Enhancing the pictorial content of digital holograms at 100 frames per second

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Abstract: We report a low complexity, non-iterative method for enhancing the sharpness, brightness, and contrast of the pictorial content that is recorded in a digital hologram, without the need of re-generating the latter from the original object scene. In our proposed method, the hologram is first back-projected to a 2-D virtual diffraction plane (VDP) which is located at close proximity to the original object points. Next the field distribution on the VDP, which shares similar optical properties as the object scene, is enhanced. Subsequently, the processed VDP is expanded into a full hologram. We demonstrate two types of enhancement: a modified histogram equalization to improve the brightness and contrast, and localized high-boost-filtering (LHBF) to increase the sharpness. Experiment results have demonstrated that our proposed method is capable of enhancing a 2048x2048 hologram at a rate of around 100 frames per second. To the best of our knowledge, this is the first time real-time image enhancement is considered in the context of digital holography.

OCIS codes: (090.0090) Holography; (090.1995) Digital holography; (090.1760) Computer holography.

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1. Introduction

In a digital hologram, a complex on-axis hologram $H(x,y)$ records the object waves that are emitted from the object points in a three dimensional (3-D) scene. Suppose the latter is a 3-D surface with the intensity of each point, and its perpendicular distance from the hologram given by $I(x,y)$ and $d(x,y)$, respectively, $H(x,y)$ can be mathematically described as [1]

$$H(x,y)=\sum_{m=1}^{X-1}\sum_{n=1}^{Y-1}\frac{I(m,n)}{r(m,n,x,y)}\exp\left[j\frac{2\pi}{\lambda}r(m,n,x,y)\right]. \qquad (1)$$

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In Eq. (1), X and Y are the horizontal and vertical extents of the hologram, respectively, and are assumed to be identical to that of the object scene. λ is the wavelength of the optical beam which is used to generate the complex hologram. The term $r(m,n,x,y)$ is the distance of an object point at position (m,n) to a point at (x,y) on the hologram. A digital hologram can be generated numerically based on Eq. (1), or acquired optically with optical means [1]. However, it is sometimes difficult to control the illumination in the capturing process, or the nature of the image scene to attain the desired optical properties (such as sharpness, brightness and contrast), hence resulting in blurriness, over or underexposure in the reconstructed image. In traditional photography, this kind of defects can be easily compensated by re-adjusting the intensity of individual pixels. However, it can be inferred from Eq. (1) that such approach cannot be applied directly to a digital hologram as each pixel in the latter is representing holistic instead of local information. Modifying a single hologram pixel will lead to a change in the entire scene, instead of localizing in the area around the pixel. Conceptually, it is possible to reconstruct the original 3-D scene, apply some sort of enhancement to correct the optical properties, and convert the result back to a hologram. However, it has been shown in some recent works (such as [2,3]) that the inverse process is both complicated and computationally intensive. Until now, only the recovery of simple image scenes have been demonstrated by the existing methods. Besides, even if the original scene is available or can be reconstructed, the generation of the hologram with the existing fast methods [4–6] is rather time-consuming. In this paper, we propose a fast method for directly enhancing the optical properties of images recorded in a digital hologram, without the need of regenerating the latter from the original object scene. Briefly, we first project the hologram onto a two dimensional (2-D) plane called the virtual diffraction plane (VDP), which is located near to the object space. At close proximity, the magnitude of the field distribution on the VDP is a de-focused version of the original 3-D scene, both sharing similar optical properties. As such, local modification on the VDP will invoke, to a good approximation, similar changes on the optical properties of the object scene it represents. On this basis, we apply a variant of the classical histogram equalization method [7] to the VDP image to flatten the probability distribution of the pixel intensity, leading to improvement in its brightness and contrast. To sharpen a selected part of the image, we apply high-boost-filtering to strengthen the edges on the corresponding region on the VDP. Finally, the VDP is diffracted back to the original plane of the digital hologram to become a processed digital hologram.

2. Virtual diffraction plane: proposed hologram enhancement method

The concept of the proposed hologram enhancement method can be illustrated with Fig. 1 showing the back-projection of a digital hologram onto a virtual plane, which we call it a virtual diffraction plane (VDP). The VDP is to be located at close proximity to the original 3D object. From the diagram, it can be seen that the object beam emerging from the object point will only cover a small region (a.k.a. the support), marked in dotted lines, on the VDP. It can also be inferred that the closer the distance between the object point and the VDP, the smaller will be the support of the diffraction pattern. For a scene composing of multiple object points, each of them will contribute to the VDP in a similar manner. As such, the VDP is a complex image which contains the amplitude and phase information of the hologram, as well as similar optical properties of the object space. Based on the above concept, our proposed enhancement method is realized in 3 stages. First, the field distribution on the VDP corresponding to the hologram is derived. Second, processing is performed on the VDP. We shall demonstrate brightness and contrast enhancement as a first example. To enhance the overall brightness and contrast of the object image, a mapping function to flatten the histogram of the magnitude of the VDP pixels is determined. The complex pixel values are then rescaled by a second function that is derived from the mapping function. This process is

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commonly known as "histogram equalization" [7], but we have extended it to process the complex VDP image. As a second example, we increase the sharpness of an area by applying localized high-boost-filtering to that region to increase the edge strength, resulting in a sharper perception. Finally, the processed field distribution on the VDP is converted to a digital hologram. These 3 stages are described in detail in the following sub-sections.

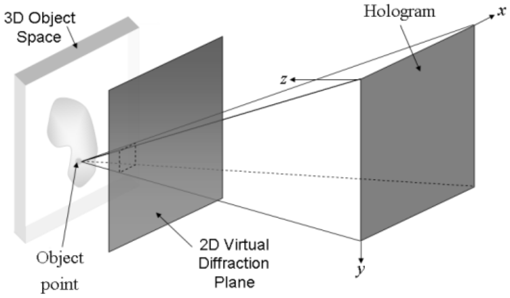

Fig. 1. Spatial relation between the 3-D object space, the 2-D VDP, and the hologram

2.1 Derivation of the VDP

Referring to Fig. 1, the VDP can be interpreted as a portal between the digital hologram and the 3-D object space which carries the information of both entities. We assume that the VDP and the hologram have identical horizontal, as well as vertical extents of X and Y units, respectively. Suppose the VDP is located at an axial distance z_w from the hologram, and denoted by the complex wavefront $u_w(x,y)$, it can be derived as

$$u_w(x,y)=H(x,y)*g(x,y), \tag{2}$$

where $g(x,y)=\dfrac{-j}{\lambda z_w}\exp\left(j2\pi z_w/\lambda\right)\exp\left(-j\frac{\pi}{\lambda z_w}\left(x^2+y^2\right)\right)$ is the complex conjugate of the free-space spatial impulse response in Fourier optics [8], and * denotes convolution.

2.2 Enhancing the VDP field distribution based on histogram equalization and localized high-boost-filtering (LHBF)

In the second stage of the proposed method, we apply image sharpening and histogram equalization to the field distribution on the VDP plane to demonstrate our proposed technique.-For image sharpening, we apply a simple high-boost-filter to an area of interest R as

$$u_w^H(x,y)\Big|_{(x,y)\in R}=A\left[u_w(x,y)-Bu_w^L(x,y)\right]. \tag{3}$$

In Eq. (3), $u_w^L(x,y)$ is a low-pass version of R, which can be a part or the whole of VDP. The value of each pixel at (x,y) is derived from the mean of a 3x3 window centered at the corresponding pixel in $u_w(x,y)$ (which is a complex quantity) as

$$u_w^L(x,y)=\frac{1}{9}\sum_{m=-1}^{1}\sum_{n=-1}^{1}u_w(x+m,y+n). \tag{4}$$

The terms A and B are constant values. The larger the values of A and B, the higher will be the brightness and sharpness of the region R, respectively. Other types of sharpening filters can be applied under the same principle.

For histogram equalization, the histogram $p(m)$ representing the probability density function of the magnitude of the pixel values in the VDP, which have been normalized to the range [0,1], is computed. Suppose there are M pixels in the VDP and $N(m)$ is the number of pixels with magnitude equals to m, the histogram is given by

$$p(m) = N(m)/M. \tag{5}$$

From Eq. (5), we can calculate the cumulative distributive function as

$$cdf(i) = \sum_{k=0}^{i} p(k). \tag{6}$$

Based on the cumulative distributive function, a mapping function is derived to convert the magnitude of each pixel value (with original value '*m*') to a new quantity '*n*' between the interval (0,1). Suppose *D* is the maximum pixel value, we have

$$n = D \times cdf(m) \tag{7}$$

From Eq. (7), we obtain a re-scaling function given by

$$T(0) = 1 \text{and} \, T(m)\big|_{m>0} = n/m. \tag{8}$$

Next, $T(m)$ is applied to re-scale the complex pixel values of the VDP as

$$v(x,y) = u_w(x,y)\,T\left(\left|u_w(x,y)\right|\right) \tag{9}$$

2.3 Generating the enhanced hologram from the VDP

In the final stage of our proposed method, the processed field distribution on the VDP, $u_{ENC}(x,y)$ (which may be have been sharpened and/or enhanced with histogram equalization), is expanded into a hologram as

$$H_{ENC}(x,y) = u_{ENC}(x,y) * g^*(x,y), \tag{10}$$

where, $u_{ENC}(x,y) = u_w^H(x,y)\big|_{(x,y)\in R}$ or $u_{ENC}(x,y) = v(x,y)$ for high-boost-filtering and histogram equalization, respectively. Our proposed method mainly involves the conversion of the hologram to the VDP (Eq. (2)), and the expansion of the enhance VDP to the hologram (Eq. (10)), which can be accomplished in the frequency space with 2 fast fourier transform (FFT) and 2 inverse FFT operations, respectively. The rest of the processes are negligible in computation time. In our implementation, we have employed the Graphic Processing Unit (GPU) to conduct the FFT. As such, the enhancement of a digital hologram of size 2048x2048 pixels can be realized in less than 10*m*s, equivalent to a rate of over 100 frames per second.

3. Experimental results

In Fig. 2, we show a 1920x960 double depth image “Lenna” to evaluate the performance of our proposed method in brightness and contrast enhancement. The image is evenly partitioned into a left side and a right side, located at 0.56m and 0.6m from the hologram, respectively. The picture is underexposed in most of the area, but overexposed along the rim of the nose. Equation (2) is applied to generate a 2048x2048 digital hologram based on wavelength of 650*n*m and hologram pixel size of 7*u*m. The numerical reconstructed image at 0.56m is shown in Fig. 2(b). Histogram equalization is directly applied to the hologram and the

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reconstructed images at 0.56m is shown in Fig. 2(c). It can be seen that although the overall brightness is increased, the reconstructed image is heavily contaminated with noisy patterns. This is caused by the distortion on the entire hologram as the intensity of each pixel is modified after the histogram equalization process. Similar finding is obtained at a reconstruction distance of 0.6m (focal distance of the right half of the image).

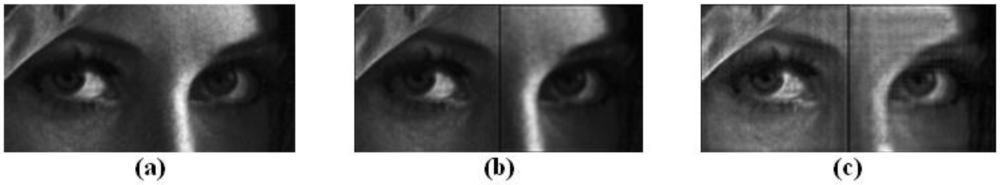
(a) (b) (c)

Fig. 2. (a) A scene image evenly divided into a left and a right sections, positioned at 0.56m and 0.6m from the hologram plane, respectively. (b) Numerical reconstruction of the hologram representing the double depth image in Fig. 2(a) at 0.56m. (c) Numerical reconstruction of the hologram representing the double depth image in Fig. 2(a) at 0.56m. The whole hologram has been directly processed with histogram equalization

Next we have applied our proposed method to enhance the hologram with the VDP positioned at 0.58m. The reconstructed images at the two depth values are shown in Figs. 3(a) and 3(b). We observe that in the reconstructed images, the brightness and contrast are improved, and the degradation shown in Fig. 2(c) is not present.


(a) (b)

Fig. 3. (a),(b) Numerical reconstruction of the hologram representing the double depth image in Fig. 2(a) at 0.56m and 0.6m, respectively. The hologram has been enhanced with our proposed method.

Similar test is performed on a hemisphere with the texture of the earth image as shown in Fig. 4(a). The hemisphere has a radius of 5mm with its tip located at 0.3m from the hologram. The hologram is generated with Eq. (1) and the target effect is to enhance the edges at the left half side of the hemisphere. First, we apply the high-boost-filter directly to the digital hologram. The reconstructed image at 0.3m is shown in Fig. 4(b). It can be seen that the image is severely distorted, although the edges on the left side is strengthened. Next, we apply our proposed method to process the left part of the VDP with high-boost filtering. The reconstructed image is shown in Fig. 4(c). We observe that the edges on the left side of the globe are strengthened and the rest of the reconstructed image is not distorted.

Subsequently, a quantitative evaluation on our proposed method is conducted based on the above pair of test samples in Figs. 2(a) and 4(a). We computed the normalized cross-correlation between a hologram which is generated directly from an enhanced 3D scene (i.e. applying histogram equalization or high-boost-filtering to the texture image $I(x,y)$ prior to the generation of the hologram), and a hologram which is enhanced by our proposed method at different positions z_w of the VDP. The normalized cross-correlation plots for the two examples are shown in Figs. 5(a) and 5(b). From both of the plots, we observed that when the distance of the VDP is close to the 3D scene, the cross-correlation is high reflecting small difference between the pair of holograms. The best result is obtained when the VDP is located somewhere within the 3D scene, in which case the cross-correlation factor is over 0.99, indicating that the pair of holograms is practically identical. To further illustrate our edge

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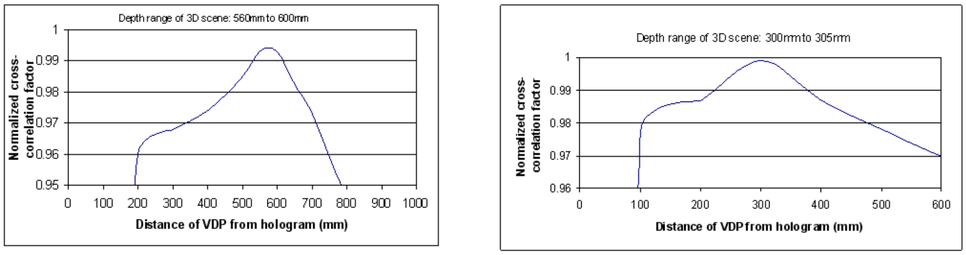
strengthening method, we apply it to a rectangular region that slides from the left to the right hand side. The animated clip on the numerical reconstructed images is shown in Media 1.


(a) (b) (c)

Fig. 4. (a) A hemisphere with the texture of an earth image positioned at 0.3m from the hologram plane. The radius of the hemisphere is 0.5mm. (b),(c) Numerical reconstructed image of the hologram representing the image in Fig. 4(a) after direct application of high-boost-filtering to the left side of the hologram, and after application of high-boost-filtering to sharpen the left side of the globe with our proposed method, respectively.



(a) (b)

Fig. 5. (a),(b) Plot of the normalized cross-correlation values between a hologram which is generated directly from an enhanced 3D scene, and a hologram which is enhanced by our proposed method at different positions of the VDP, representing the “Lenna” and the “hemisphere”, respectively.

4. Conclusion

In this paper, we report a method based on the concept of VDP to enhance the optical properties of pictorial contents that are recorded in a hologram. Our proposed method has the following advantages. First, it provides a means for enhancing the pictorial contents represented in a hologram, without the presence of the original 3D scene. This is important as the 3D scene may be unavailable, and it is difficult, if not impossible to reconstruct the 3D scene from the hologram. Second, our proposed method is non-iterative, which is lower in complexity than iterative enhancement techniques, such as the Gerchberg-Saxton algorithm. Third, as reflected by the normalized cross-correlation factor, a hologram enhanced by our proposed method is practically identical to the one that is generated directly from an enhanced 3D scene, if the VDP is near to the latter. We have demonstrated that with our proposed method, the brightness and contrast of the reconstructed images, especially in the over-exposed and the under-exposed areas, can be corrected to give pleasing visual quality. In addition, regions that have been processed with high-boost-filtering in the VDP, exhibits prominent improvement in the sharpness. To speed up the computation time, we have employed a commodity PC, which is equipped with a GPU, in realizing the enhancement process. As such, a digital hologram of size 2048x2048 pixels can be enhanced at a rate of over 100 frames per second.

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