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Deblurring of Motion-Blurred Photographs Using Extended-Range Holographic Fourier-Transform Division, G. W. Stroke, F. Furrer and D. Lamberty, Optics Communications, Vol. 1, No. 3, July/August 1969.

Technical Report No. 188

DEBLURRING OF MOTION-BLURRED PHOTOGRAPHS USING EXTENDED-RANGE HOLOGRAPHIC FOURIER-TRANSFORM DIVISION

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Received 2 June 1969

The method of a posteriori image-correcting deconvolution by holographic Fourier-transform division (Stroke and Zech, Physics Letters 25A (1967) 89) has been successfully extended to the deblurring of photographs blurred by motion with the aid of a photographic (positive + negative) "masking" process, used to obtain the required great linear dynamic range (especially in the Fourier-transform domain), in anticipation of extended-range high-resolution films now under development.

There has arisen an increasing interest in methods which permit one to extract *a posteriori* a sharpened image from a photograph blurred as a result of various instrumental and recording imperfections, including blurring by atmospheric turbulence and indeed by motion. In a general way optical image deblurring methods are based on the principles of 'spatial filtering' described by Maréchal and Croce [1]. Considerable success in implementing these principles were demonstrated already a decade ago by Tsujiuchi [2] who showed that the required complex (amplitude and phase) filters [3] could be realized by a combination of two filters: the amplitude filter, realized by photography, and the phase filter, realized by vacuum evaporation. The Tsujiuchi method is particularly suitable for the preparation of filters which may be described in analytical form. It has been used, for instance, to deblurr images blurred by artificial (laboratory) turbulence and indeed for certain types of motion [4]. Several other image-deblurring methods have also been demonstrated, including digital-computer implementation of the required Fourier-transform division [5] as well as purely electronic methods, particularly suitable in conjunction with television devices [6,7]. The relative merits of these and other methods are forming the subject of current investigations by a number of authors. Somewhat in analogy with the results of the investigations of Jacquinot and Chabbal, with regard to relative merits of various forms of spectroscopy, it is probable that each of the image-deblurring methods may be particularly suitable for some types of applications, while not necessarily being the most powerful general method. However, in keeping with the suggestion by Stroke and Zech [8] it has become increasingly apparent that the most general method for optical image deblurring will no doubt be most readily implemented by holographic means. The general background for the holographic image deblurring methods may be found in refs. [8-11], in which we also discuss the difference between the holographic image restoration methods (*solution* of an integral equation) on the one hand, and, on the other, the correlative character recognition methods [12] (*formation* of an integral equation). In addition to the methods of refs. [8-11], which use a holographically synthesized filter for the purpose of solving the integral equation (convolution integral) by division in the spatial Fourier-transform domain, Stroke [13,14] has also proposed a different type of holographic method which permits one to achieve 'image-deblurring' as well as 'aperture synthesis' simply by taking a hologram of the blurred photograph and by illuminating it with the light from the spread function $h(x, y)$, in one of the arrangements. These methods [13,14] are particularly suitable for the case when the auto-correlation function of the spread function is sharply peaked. Detailed comparison of the various holographic methods are given in ref. [15]. It may be of interest to further note that spatial Fourier-transform divi-

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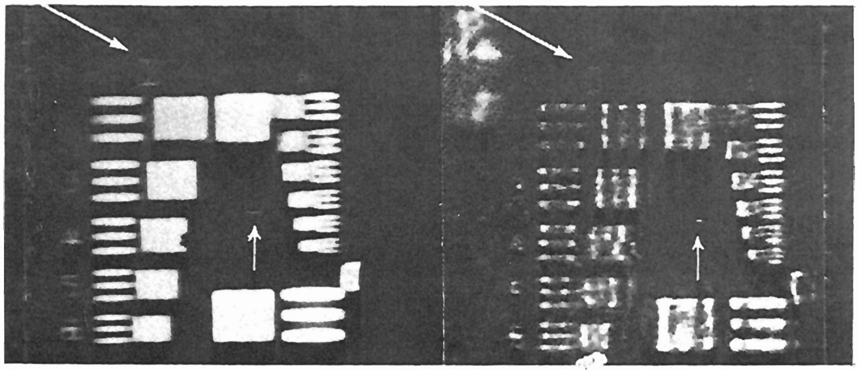

a b

Fig. 1. a) Photograph of 4 × 4 mm test chart, deliberately blurred by motion of the 240 mm Schneider Symmar lens (f/5.6) used in the recording of the photograph in white light (zirconium arc). The dimensions of the blurred photograph are 10 × 10 mm. The lens was deliberately moved by hand with the aid of a micrometer and ball-slide arrangement. The type of motion can be evaluated by looking at the "spread function" $h(x,y)$ indicated by the small vertical arrow. It can also be seen by the "doubling" of the numerals (for instance that indicated by the slanted arrow), showing that the motion was in fact not linear with time.
b) Holographically deblurred photograph, using method of Stroke and Zech [8] with "extended-range" filter as described in text. The clearly apparent considerable degree of 'deblurring' may be evaluated by noting that the spread function of fig. 1a has been reduced almost to a point (indicated by vertical arrow), and also that the "doubled" numerals, which had almost equal intensity in fig. 1a, have been restored to a single numeral. It is important to note that restoration of a *single* image from such "doubled" motion-blurred photographs, as achieved holographically here, could not possibly be achieved by the well-known purely photographic 'masking' and printing methods, as used in reproduction, among other applications. It is also important to note that nothing more than the spread function $h(x,y)$ (fig. 1a) was required to synthesize the image-deblurring deconvolution filter (see fig. 2).

sion filters may in some instances be generated in binary form by computer: as shown by Lohmann and Paris [16], it is necessary for this purpose to have some way of first obtaining an analytical expression for the required filter. In the methods which we discuss here, the required Fourier-transform division filter is directly generated by an analogue optical method [8] starting from the spread function $h(x, y)$ (see figs. 1 and 2).

Before giving the experimental details for the results shown in figs. 1 and 2, we give the theoretical principles of our method [8] as it applies to this work. Let $g(x,y)$ describe the exposure E [proportional to the intensity distribution $I(x,y)$] in the original blurred photograph. Let $f(x,y)$ be the image which would be formed by the given optical instrument in the absence of image-degrading blurring. We recall that $f(x,y)$ may be considered as the "diffraction limited" image which would be formed by the given instrument if it had no aberrations or other blurring imperfections, notably motion, which we consider here. The blurred photograph may therefore be described by the equation

$$g(x',y') = \iint f(x,y)\, h(x'-x, y'-y)\, \mathrm{d}x\mathrm{d}y \qquad (1)$$

where $h(x,y)$, the spread function, is the blurred image of a single point in the object domain. Within the band limits, discussed in ref. [15], eq. (1) may be written in the spatial Fourier transform domain [3] in the form

$$G = FH \,. \qquad (2)$$

Within the same limitations, we may extract the function F_{BL} from G by Fourier-transform division, in the form

$$F_{\mathrm{BL}} = G/H = GH^{-1} \,. \qquad (3)$$

The symbol F_{BL} is used to indicate the well-known fact that no direct image-restoration method is capable of restoring those spatial frequencies in F which have been degraded to zero in the original image-recording (i.e. photography) process. Nevertheless, extensive experience has now shown without any doubt that image-restoration methods, such as that which we describe, result in a considerable visual improvement of a blurred image (see e.g. fig. 1), even

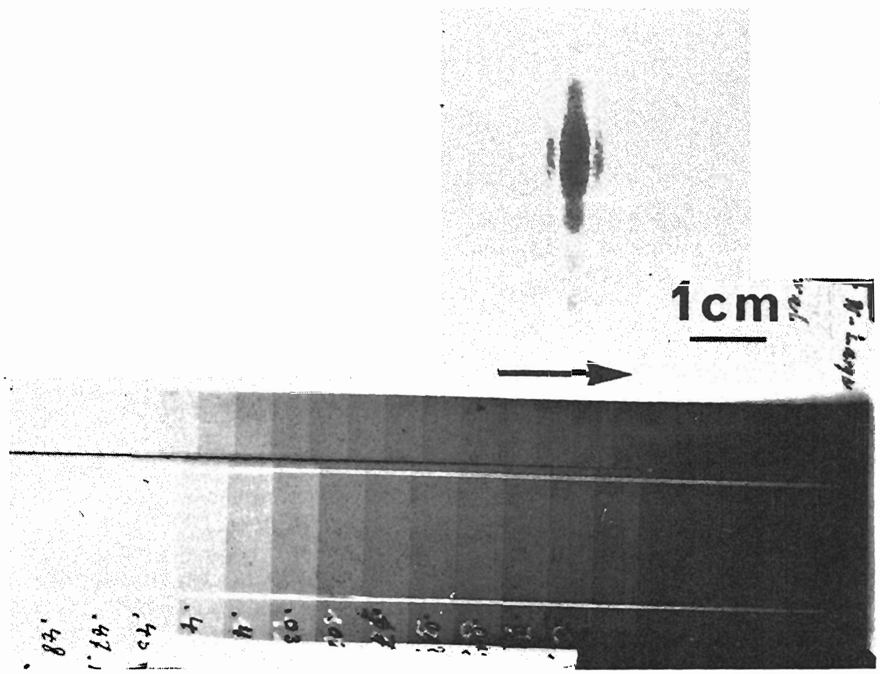

Fig. 2. Positive print of Fourier-transform division filter component $|H|^{-2}$ used in the holographic deblurring shown in fig. 1, together with density step-wedge used to obtain the filter over an "extended" dynamic range, as described in text. The arrow indicated the orientation of the filter relative to the direction of blurring motion (filter parallel to motion). The scale of the filter as used with 2300 mm focal length Fourier-transforming lenses is indicated by the 1cm mark.

though the information content will, in general, be probably even slightly degraded in the restored image, as compared to the blurred image. The paradoxical nature of this fact may be explained by the observation that the human observer is capable of more readily recognizing and interpreting images in a "restored" form than in their original "blurred" form.

The Fourier-transform division filter H^{-1} required to perform the division in eq. (3) may be realized in the form of a two-component "sandwich"

$$H^{-1} = H^{*}/|H|^{2} \tag{4}$$

as first proposed by Stroke and Zech [8], where we recall that $H(u,v)$ is related to the spread function $h(x,y)$ by the spatial Fourier transformation

$$H(u,v) = \iint h(x,y)\, \exp[2\pi i(ux+vy)]\, dx dy \tag{5}$$

given in normalized form [3], with similar equations holding for $G(u,v)$ and $F(u,v)$ in relation to $g(x,y)$ and $f(x,y)$. The H^{*} part of the filter is a Fourier-transform hologram, and the $|H|^{2}$ part is a photograph of H, developed with a photographic "gamma" equal to 2 (see refs. [3,8-11,15]). It is a solution to the crucially important (and heretofore very difficult) problem of obtaining the recording of $|H|^{2}$ over the required large exposure range with a linear curve of slope equal to 2, which we wish to briefly report here. It is important to recognize that intensity ranges in the spatial frequency (Fourier-transform) domain will in general be considerably larger than in the spatial (photographic transparency) domain. For instance, in one case, we found, in agreement with theoretical prediction, that a test chart with spatial frequencies up to 40 lines/mm had an intensity range in the Fourier-transform domain in excess of 10^{4} i.e. $\log E$ in excess of 4.0. Normally processed 14C70 AGFA-GEVAERT film, which we use in our holographic work, only permits one to cover an exposure range of just about 1.0 with a gamma of 2, rather than the range of 3.0 which we require.

It has been clear to one of us (GWS) for quite some time that a solution to this problem would consist in obtaining certain types of special photographic emuslions, with "extended dynamic range" of a type not available. Thanks to a most kind suggestion of Professor Dr. W. F. Berg, and following further suggestions by Professor Dr. E. Klein and Dr. E. Moisar, of AGFA-GEVAERT [17], it appears that such 'extended dynamic range' film, suitable for holographic image processing, is indeed theoretically achievable and may soon be available for experimental purposes. In the meantime, however, it appeared important to us to verify that a considerable improvement in our holographic image-deblurring methods would indeed result from the use of a method which in effect would provide the required maximum possible dynamic range. The experience of one of us (FF) with photographic "masking" methods [18] has proven to give us the desired solution, following a kind initiative of Professor Dr. W. F. Berg to this effect. The theory and principles of the photographic masking process are well-known [18] and we do not propose to discuss them further here. However, it may be of interest, as an example, to give an outline of the steps used to obtain the $|H|^{-2}$ filter by this means. As a first step, by suitable choice of emulsion, developer, developing time and temperature, we determine that we can record over an exposure range $\log E = 3$. Then we proceed as follows:

1. Place $\log E = 3$ density filter in front of H-recording plate.

2. Expose test exposures of H on 14C70 film until peak of $|H|^2$ is just observable above the fog. In our case, exposure time $x = 400$ seconds, developer D76, developing time 1.5 minutes, temperature 75°F.

3. In an enlarger, using Wratten 25A red filter, place $\log E = 3$ density filter in front of unexposed 14C70 film.

4. Adjust enlarger brightness until $x = 400$ seconds is just recorded through the $\log E = 3$ filter.

5. Remove $\log E = 3$ filter from in front of H.

6. Record H for $x = 400$ seconds on negative N_1.

7. On same negative N_1 expose by contact in the enlarger a step wedge for $x = 400$ seconds (using the Wratten 25A filter). The result of steps 6 and 7 appear as in fig. 2.

8. Develop negative N_1 as in 2. Fix, wash, dry.

9A. Contact print N_1 in white light on 14C70 film, and develop (Developer: D76, 1:1, 6 minutes, 75°F). This is print P_{1-M}.

B. Make "unsharp mask" print on 14C70 film of P_{1-M} in white light using a sheet of plastic diffusor between P_{1-M} and film. This is masking negative N_{1-M} (developer: D76, 1:1, 1 minute, 75°F).

C. Copy N_{1-M} on 14C70 film in white light. This is positive P_1. (developer: D76, normally concentrated, 6 minutes, 68°F).

10. Contact print N_1 in white light on 14C70 film (D76, normally concentrated, 6 minutes, 75°F). This is print P_2.

11. Draw graph $D - \log E$ for $P_1 + P_2$ (using red filter in sensitometer), in collimated (parallel) light.

12. If graph of 11 is not a straight line, repeat step 9 or step 10 or both until $P_1 + P_2$ give a straight-line $D - \log E$ curve.

13. Now make contact print of $P_1 + P_2$ on 10E70 AGFA-GEVAERT plate. (D76, normally concentrated, 3 minutes, 68°F).

Step 13 gives a negative N_2 having (under successful conditions) the desired gamma equal to 2 over a density range as large as possible. In our case the range extended over a density of 4($\log E = 2$). A positive print of N_2 (as used in our experiments to obtain the deblurring of fig. 1) is shown in fig. 2. This is the $|H|^{-2}$ filter component of our $H^*/|H|^2$ filter.

We also used a comparable masking method to obtain the $J_N J_P = 2$ transmittances for $g(x,y)$ and $h(x,y)$ according to refs. [8,10,11]. More extensive details will be given in a future publication [19].

We wish to acknowledge the generous support of the National Aeronautics and Space Administration (Grant NGR-33-015-068-090), the National Science Foundation, and the Office of Naval Research for the pursuit of this work. We also wish to particularly acknowledge most fruitful conversations with Professors D. Gabor, W. F. Berg, E. Klein and H. Nassenstein, and with Dr. E. Moisar.

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