College of Engr Report # 198

Volume 1. number 8 OPTICS COMMUNICATIONS March 1970

SPATIAL-DOMAIN LASER-LIGHT SCANNING DECONVOLUTION OF BLURRED PHOTOGRAPHS USING THE GENERAL HOLOGRAPHIC DEBLURRING FILTER

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Received 24 February 1970

Spatial-domain deconvolution by scanning of blurred photographs has been obtained, using as scanning function the Fourier transform of the 1967 Stroke and Zech holographic Fourier-transform division filter and photoelectric integration. The required filters, adaptable for field-varying spread functions, are photographically realized from the experimental point-spread functions.

There has appeared an increased interest in the possibilities of optical "deblurring" of photographs blurred by imperfect focus, image motion, aberrations and indeed by atmospheric turbulence among other causes. We recently proposed [1] that the deblurring may be realized in the general case by scanning the blurred photographs with laser light directly in the *spatial domain*, as illustrated in fig. 1. Our method is based on the use of the general holographic Fourier-transform division filter, first described by Stroke and Zech in 1967 [2]. A photograph of the experimental arrangement which we used to verify our theory in a model is shown in fig. 2 and experimental results obtained with it in fig. 3. In our arrangement, the use of the ho-

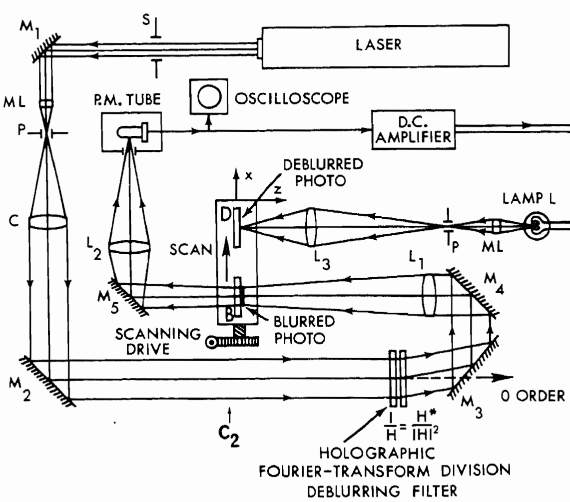

Fig. 1. Schematic diagram of spatial-domain scanning image-deblurring apparatus. In practice the lamp L is preferably a linearly modulated laser. ML = microscope lenses. L_1 = Fourier transforming lens. L_2 = integrating lens, imaging the scanned region of the blurred photograph onto the photomultiplier tube P. M. The adjustment of the $1/H$ filter may be readily carried out by visually observing the deblurring of the spread function $h(x, y)$. For this purpose the blurred photo containing $h(x, y)$ is placed into the collimated beam produced by C, in the back focal plane of an auxiliary lens C_2 (of which the front focus is on the $1/H$ filter): the blurred image point is observed in the focal plane of L_1, using an auxiliary mirror.

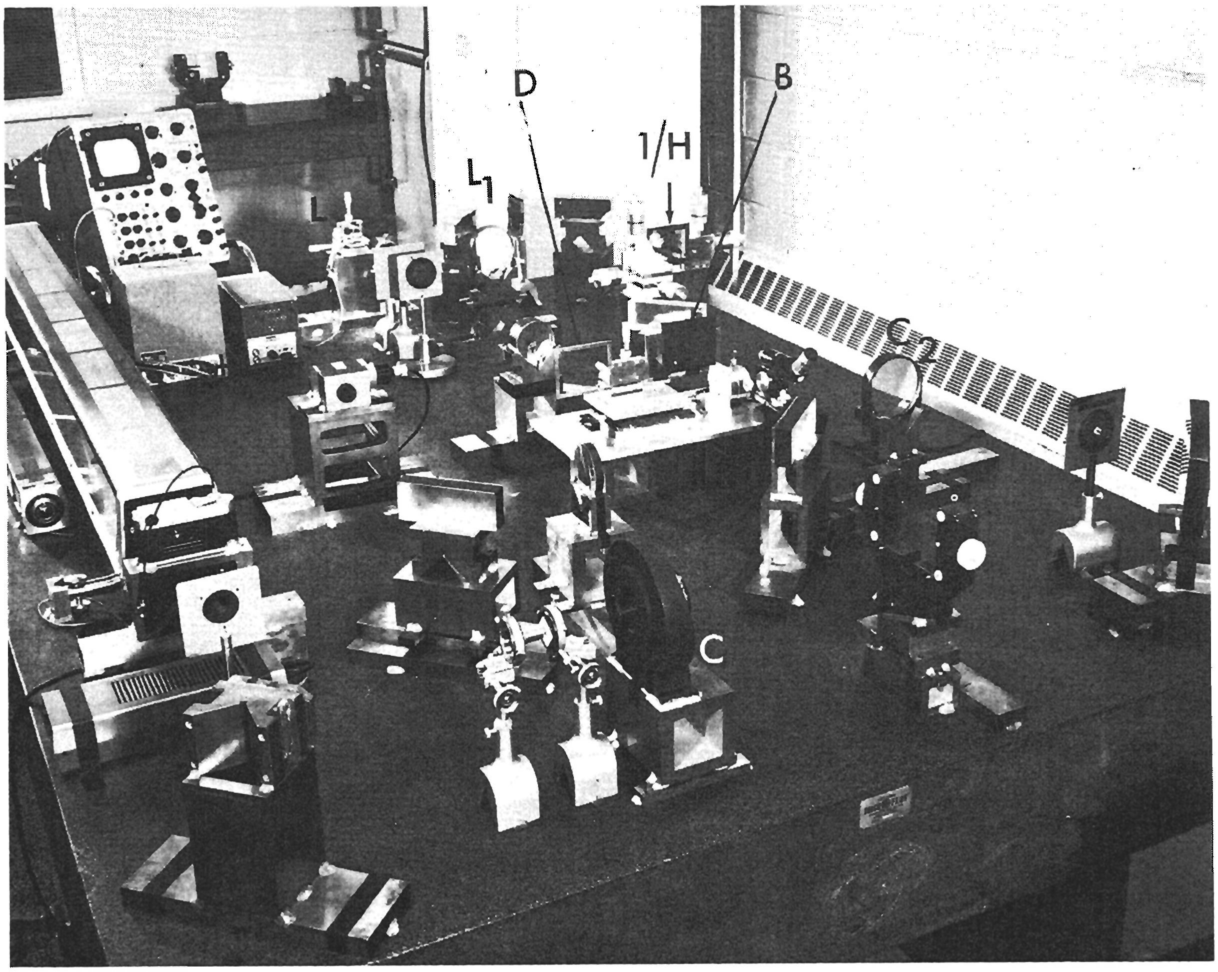

Fig. 2. Photograph of the experimental apparatus used, according to fig. 1. On-axis use of all lenses with optimum aberration correction characterizes the arrangement.

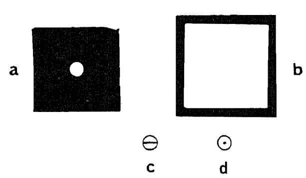

Fig. 3. Experimental image-deblurring result, according to spatial-domain scanning method described in text. a. 2 mm diameter badly blurred image $h(x, y)$ of a point imaged by a f = 240 mm lens. b. Deblurred image obtained by a single scan through the diameter of a. using arrangement of fig. 2. c. Theoretical non-deblurred image using single diametral scan with point. d. Theoretical deblurred image. The deblurring of an entire 'half-tone' photograph using the same $1/H$ filter as that used in going from a. to b. is shown in fig. 4.

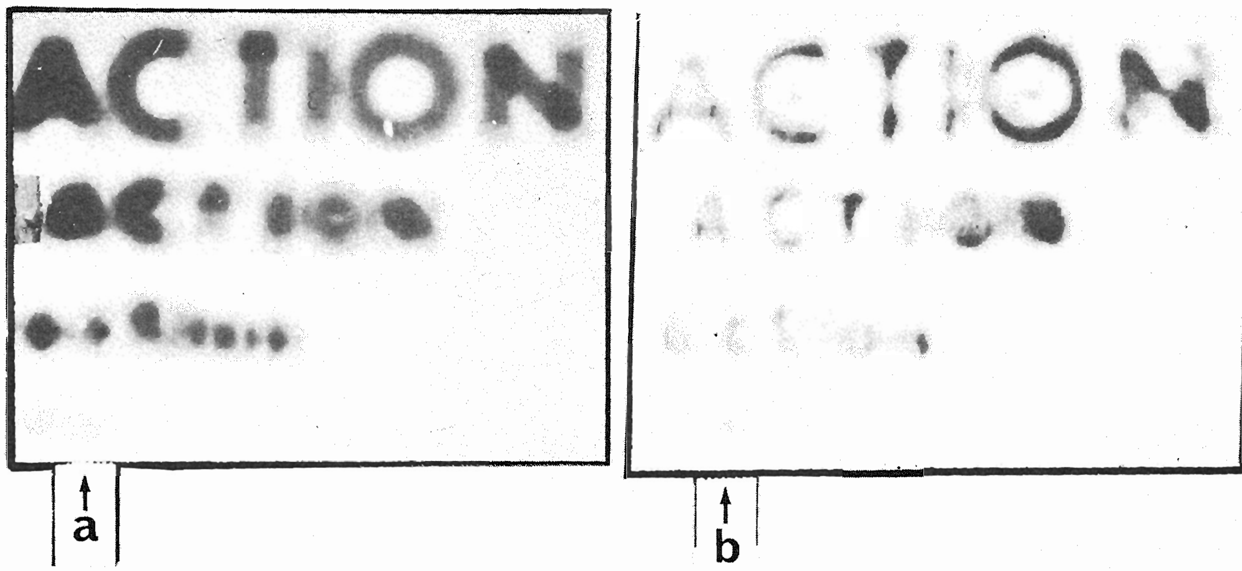

Fig. 4. Experiment illustrating the capability of the $1/H$ filter used for the scanning deblurring in fig. 3 to deblur a complete two-dimensional half-tone photograph. The result shown here was obtained by the direct spatial-freqency holographic Fourier-transform division method according to refs. [2,11,12]. a. blurred 2 mm diameter $h(x,y)$ spread function. b. deblurred point.

lographic filter permits one to generate the required positive and negative parts of the all-real [1] deblurring "scanning function" $s(x,y)$ in a single step, by Fourier transformation from the holographic filter, and thus to use a single photoelectric cell for the required deblurring integration. Our arrangement thus permits one to maintain the advantage of the holographic Fourier-transform division filter [2], namely that it may be simply generated by photographic and holographic procedure [3,4] directly from the experimental point-spread function, without any analytical or electronic computation.

The work which we present here, together with our theory [1], may be considered as a generalization of the incoherent-light spatial-domain image deblurring methods which had been proven to work in cases when the scanning "deblurring" function $s(x,y)$ could be computed rather than generated by experiment, as we do here). Thus a form of spatial-domain image deblurring was used by McLean [3] in an arrangement where a photographic spatial-domain correcting 'mask' was used directly with an annular-aperture lens, to correct for its well-known $J_0(\pi D\theta/\lambda)$ diffraction pattern, in view of the Wild "Culgoora" radioheliograph application. More recently, Tsujiuchi [4] and Swindell [5] showed that spatial-domain deconvolution may be used to 'deblur' photographs, when it is possible to generate separately the computed positive and negative parts of $s(x,y)$, for instance with two orthogonally-polarized beams, and to use two photocells for the required integration and the associated subtraction. In our method [1], the use of the holographic deblurring filter [2] permits one to maintain the field-amplitude summation property of incoherent-light image-processing arrangements for the deblurring of each elementary blurred image point $h(x,y)$. At the same time, however, our spatial-domain scanning method is also inherently *spatially incoherent*, since the blurred points are successively scanned one after the other, and the blurred image reconstructed point by point. Moreover, the phase-degrading transmission variations across *extended* regions of the photographic emulsions (which tend to plague spatial-frequency domain image deblurring methods) are made to be negligible, in our case according to previous work [6], even though we scan with laser light. Indeed, since the scanning is a strictly *local* process, we take advantage of the well-known excellence in phase transmission uniformity of photographic emulsions (see e.g. the comparison of fig. 2b and fig. 5 in ref. [6]). For completeness [7], we may again draw attention to purely electronic television "image enhancing" arrangements originated by Goldmark and Hollywood [8], notably in the form most recently described by McMann and Goldberg [9]. Of course, our scanning method is destined for using a linearly modulated light source, notably a laser [10] for the image reconstruction, rather than the incandescent lamp which we used for simplicity and illustration.

The mathematical description of our method may be briefly summarized with the aid of the following equations. Let the blurred photograph be

$$g(x'y') = \iint_{-\infty}^{+\infty} f(x,y)\,h(x'-x, y'-y)\,\mathrm{d}x\,\mathrm{d}y = f\otimes h\,, \qquad (1)$$

where $f(x,y)$ is the desired "diffraction-limited" image as usual [7], and $h(x,y)$ is the point-spread function. When the image is illuminated with a "scanning function" having a field amplitude $s(x,y)$, the field transmitted through the emulsion is equal locally to $s(x,y)\,g(x,y)$ with the usual photographic processing precautions [7]. By definition of the convolution integral, the photoelectric current at the focal point of the integrating lens L_2 (fig. 1) becomes equal to

$$s\otimes g = s\otimes f\otimes h\,, \qquad (2)$$

when the photograph $g(x,y)$ is scanned with $s(x,y)$. Accordingly the scanning process will extract the "diffraction-limited" function f (within the same approximations as in refs. [3,4]) provided that one can realize the condition

$$s\otimes h \cong \delta\text{ - function} \qquad (3)$$

that is equivalently $SH \cong 1$, where S and H are the spatial Fourier transforms of s and h. Therefore, the scanning function must be

$$s(x,y) = T[S] = T[1/H] \qquad (4)$$

where

$$T[\dots] = \iint_{-\infty}^{+\infty} [\dots]\exp[2\pi\mathrm{i}\,(ux+vy)\,\mathrm{d}x\,\mathrm{d}y$$

is the usual spatial Fourier transformation, and $H = T[h]$. It is eq. (4) which shows that the required scanning function $s(x,y)$ may be indeed be directly generated as an aerial image by Fourier transformation in laser light, using the Stroke and Zech [2] holographic Fourier-transform division filter $[1/H]$ as shown in fig. 1.

Our model experiment, illustrated in fig. 3, has fully born out the theoretical prediction. For theoretical reasons it appeared essential to demonstrate that a single badly-blurred point $h(x,y)$(2 mm diameter blur circle, f = 240 mm) could be deblurred, as shown. Indeed, as we illustrate in fig. 4, by direct holographic image deblurring [11, 12] using the same $[1/H]$ filter, as in fig. 3, the capability of deblurring a single blurred point in a photograph is also the necessary condition for the deblurring of a complete blurred image.

We may recall in conclusion that the deblurring scanning function $s(x,y)$ is always a real function, partly positive and partly negative, as a consequence of the fact that the blurring spread function $h(x,y)$ is real (i.e. an intensity distribution) and therefore both $H = T[h]$ and $S = 1/H$ are hermitian (e.g. $S^*(u,v) = S(-u,-v)$), as we show in ref. [1].

We wish to thank Professor Dennis Gabor for his kind interest in this work, Professor J. Tsujiuchi and Professor W. Swindell for private communications regarding unpublished aspects of their work, and Drs. L. Beiser, J. Christensen, W. E. Glenn and R. McMann of CBS Laboratories for fruitful discussions and kind suggestions. We also gratefully acknowledge support of this work by the National Aeronautics and Space Administration (Grant NGR-33-015-068).

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