Retrieval of Good Images from Accidentally Blurred Photographs

Holographic principles make possible image improvement in many cases of current scientific interest.

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Meaningful information displayed in considerably improved form can now be extracted from photographs that at first sight are considered blurred to an irretrievable degree.

In fact, blurring in photographs does not scramble the imaging information irretrievably, but rather it encodes it in a retrievable form. The degree of retrieval, although generally not perfect, is nonetheless quite significant in many cases of current interest in science. The "retrieved" information is already contained in the original blurred photograph, of course, but the deblurring makes it possible to display it in a form more directly interpretable by the human observer.

The results are obtained by a method of image processing known as "deconvolution." The method is a form of computing also known as "image deblurring." It decodes the blurred photograph and turns it into an improved image. The required mathematical operations can be performed either by digital electronic computation or by optical analog computation based on the use of lasers and holography (*1*). Successful applications in science range from x-ray astronomy to electron microscopy; deblurring has now been applied to image improvements in archeology (Figs. 1 and 2). In practice, so far, the best results are still being obtained with the aid of holography, even though considerable progress is being made in digital image processing. The power of holographic processing of images results from the natural ability of lenses to carry out the fundamental Fourier-transform operations involved in the deconvolution, in a manner comparable to the relation between a crystal and its x-ray diffraction pattern.

Early indications of the capabilities of holographic image deblurring were presented in two previous articles in *Science* (*1, 2*), particularly in the text of the 1971 Nobel lecture of Gabor (*2*). A number of successful improvements of images in high-resolution electron microscopy (*3*) have since been reported in specialized journals.

For the last several years we have also been trying to determine whether image deconvolution methods could be used for the improvement of images which may contain information of scientific value, but which were blurred by accident, under conditions where access to the original scene or specimen was either impossible or impracticable. Often one is faced with a complete absence of any a priori information either about the object (or scene) that was photographed, or about the nature of the blurring. This situation is different from the image improvement of test photographs and model experiments where either one or the other or both are known (*1, 4*), or even from electron micrographs recorded in defocusing phase contrast, where the blurring is introduced deliberately in order to obtain adequate image contrast.

Accidentally blurred archeological photographs may illustrate the case in point. Over the last 2 or 3 years we have carried out, among other work, a series of studies in order to ascertain whether some approach could be found for dealing with the improvement of such photographs. We now present the results here. These results may be helpful in drawing attention to the known capabilities and potential of this method in view of scientific applications of interest to those who may not be experts in optics, in computer sciences, or in one of the special fields, such as electron microscopy.

In a general way, the problem of image deblurring (deconvolution) involves three factors: (i) the intensity distribution in the blurred photograph, (ii) the intensity distribution in the original scene, and (iii) the blurring function (impulse-response function), that is, the intensity distribution in the image of a single point in the scene, blurred as it is under the particular conditions of the blurred photograph. In practice, finding the blurring function is generally sufficient for extracting a greatly improved image of the original scene from the blurred photograph.

The principles may be best illustrated with some examples. Figure 1 shows the improvements in the case of a photograph of fragments of a Greek pot accidentally blurred during the recording. As stated by Dusenbery of the New York University Institute of Fine Arts (*5*):

> This is a tragic situation for us. Fragments of a large Greek pot with painted scenes were found in 1939. Unfortunately, these two out-of-focus photographs were the only ones made. During the war our storeroom was vandalized and a number of objects vanished, including the principal part of this fragment. In the last few years, more fragments of the same pot have been recovered, and we can see that it was a work of more than ordinary quality and interest. The subject matter may be unique. So it is of great interest to us to recapture all we can.

A copy of this original blurred photograph of the pot just described is shown in Fig. 1a. The improved image extracted from it is shown in Fig. 1b. According to the further comments of Dusenbery (*6*) regarding the improvements shown, they seem to have fulfilled her hopes.

> I have wrested a lot of information from it about the unique piece of Greek body armor it shows, and also some details of the drawing style which may help us to identify the splendid artist (by hand if not by name) who drew it.

The problem in this instance was, first of all, to try to find the blurring function (that is, the image of a point blurred like the rest of Fig. 1a). Upon detailed analysis, we identified the blurring function shown by the arrow in Fig. 1a, and in an enlarged form in Fig. 1c (negative copy). By means of the method given in (*7*), the impulse-response function (blurring function) was used to produce the holographic Fourier-transform division filter (*1*), of which the amplitude component is shown in Fig. 1d. A Fourier transform with respect to magnitude relation exists between Fig. 1c and Fig. 1d. The deblurring operation (deconvolution) is carried out in a coherent opti-

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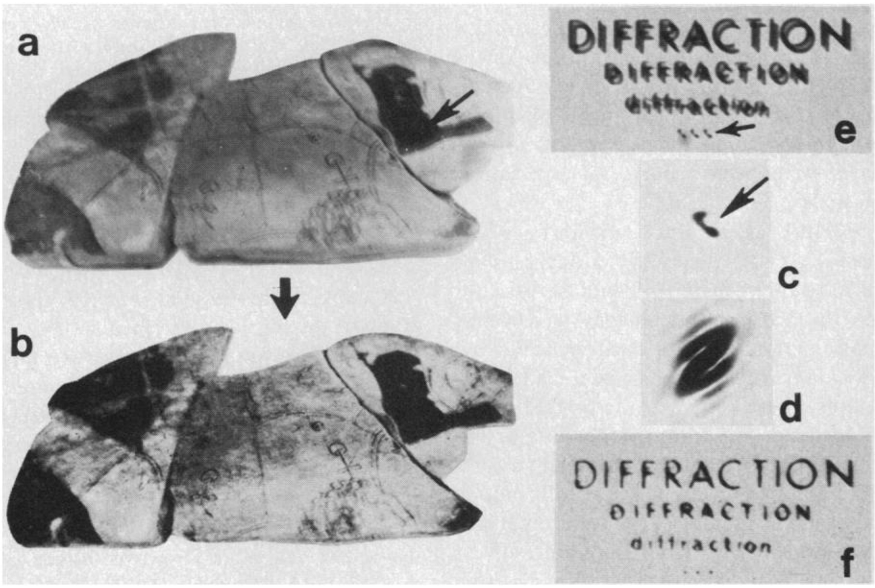
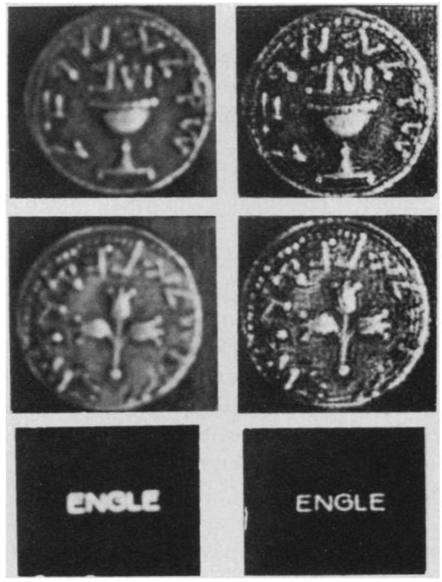
cal image processing arrangement (*1*) by illuminating the blurred transparency with a collimated beam of laser light. The holographic deblurring filter consists of a "sandwich" of two photographic transparencies, one which is the amplitude component (Fig. 1d), and the other which is a hologram. The filter is placed in the focal plane of a lens L_1 following the blurred transparency, and the deblurred image (Fig. 1b) appears in the image plane of a second lens L_2 focused onto the blurred transparency through the filter.

The improvements from Fig. 1a to Fig. 1b may perhaps not seem to be readily apparent in detail, in the terms described above. In fact, the extent of damage caused by the blurring is revealed in Fig. 1e, which was deliberately blurred by the same blurring function (see arrow in Fig. 1e). The degree of improvement is evident in Fig. 1f, which was extracted from Fig. 1e by the same filter and arrangement as that used for extracting Fig. 1b from Fig. 1a. What is noteworthy in this case is that the blurring was caused by a highly irregular motion of the camera during the recording (see arrows in Fig. 1, a and c), and that the direct holographic construction of the deblurring filter was no more difficult in this case than in cases of, say, simple linear motion.

A different approach for determining the blurring function, in the case of another type of archeological photograph, was used in the improvement of blurred photographs of shekel coins (Fig. 2) (*8*). These coins are shekels from ancient Judea, which most recent research teams have assigned to the period of the First Revolt of the Jews, A.D. 66–70 (*9*). These rare coins, approximately 23 mm in diameter, are from a private Vatican collection and the Jordan collection; unfortunately, the originals, recorded by Professor C. Colbert of Wright State University Research Institute, were accidentally blurred by a mechanical disturbance in the focusing assembly of the 35-mm Leica camera used in the Middle East. Apparently there was no further possibility for returning for a repetition of the original photography, notably in order to help in bringing out the archeologically significant details of the coins after the image blurring was discovered





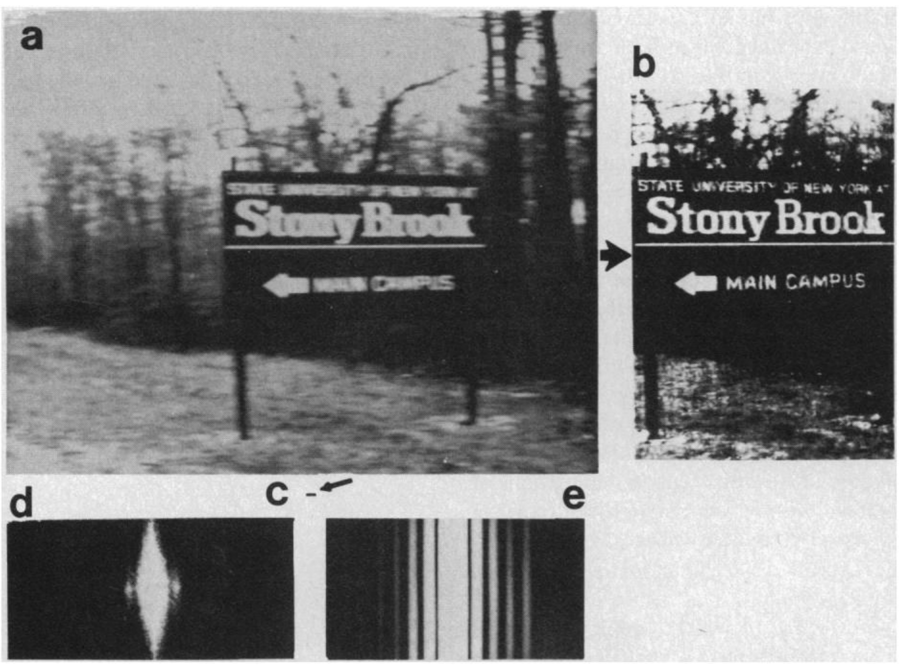


Fig. 1 (top left). Improvement of a blurred photograph of fragments of a Greek pot. (a) Original blurred photograph [arrows point to the "blurring function," also shown enlarged in (c)]. (b) Deblurred image extracted from (a) by holographic deblurring. (c) Blurring function (impulse response) (negative). (d) Fourier-transform spectrum (magnitude) of the blurring function (c) used to construct the holographic image deblurring filter (see text). (e) and (f) A blurred photograph and the deblurred image of a test object blurred and improved, respectively, to the same degree as (a) and (b). Fig. 2 (above). Improvement of blurred photographs of two Judean shekel coins together with test photograph improvement. Original blurred photos are on left, deblurred images are on right (see text). Fig. 3 (bottom left). Improvement of a motion-blurred photograph of an outdoor scene. (a) Blurred photograph. (b) Improved image extracted from (a) by holographic image deblurring (deconvolution). (c) Blurring function, shown by arrow, and used to construct the deblurring filter. (d) Fourier-transform spectrum of (a) which permits one to deduce the type and extent of blurring by comparison with the spectrum of the slit aperture (c) as shown in (e).

upon development of the film, after return to the United States. In this case, a plaster replica of other coins of this type, as well as the original camera, was used in our laboratory, first of all, to produce a photograph blurred to the same degree as that shown in Fig. 2. Then a point source of light was placed in the plane of the replica in order to produce a photograph of the blurring function from which, in turn, the holographic deblurring filter was made as described (*7*). Improvements of some letters comparable to the shekel coin writing and blurred artificially to the same degree are shown for comparison. Extension of such improvements to the blurred images of the whole series of some 70 coins appears to be of great interest, and should be even further helpful in several aspects of a historical and economic analysis of the daily life in Jerusalem when it was under siege by the Romans (*10*).

In the two cases described, it was possible somehow to reconstruct the blurring function by inspection of the photograph itself. A powerful alternate method, necessary in other cases, consists in analyzing the Fourier transform (diffraction pattern) of the blurred image, which may be obtained very simply by illuminating the blurred transparency with a collimated beam of laser light and photographing the diffraction pattern (that is, the "spectrum") in the focal plane of a lens after the transparency. An example is shown for the case of a blurred photograph of a scene (Fig. 3a). The spectrum of the blurred photograph of Fig. 3a is shown in Fig. 3d. By previous knowledge of diffraction patterns (*11*) one recognizes that the diffraction pattern shown in Fig. 3d is similar, manifestly, to that which would be produced by a little horizontal slit aperture, such as that shown by the arrow in Fig. 3c. In fact, the spectrum produced by an actual slit aperture is shown in Fig. 3e. Measurement of the spectrum in Fig. 3d permits one to establish the extent of linear motion which would have blurred a point in the scene to a little slitlike line. With the use of the slit aperture of appropriate length (about 1.3 mm at the scale shown in Fig. 3a and Fig. 3c), a holographic deblurring filter was readily constructed and used to extract a noticeably improved image (Fig. 3b) from the blurred photograph of Fig. 3a. We have obtained similar improvements with no more information than the availability of the photograph itself (so-called "blind" cases), and the previous knowledge of diffraction patterns, for defocused photographs as well (*12*). The analysis of the diffraction patterns (spectra) is quite comparable to that used in crystallography and in electron microscopy (*13*).

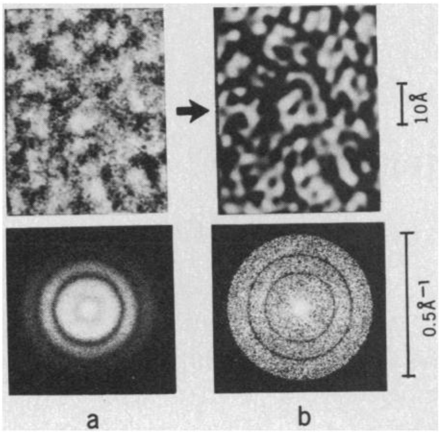


Fig. 4. Improvement of high-resolution electron micrographs. (a) Electron micrograph of a thin amorphous carbon foil specimen (top) and Fourier-transform spectrum of micrograph (bottom) displaying the so-called "Thon diffractogram" which characterizes quantitatively the degradation of the micrograph (*3*). (b) Improved image extracted from (a) by holographic deconvolution (top) together with its spectrum (bottom) which is used to verify the degree of improvement. This improvement was shown to be a real one (*3*), notably in the correction of the contrast inversions. Just like in the smaller characters of Fig. 3, it is clearly impossible to interpret correctly the smaller details in the blurred electron micrograph (say below 10 or 20 Å), which also shows noticeable electron granularity noise, whereas meaningful imaging information down to the diffraction-limited resolution (of about 3 to 4 Å) is revealed in the deblurred image, as shown in (*3*), together with notable suppression of the electron noise.

The importance of the spectrum analysis method in image improvement may be clarified by an example which does not fall into the category of the accidentally blurred photographs emphasized here, but which is of considerable practical significance. This is the case of high-resolution electron microscopy where holographic deblurring methods have started to overcome inherent imaging limitations of the microscopes themselves (*3*). It may be of interest therefore, we believe, to reproduce here one of the most revealing illustrations (Fig. 4).

A greatly enlarged portion of an electron micrograph of a thin (50 Å) amorphous carbon foil specimen recorded in defocusing phase contrast in a high-resolution Siemens Elmiskop 102 electron microscope (*3*) is shown in Fig. 4a together with its corresponding spectrum. In this case, the spectrum can actually be used rigorously for construction of the required deblurring filter. Figure 4b shows the improved image which was extracted with the aid of the filter from the original micrograph of Fig. 4a, together with the corresponding spectrum. The considerable improvement observed was shown to be a real one (*3*) and helps to illustrate the range of applications of image improvement methods and of their role in extracting meaningful information in a number of fields of science where photographic image display is used. For details of implementation and mathematical background see (*1, 7, 11*).

References and Notes

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4. A. Rosenfeld, *Picture Processing by Computer* (Academic Press, New York, 1969), pp. 1–196.
5. This blurred photograph was one of two sent (to G.W.S.) on 16 December 1972 by Mrs. Elsbeth Dusenbery of the New York University Institute of Fine Arts with the statement that no improvements could be obtained with the usual photographic techniques and with the request that we attempt to apply to it the method of holographic image improvement.
6. E. B. Dusenbery letter to G. W. Stroke of 19 December 1973.
7. G. W. Stroke and M. Halioua, *Phys. Lett.* **39A**, 269 (1972).
8. The two photographs of the two coins shown in Fig. 2 were sent to us on 20 December 1972 by C. Colbert, director of the Radiological Research Laboratory, Wright State University Research Institute, Inc., Dayton, Ohio. Colbert's films were taken in 1966 under a grant from the American College of Learned Societies.
9. C. Colbert, *Year Book of the American Philosophical Society 1965* (American Philosophical Society, Philadelphia, 1965), pp. 501–503.
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12. ——, M. Halioua, V. Srinivasan, *Phys. Lett.* **51A**, 383 (1975).
13. See, for example, H. S. Lipson, *Optical Transforms* (Academic Press, New York, 1972), pp. 1–265.

14. The experimental results reported here were obtained in part with the aid of NSF grant K-033-820-X00 to X02. M.S.'s participation in the work at Stony Brook was supported by Nippon Kogaku, K.K., of Tokyo and the electron micrograph image improvement work is a part of a collaborative effort of the Stony Brook Electro-Optical Sciences Laboratory with the Siemens AG Electron Microscopy Division, Berlin.