COLLEGE OF ENGINEERING

REPORT # 115

College of Engineering Report # 115

Reprinted from

PHYSICS LETTERS

Volume 26A, number 9, 25 March 1968

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NORTH-HOLLAND PUBLISHING COMPANY
AMSTERDAM

A POSTERIORI HOLOGRAPHIC SHARP-FOCUS IMAGE RESTORATION FROM ORDINARY BLURRED PHOTOGRAPHS OF THREE-DIMENSIONAL OBJECTS PHOTOGRAPHED IN ORDINARY WHITE LIGHT

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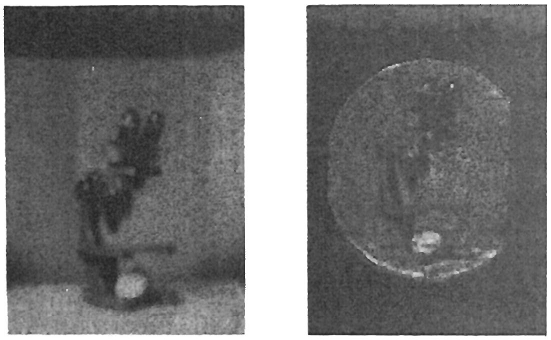
Received 27 February 1968

Application of the Stroke and Zech holographic Fourier-transform division methods has permitted us to restore into sharp focus images of three-dimensional objects from ordinary, blurred, out-of-focus photographs, obtained in ordinary, incoherent white light.

Figure 1b shows an "in-focus" image $f(x,y)$ which we have obtained by a posteriori holographic image restoration from the deliberately out-of-focus photograph $g(x,y) = f(x,y) \circledast h(x,y)$ of a three-dimensional object, shown in fig. 1a, where $h(x,y)$ is the "out-of-focus" spread function, and $\circledast$ a spatial intensity convolution. The out-of-focus photograph $g(x,y)$ was obtained in ordinary, incoherent white light, in a conventional photographic camera.

A theory for such holographic image restoration, based on holographic Fourier-transform division, was first proposed in 1967 by Stroke and Zech [1] and shortly thereafter experimentally verified by Lohmann and Werlich [2] for a single point and a plane, single "black-on-white" letter "T". The image-deblurring result which we show in fig. 1 for a three-dimensional continuous-tone object, has been obtained according to a form of our method of ref. 1, first presented by one of us [GWS] on 5 September 1967 at the Colloquium on Modern Optics in Québec, and to appear in ref. 3. In a general way, image restoration methods are extensions of the "spatial filtering" principles, first described by Maréchal and Croce in 1953 [4], which may now be considered to appear generally realizable with the aid of complex filters realized in the forms of holograms, as first introduced by Dennis Gabor in 1948 [5]. Several comparable, remarkable, non-holographic image-restoration examples have been described, notably by Tsujiuchi [6], using separate materializations of the complex components (amplitude and phase) of the filters, and by Lohmann et al. [7], using computer-generated filters, as well as in apodisation and Fourier-transform spectroscopy (references in ref. 1). One of us (GWS) has long noted the importance of "de-blurring" (deconvolution) image restoration, such as that which we describe, in applications ranging from astronomy and radio-astronomy, to imaging with other radiations, for instance micro-waves, ultrasonics and X-rays.



a b

Fig. 1a. Ordinary, white-light. blurred, out-of-focus photograph. b. "In-focus" 'de-blurred' image of 3-D object obtained from blurred photograph (a). by a posteriori holographic Fourier-transform division (see text). Residual granularity imperfections in this early example are caused by omission, in this case, of index-matching immersion, required to minimize spurious phase-variation effects. Successive 'sections' of the 3-D image may be brought into 'best focus' from the same blurred photograph, successively with different filters, eg.g. for 3-D microscopy applications.

In order to suitably linearize the photographic process, in the various steps of the restoration, so as to produce electric-field amplitude transmissions proportional to the recorded exposures ("intensities"), $g(x,y)$ and $h(x,y)$, we produce positive copies (P, with gamma = γ_P) of the negatives (N, with gamma = γ_N) of the "intensity" records $g(x,y)$, respectively $h(x,y)$ in such a way that we achieve the product $\gamma_N\gamma_P = 2$ ["coherent optics 'Goldberg' condition", see ref. 3]. From the electric-field amplitude $h(x,y)$, transmitted by P, in coherent (laser) light, we realize, by spatial Fourier transformation the two filter components $\bar{H}^*$ and $|\bar{H}|^{-2}$, required to synthesize, when placed in series, after each other, the filter $\bar{H}^{-1} = \bar{H}^*/|\bar{H}|^2$, as required for the multiplication of $\bar{G}$ = [spatial Fourier transform of $g(x,y)$], to obtain $\bar{G}\bar{H}^{-1} = \bar{F}$, and from $\bar{F}$, in the same 'coherent optics' spatial filtering arrangement, by Fourier transformation, the desired restored image function $f(x,y)$. (For a general background relevant to coherent optical image-processing and filtering arrangements, see e.g. ref. 8]. Another important experimental requirement is that the processing of the $|\bar{H}|^2$ record be with a gamma = 2, to obtain the $|\bar{H}|^{-2}$ filter component. Pre-exposing of the various records, to work in the "middle" of the photographic H-D (see ref. 8) curves, and measurement of the slopes (arc tan γ) of the curves, with beam shapes as used in the processing, needs to be carefully observed. Further theoretical aspects, notably those related to the effects of "zeros" in the dividing function $\bar{H}^{-1}$, and to "noise", will be discussed in subsequent papers, together with related extensions to Hilbert-transform perfecting of "ghost-image" filtering [8].

One of us (GWS) wishes to acknowledge the many kind comments and fruitful suggestions of Professor Dennis Gabor and fruitful participation of R. G. Zech in early aspects of our image-restoration work. The generous assistance of the National Science Foundation and of the Office of Naval Research is acknowledged with much gratitude.

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