented in section 4.

2: The Log-ratio approach

In the following, let F and G represent the pixel gray levels of an image and let a represent a real number. In the log-ratio approach, a vector space for images is constructed by defining a mapping [4]: $\Psi(F)=\log((M-F)/F)$ from the image space $(0,M)^n$ to the real number space $\mathbf{R}^n$, where n is number of pixels in an image. The vector addition $\oplus$ and scalar multiplication $\otimes$ operations in the image space are implicitly defined as:

$$F \oplus G = \Psi^{-1}(\Psi(F)+\Psi(G)) \qquad (2)$$

and

$$a \otimes F = \Psi^{-1}(\alpha\Psi(F)) \qquad (3)$$

where Ψ^{-1} represents the inverse mapping. The explicit definitions of the above operations are given below:

$$F \oplus G = \frac{M}{\frac{M-F}{F}\frac{M-G}{G}+1} \qquad (4)$$

and

$$a \otimes F = \frac{M}{\left(\frac{M-F}{F}\right)^a+1} \qquad (5)$$

It is easy to derive the subtraction operation Θ as:

$$F \Theta G = \frac{M}{\left(\frac{M-F}{F}\Big/\frac{M-G}{G}\right)+1} \qquad (6)$$

Since the above operations are defined in a vector space, they are closed. This means that image processing using these operations results in another image whose gray level is still within the same range of the original image. Therefore, the Log-ratio approach provides a mathematical solution to the out-of-range problem encountered in image processing. The nonlinear characteristics of the above addition and multiplication operations are demonstrated in Fig. 1. As we will see in the next section, these nonlinear properties are useful for image enhancement.

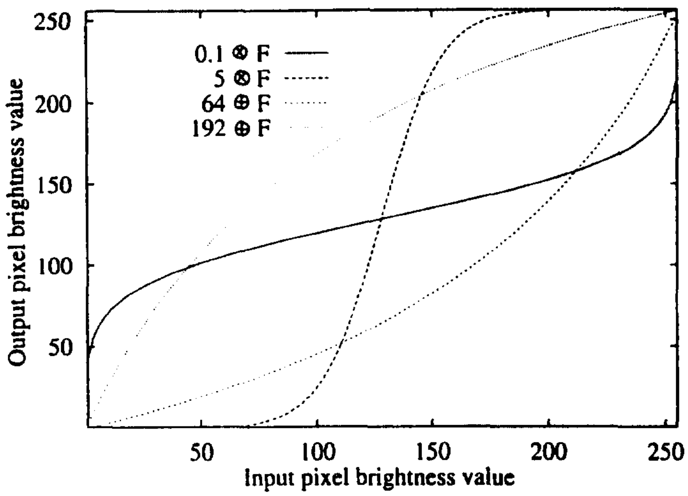

Fig. 1 The nonlinearity of the operations defined in the Log-ratio approach

3: A new image enhancement algorithm

In this section the Log-ratio based image enhancement algorithm is first presented. A multiscale extension of this algorithm is then described.

Let $F(x,y)$ and $F'(x,y)$ represent the gray level values of the original and the processed images, respectively. The proposed algorithm is expressed as:

$$F'(x,y) = A(x,y) \oplus b \oplus a \otimes (F(x,y)\ \Theta\ A(x,y)), \qquad (7)$$

where $A(x,y)$ is a low-pass-filtered version of $F(x,y)$. A comparison of equations (1) with (7) shows that the proposed algorithm is actually Lee's algorithm implemented using the generalized addition and multiplication operations.

It is noted that $A(x,y)$ may be generally regarded as the result of a linear or nonlinear low pass filter and the process $(F(x,y)\ \Theta\ A(x,y))$ can then be regarded as a nonlinear high pass filter. Therefore, the proposed algorithm can be regarded as a generalized unsharp masking algorithm. The two parameters a and b control the sharpness and the contrast of the output image, respectively.

To see this, let us first consider a case where $a=0$ so that $F'(x,y)=A(x,y)\oplus b$. It can be easily seen from Fig. 1 that when $b>M/2$, the new addition operation is actually a re-scaling process which nonlinearly expands the dynamic range of the dark area of an image. This property is very useful for enhancing the contrast of an underexposed image. One can also easily see that when $b < M/2$ the dynamic range of the bright area of an image is nonlinearly expanded. This is useful for enhancement of an over-exposed image.

Secondly, the effect of the process: $E(x,y) = a \otimes (F(x,y) \ominus A(x,y))$ can also be understood using Fig. 1. When $a > 1$, $E(x,y)$ which represents the high spatial frequency information of an image, will be nonlinearly amplified. Thus, the sharpness of an image is changed. When a is very large (for example, $a = 32$), the new multiplication operation functions almost as a thresholding process, i.e., $E(x,y) \approx M$ if $(F(x,y) \ominus A(x,y)) > M/2$ and $E(x,y) \approx 0$ if $(F(x,y) \ominus A(x,y)) < M/2$. Therefore, the edges of an image are outlined. When $E(x,y)$ is added to the original image, overshoots on both sides of an edge are generated. This effect is similar to that of the unsharp masking technique. We also note that when $a < 1$, the resultant image is smoothed and when $a = 0$, the proposed algorithm functions as a nonlinear filter with contrast enhancement.

The above algorithm has been extended to multiscale processing which is shown in Fig. 2.

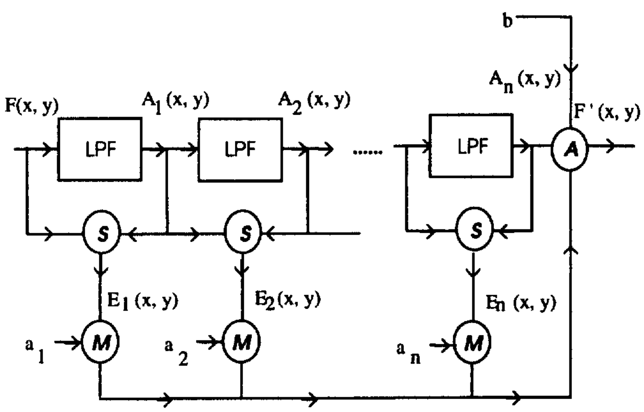

Fig. 2 Block diagram for the multiscale image enhancement algorithm. The letters ***A, M*** and ***S*** represent the LR based addition, subtraction and multiplication operations, respectively. *LPF*(.) represents a low pass filter (linear or nonlinear), and *n* is the number of scales.

In this figure, the multiscale decomposition is accomplished by:

$$F(x,y) = E_1(x,y) \oplus E_2(x,y) \oplus \ldots \oplus E_n(x,y) \oplus A_n(x,y), \quad (9)$$

where

$$A_0(x,y) = F(x,y),$$
$$A_n(x,y) = LPF(A_{n-1}(x,y)),$$

and

$$E_n(x,y) = A_{n-1}(x,y) \ominus A_n(x,y).$$

The multiscale enhancement algorithm can then be expressed as:

$$F'(x,y) = a_1 \otimes E_1(x,y) \oplus a_2 \otimes E_2(x,y) \oplus \ldots \oplus a_n \otimes E_n(x,y) \oplus A_n(x,y) \oplus b. \quad (10)$$

We can see that when n=1, equation (10) becomes identical to equation (7), therefore the parameters a_i and b in the new algorithm have the same effects as described earlier in this section (equation (7)). However, the new algorithm gives us more freedom in enhancing an image. For example, one can set the first few parameters $a_i < 1$ $(1 \le i < k)$ to suppress the fine texture or noise, and set other parameters $a_i > 1$ $(k < i \le n)$ to enhance the edges of the large objects.

From the computational point of view, the above algorithms seem time consuming. However, we can simplify these algorithms by using the mapping function $\Psi(F) = \log((M - F)/F)$. For example, equation (7) can be simplified as:

$$\Psi(F'(x,y)) = \Psi(A(x,y) \oplus b \oplus a \otimes (F(x,y) \ominus A(x,y)))$$
$$= \Psi(A(x,y)) + \Psi(b) + a(\Psi(F(x,y)) - \Psi(A(x,y))).$$

The final resultant image is obtained by taking the inverse mapping : $\Psi^{-1}[\Psi(F'(x,y))]$.

4: Simulation results and comparison

Simulation experiments using several kinds of images including medical images and satellite images have been conducted to evaluate the performance of the proposed algorithm. Fig 3(a) is the original digital subtraction angiography (DSA) image, Fig 3(b) is the enhanced image using the proposed algorithm with $a = 5$ and $b = 180$. (equation 7). This example clearly demonstrates that the proposed algorithm can effectively enhance the contrast and sharpness of an image. A lot of details that can not be seen in the original image are clearly revealed. Similar results have also been obtained using LANDSAT images.

The multiscale processing algorithm has been tested using the peppers image shown in Fig. 4(a). First, the image is decomposed into three layers and is then processed by the multiscale algorithm with the parameters $b = 180$,$a_1 = 1$, $a_2 = 5$, and $a_3 = 5$. The resultant image is shown in Fig. 4(b). Second, for comparison, the algorithm expressed in equation (7) is used with the parameters : $b = 180$ and $a = 5$. The resultant image is shown in Fig. 4(c). A comparison of Fig. 4(b) with Fig. 4(c) shows that both algorithms can considerably enhance the image.

Details that can hardly be seen in the dark areas of the original image are now visible. However, the multiscale algorithm results in a less noisy image. As another example to show the advantages of this algorithm, one can set the parameters: $b = 180$, and $a_1 = 0$, $a_2 = 0$, $a_3 = 5$. In the resultant image, the fine textures and noise can be smoothed out, whilst the edges of large objects are simultaneously enhanced.

The comparison of different image enhancement methods is difficult, since it requires that each method be "tuned" to its best state, but there seems to be no criterion for such "tuning". Further, a specific enhancement method may best fit one application, but may completely fail in another. Therefore, emphasis now will be given to a discussion of the advantages and the disadvantages of various typical image enhancement techniques in manipulating the dynamic range and in improving the sharpness of an image.

The histogram equalization is a general contrast enhancement method and needs no "tuning". Its goal is to obtain a uniform histogram for the output image. This is useful in stretching the contrast of images with narrow histograms.

It has been applied to Fig. 3(a). The resultant image is shown in Fig. 3(c). It can be seen the histogram equalization failed to enhance the DSA image. Therefore, the histogram equalization technique is not suitable for revealing the dark details in an image with a broad histogram, such as the DSA images. The reason is that histogram equalization always leads to "clumping" of pixels in adjacent histogram bins. This leads to some loss of contrast between close gray levels. Thus histogram equalization is unlikely to be any help of in improving contrast over a small range of intensities.

The proposed algorithm has also been compared with Lee's algorithm. We observed that by properly setting the parameters of Lee's algorithm and fine tuning of the following linear rescaling process, similar results as those of the proposed algorithm can be obtained. Let *max* and *min* represent the maximum and minimum values of the pixel brightness of an output image, and let α represent a scaling factor, then the rescaling process is expressed as:

$$F_1(x,y) = \frac{255}{\alpha(max - min)} F(x,y) - \frac{255 min}{max - min}, \quad (11)$$

where $F_1(x,y)$ and $F(x,y)$ are the output and the input of the rescaling process, respectively. The parameter α is usually set less than one, so that the process will not be fooled by a few pixels with extreme values. It is easy to see that when $\alpha < 1$, there are some pixels with brightness values which are still out of the range of [0, 255]. Thus, a further hard-limiting process is needed. Therefore, the proposed algorithm has an advantage over Lee's algorithm in that it does not need the further rescaling process.

5: Conclusion

In this paper, we have addressed two basic problems associated with typical image enhancement techniques: the out-of-range problem and the conflicting requirement for edge sharpening and noise filtering. We have proposed a vector space based approach-the Log-ratio approach-to solve the first problem and the multiscale processing to solve the second. The proposed algorithm have been successfully used to interactively modify the contrast and sharpness of different kinds of images.

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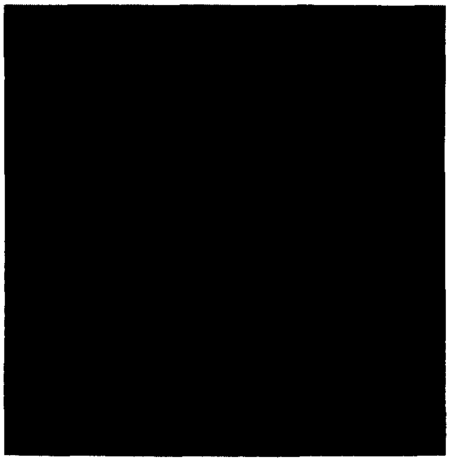
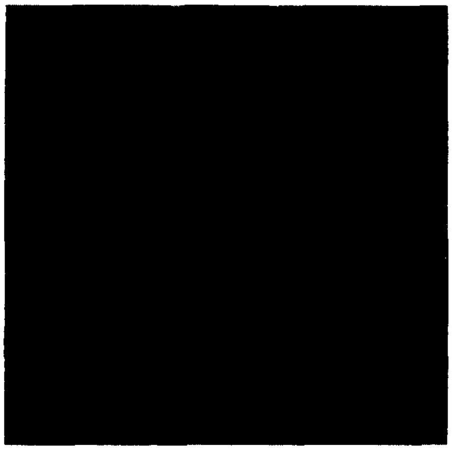


(a)



(b)

(c)

Fig. 3. (a) Original image. (b) Enhanced by the proposed algorithm (equation 7). (c) Enhanced by histogram equalization.

(a)

(b)

(c)

Fig. 4. (a) Original image. (b) LR approach multiscale enhancement (equation 10). (c) LR approach enhancement (equation 7).