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Digital Image Processing Technology and Its Application in Forensic Sciences

To the average semitechnical individual who, on the one hand, is subject to the whims of an aberrant computer that sends him credit card statements for an account unknown to him, or who is provoked by computer-produced sales letters in which his name is inserted at key points, digital computers are the degrading and impersonal taints of modern technology. On the other hand, to the astronaut in transit to the moon, the computer is his link with life. Between these two diverse extremes digital image processing has become a technical fact of life.

The application of this highly specialized field to the forensic sciences is beginning to be considered a logical step in the development of criminalistic laboratories. In this paper, an application is presented and discussed which may be considered innovative as well as controversial. It is the belief of the authors that present and probable future uses of this methodology, newly derived from space exploration, research, and development, can prove to be a powerful new tool in the forensic sciences.

Employing a methodology similar to that which provided clear transmission of images of the lunar and Martian surfaces, the Civil Systems Program Office of the Jet Propulsion Laboratory (JPL), was requested to use digital image processing techniques to enhance a palm print. The problem: "Could the palm print, recorded in blood on a textured cotton fabric bed sheet, be sufficiently restored to enable identification by traditional latent fingerprint identification techniques?"

In the application cited here, there was a new challenge. Several areas of the bed sheet contained impressions of the heel of a hand; to the unaided eye, these appeared to show friction ridges. Closer examination, under magnification, revealed that it would be difficult to establish and locate points for identification purposes because the weave pattern of the sheet interfered with the pattern of ridges from the palm. Thus the technical problem, apparently, was to remove or reduce the effect of the weave pattern and to enhance or make more distinct the pattern of the ridges and to establish whether the application of blood on a sheet is a linear or a nonlinear process.

The approach taken by JPL to this problem was to use digital image processing, a technique developed for enhancing pictures received from spacecraft. Digital image processing has been used to enhance thousands of such pictures and has been instru-

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mental in revealing countless, otherwise hidden features of the landscapes of both the moon and Mars.

The feasibility of using digital computers to improve the quality of photographic images was demonstrated in 1964 at the Jet Propulsion Laboratory when pictures of the moon transmitted by Ranger VII (the first spacecraft to take close-up photographs of the lunar surface) were computer processed to correct various types of image distortion inherent in the on-board television camera [*1*]. Image enhancement techniques were again applied successfully to photographs from television cameras on board the five successful soft-landing Surveyor spacecraft [*2*]. And also, the Mariner 4 flyby of Mars in 1964 and the subsequent 1969 missions to Mars by Mariners 6 and 7 used the method.

During the historic orbiting of Mars in 1971 and 1972, Mariner 9 transmitted large numbers of images. Again, digital image processing was employed. The technology of digital image processing evolved concurrently with the development of faster computers and more sophisticated data analysis techniques and is now considered to be an integral part of space television experiments.

General Applications to Other Agencies

Today, image processing techniques are being applied to pictorial data in other scientific fields such as medicine and biology.

Nathan [*1,3*] is currently conducting extensive research under a National Institutes of Health grant for the development of a computer resource for pictorial data processing. The basic thrust of this effort is to develop and operate a computer-centered facility for the enhancement, manipulation, extraction, and analysis of biomedical imagery. Applications include X-ray photographs, light and electron micrographs, and scanning electron microscope images.

Selzer [*4-6*] is actively developing image processing techniques for atheromatous plaque detection under a National Heart and Lung Institute grant. This effort is being jointly undertaken with the Specialized Center of Research at the University of Southern California. The program contains elements of atherosclerosis lesion detection, prevention, evaluation, and diagnosis which evolve from the analysis of blood vessel angiography by computer methods.

Castleman and Wall [*7*] are currently developing a clinical prototype automated system for chromosome analysis under a grant from the National Institute of Child Health and Human Development (NICHD). This effort is being jointly undertaken with the City of Hope Medical Center, Los Angeles, Calif. The primary effort will be the development of an automated microscope system for fast and efficient location of high quality metaphase chromosome spreads. The analysis and classification of these spreads will be accomplished by digital image processing techniques.

Blackwell [*8*] has conducted research in the use of image processing techniques on fingerprints. His primary effort has been directed toward processing degraded and low quality latent and recorded fingerprints.

With the belief that image processing techniques can and should be investigated, discussions have occurred with both San Diego and Los Angeles county officials. These discussions have centered around (1) the design of an extensive test program to evaluate the various processes which could be employed to fingerprint identification problems, (2) development of joint participation research activities to undertake such a program, and (3) exploration of how to best obtain support for such an undertaking. Further discussions relating to the establishment of reliability for the types of processing considered and the possible training of one or more key criminalists in image processing have also occurred. If these plans are carried out, it is possible that a true technology transfer in image processing can be made.

Blackwell [9] has also investigated the potential application of image processing techniques to the problem of firearms classification and identification. Efforts undertaken indicate that there is a very high potential for successful applications in this area of forensic science. Discussions with the Los Angeles Sheriff's Department and the California Department of Justice indicate that support for (1) a semiautomated firearms identification system as a separate objective may be possible or (2) such a system could well be incorporated into a more comprehensive crime laboratory information system. Other activity relating to the processing of images from surveillance system photographs, motion picture frames, and television are also applications which have been investigated by Blackwell.

Video Film Converter

A fundamental part of the digital image processing system is the video film converter or flying spot scanner, a device used to read and record image data. In the read mode, film transparencies are scanned by a beam of light from a flying spot scanner tube. The intensity of the light transmitted through the film is proportional to the transmittance or optical density of the film. The transmitted light is focused onto a photomultiplier tube and its electrical output signal is quantized into any one of 64 levels by an analog-to-digital converter. These levels correspond to 64 levels of gray, ranging from white (0) to black (64).

In the playback mode, the process is reversed. Image or picture data come from the computer as discrete data points and modulate the intensity of the light beam as it moves sequentially across the face of the flying spot scanner tube. Each data point is recorded on film at its particular gray level; Fig. 1 shows the film conversion and playback process.

The Technical Problem: Image Processing to Remove "Noise"

The practical limit to all quantitative or photointerpretive measurements on a properly encoded image is the presence of noise. In the image with which this paper is concerned—the bloody palmprint—the "noise" is the weave pattern of the bedsheet. Enhancement processes, such as filtering to improve image resolution, can sharpen features only at the expense of overall signal-to-noise ratio. For these reasons, one of the most important initial steps in digital image processing is the suppression of noise so that subsequent enhancement can be performed on images of maximum signal-to-noise ratio.

Many noise sources exist in imaging systems such as television systems, ranging from random, wide-band shot and thermal noises to very highly structured periodic noises. The precise separation of any noise from a single image must be based on one or more quantifiable characteristics of the noise signal which distinguishes it uniquely from the other picture components.

For typical spacecraft imaging systems, the highly structured or phase-coherent noises appear as two-dimensional pattern in the image, exhibiting periodicity not only along the scan lines but perpendicular to them as well. If one computes a two-dimensional Fourier transform[3] of an image containing phase-coherent noises, this two-dimensional structure becomes evident.

[3] The essence of noise removal in an image is to isolate and remove the various identifiable and characterizable noise components as rigorously as possible so as to do a minimum of damage to the

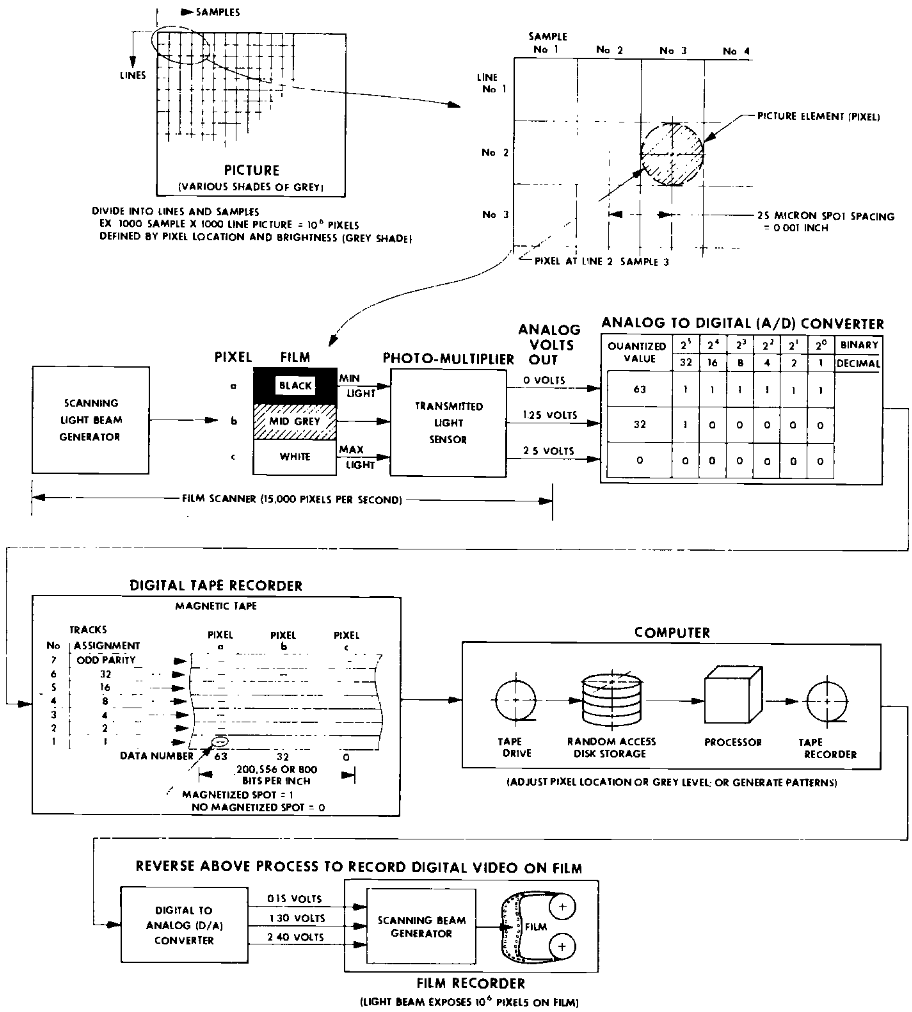

FIG. 1—*Video film conversion.*

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actual image data. If the image contains noise components which are periodic or repeating within the image, then these noise components can be characterized by computing a two-dimensional Fourier transform of that image.

The Fourier transform is a reversible numerical or optical means of converting a spatial representation to a frequency representation. To simplify the concept, one can visualize a one-dimensional curve from Point A to Point B. This curve can be approximated a number of ways using different mathematical approaches. Conceptually, the use of a Fourier transform can be visualized as a method of exactly reproducing that curve from Point A to Point B with a series of trigonometric terms (sines and cosines). If this concept is then extended to two-dimensional forms and now the reproduction of surface, such as an image, by trigonometric terms is visualized, one can conceptually imagine what a Fourier transform is.

Since trigonometry can be related to the study of vibratory characteristics, it is not difficult to see how a real image can be readily converted to another image whose characteristics relate to frequency, amplitude, and phase angles.

An example of this type of image (signal plus coherent noise) and its associated Fourier transform are shown in Fig. 2 to illustrate the process of pattern separation using Fourier transform techniques. Pattern A in Fig. 2*a* is a series of concentric rings of increasing diameter. Its Fourier transform consists of a series of rings also, but of

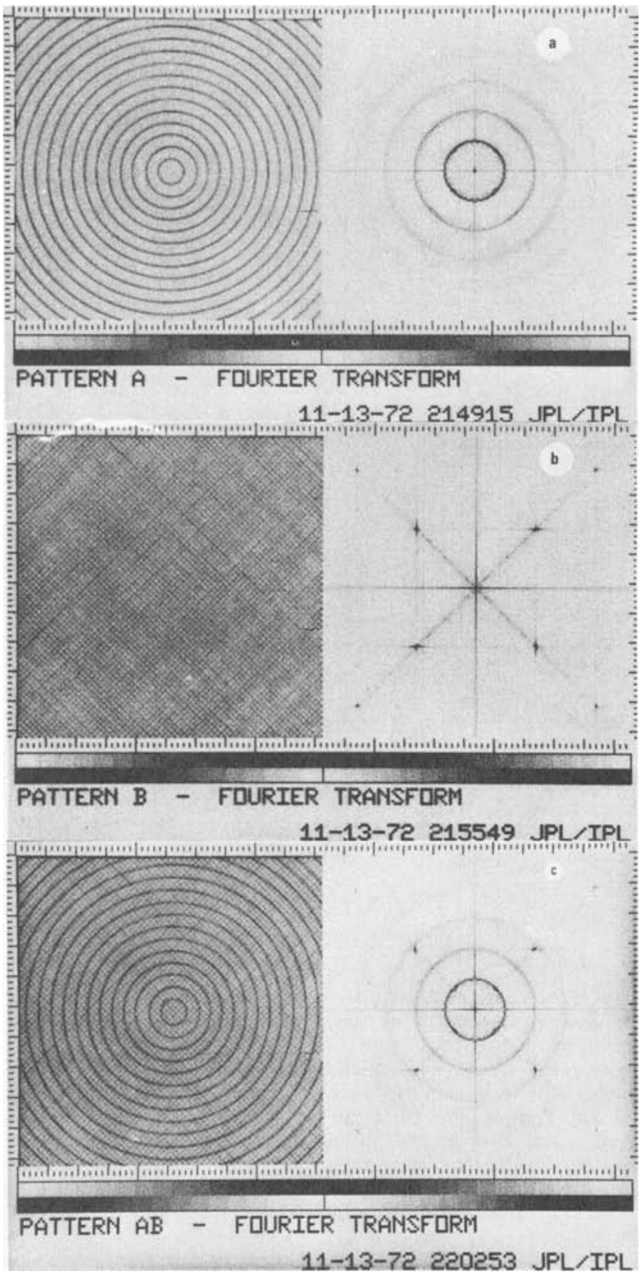

FIG. 2—*Pattern separations using Fourier transform techniques:* (a) *Pattern A,* (b) *Pattern B, and* (c) *Pattern AB.*

decreasing contrast. The position of the innermost ring, the lowest or first harmonic of Pattern A, is determined by the frequency of the concentric rings seen in Pattern A. The other rings appearing in the transform are higher orders or harmonics and their presence adds to the definition and sharpness of the concentric rings in Pattern A.

The Fourier transform of Pattern B in Fig. 2*b* shows the noise components as well-defined spikes. The amplitude of the spikes and their location are determined by the frequency and orientation of Pattern B. It can be seen that the characteristics of this transform differ significantly from those seen in the Fourier transform of Pattern A. The spikes or black dots of Pattern B's transform are not only different in character but their location indicates that more energy is in higher frequencies in Pattern B than in Pattern A.

Figure 2*c* shows the combination of Pattern A and Pattern B. It was obtained by photographing, with top lighting, a composite of A overlaying B and then scanning into the computer this composite image. It can be seen that Pattern AB produces a transform containing components of both A and B. The objective is to remove as much of B from A as feasible. It is possible to identify the noise spikes as having high amplitudes at moderate to high spatial frequencies. Moreover, they will have a predictable two-dimensional pattern which exhibits periodicity quite different from those components caused by the concentric rings. This identification is strengthened by the characteristics of the concentric rings of Fourier transform. This pattern exhibits high amplitudes at relatively low spatial frequencies and whose second and higher orders, while close to the frequency of the spikes, are of lower amplitude.

The approach used in this study was to create a mask to eliminate the noise spikes. This mask was an array of numbers consisting of ones and zeroes. The ones were positioned within the array at points where data in the transform contained no noise spikes. The zeroes were arranged in small rectangles within the array at positions where the noise spikes would be located. Multiplication of the mask times the transform thereby eliminated the noise spikes, as shown in Fig. 3 (zero times any number equals zero). The ones within the mask permitted retention of those parts of the transform which contained no noise spikes.

There are some deficiencies in this procedure. The more obvious is that of misidentification of noise spikes. Another is in the size and shape of the rectangular areas and the inclusion of true image information within these areas. However, care was taken in visually selecting these regions to ensure that the number of misidentified elements was very small, and it was found that this technique did not introduce a significant amount of spurious information into the resultant image.

Processing the Bed Sheet

An image of the cotton fiber bed sheet was computer processed in the same manner as in the example associated with Fig. 2. The sheet was photographed with multiple exposures using top lighting only. For computer processing, the film transparency which exhibited the best contrast and sharpness of detail was selected for subsequent scanning.

Consideration was given to attempting to photograph the sheet with bottom lighting through the use of a light box. It was believed that a combination of top and bottom lighting would have yielded a transparency which showed more of the blood pattern and less of the sheet's weave pattern. This process was not used for the transparency, which was subsequently scanned, because of time constraints and other factors relating to the availability of the bed sheet. However, at a later date, the sheet was photographed using a combination of top and bottom lighting and the results indicated that this procedure

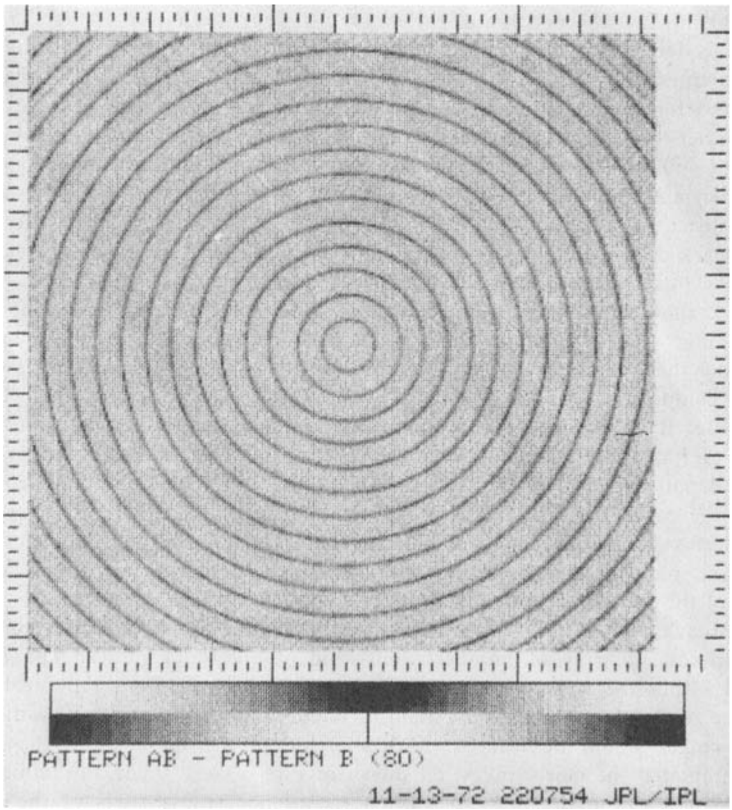

FIG. 3—*Pattern AB with Pattern B removed.*

yielded photographs and transparencies which, in retrospect, would have simplified the subsequent computer processing.

The transparency selected for processing was scanned and the procedures previously described were followed. A photograph from this transparency after scanning, but without processing, is shown in Fig. 4. A smaller area from Fig. 4 was selected because it appeared to contain more continuous ridge information as well as minutia. This smaller subsection is seen in Fig. 5.

As in the previous example, the locations of the noise spikes in the Fourier transform were mapped and a mask was prepared which could be applied to the transform for their removal. Figure 6 shows the Fourier transform of the small subsection under consideration. It is interesting to note that the structure of many of the features seen in the picture of the transform are similar to those shown in the model, except for the features associated with the ridge pattern. In the model the ring pattern is concentric and continuous and therefore the transform is highly structured and predictable. In the bed sheet the ridge pattern is somewhat L-shaped, discontinuous, and contains ridge endings and bifurcations. It therefore will result in transform features (amplitudes) which will be clustered at or in the vicinity of the axis of the transform. They will, in effect, be intermediate frequency, high amplitude features which have only very low

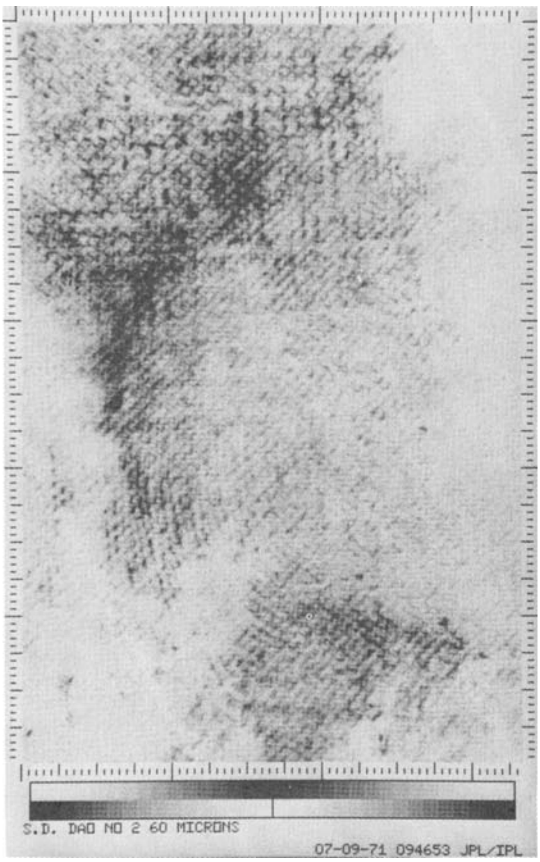

FIG. 4—*Palm print picture before processing.*

amplitude second and higher order components. It should be recognized that while the Fourier components of the ridge pattern would be difficult to map and extract, the components for the weave of the sheet are not difficult to isolate. They are, for the most part, predictable and can be located because of the repetitious nature of the weave. It was on this basis that the noise pattern was eliminated from the transform.

Figure 7 shows the sheet weave noise pattern that was removed from the photograph in Fig. 5. Figure 8 shows the ridge pattern remaining after digital processing has removed the sheet weave noise pattern. An additional step was performed to obtain Fig. 9. A blocking mask was applied to the center section of the transform to change the average gray level of the picture to a level that would increase the contrast between the ridge pattern and the background. The effect is the same as masking out the noise spikes, except in this process only the very lowest frequencies have been removed. Figure 10 results from applying an enhancement factor of 3 to Fig. 9 to increase the relative contrast. It can be seen that Figs. 9 and 10 represent the end product of a process which can prove to be useful to future similar problems.

Two basic positions can be taken relating to the utilization of the Fourier transform. On the one hand it can be argued that the composite image formed by the bloodstained

FIG. 5—*Area of palm print picture selected for noise removal processing.*

ridges on the sheet was combined in a nonadditive manner. For example, the argument can be made that Pattern AB in Fig. 2*c* was not obtained as a sum of two patterns (A + B), but by some nonlinear process such as (A × B). It could be further argued that the use of the Fourier technique dictated that the two patterns (palm print and sheet weave) must be combined in an additive manner to be correctly separated using Fourier techniques. It could be further contended that the two patterns, because they were not combined additively, were thereby incorrectly separated. Further, because of this incorrect separation, spurious information was created or introduced in the resultant picture.

A counter argument would acknowledge that this interpretation of the use of the Fourier transform was a correct one. However, it can be offered that the patterns could be separated. This contention can be reached partly because of experience with Mariners 6 and 7 images containing a nonlinear element of noise which was separated by a Fourier approach, and partly because of a simulation which was conducted. The simulation, run under controlled conditions, consisted of obtaining a blood sample, smearing the heel of a palm, and pressing the palm on a cotton sheet spread over a cushion. Procedures identical to those followed in processing the actual bed sheet were

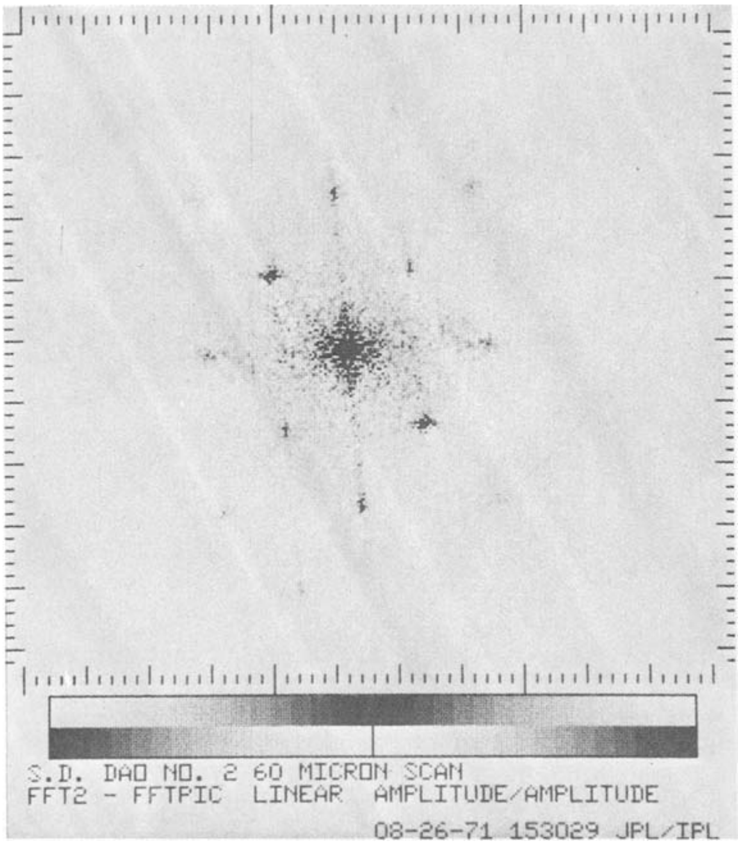

FIG. 6—*Fourier transform of picture area selected for noise removal processing.*

used in processing this simulation. The results of this processing indicated that no spurious information was introduced into the final resultant products.

It was further found that the visual comparison of transforms made by patterns combined additively differed significantly from those created by multiplicative (for example) combinations. The bed sheet transform resembles the additive combination more closely than the multiplicative combination. Figures 11 and 12 are two such comparisons.

Figure 11 is the Fourier transform of the patterns seen in Fig. 2*c* which have been combined additively, that is, (A + B). Figure 12 is the Fourier transform of two patterns combined multiplicatively, that is, (A × B). It can be seen that the two transforms differ significantly from each other. Figure 12 exhibits smaller, ringlike harmonics around the spikes associated with the crosshatching of Pattern B. This is caused by the convolution of the two patterns via multiplication. When Fig. 6 is examined and compared with these examples it appears to more closely resemble Fig. 11, the additive example, than Fig. 12, the multiplicative example. The Appendix of this paper delineates another approach and an example which can be used to separate multiplicatively combined patterns.

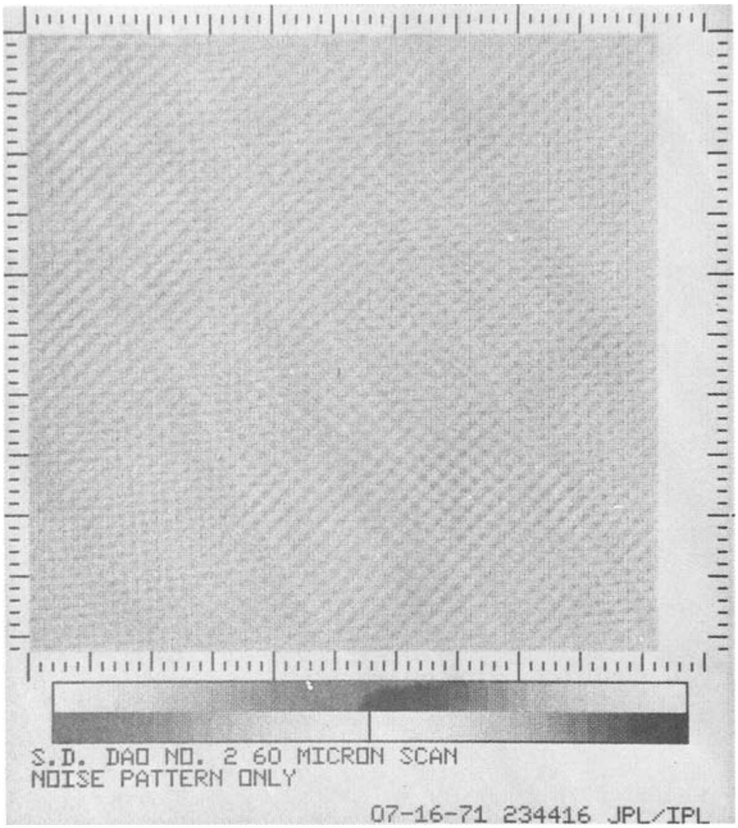

FIG. 7—*Sheet weave noise pattern removed from Fig. 5.*

Significance of the Technique Developed

The widespread acceptance of the new methodology as it pertains to the processing of images transmitted to earth by spacecraft provides a basis for its extension to meet a real and immediate requirement for these same techniques as applied to the needs of law enforcement agencies, and to the judicial system.

It is therefore mandatory to establish an interface through which advanced technologies, such as digital image processing, will become working tools in the various specialized aspects of forensic science such as fingerprint identification. The benefits of applying advanced theories and processes must be emphasized and proved in a manner which reveals the underlying principles and methods. In this way, the profession will be able to examine the process to its own satisfaction and determine its place in the forensic sciences. Without this acceptance by the profession, new technology has no credibility in the adjudication process.

The authors believe that image processing is a powerful tool that can be used to aid forensic scientists in identification of fingerprints left at the scene of a crime. It is their

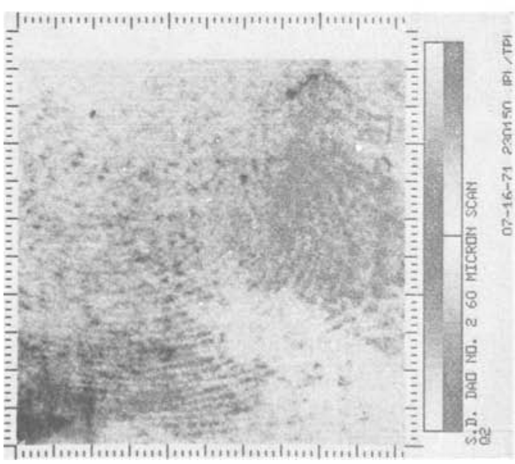

FIG. 8—*Ridge pattern remaining after sheet weave pattern removal.*

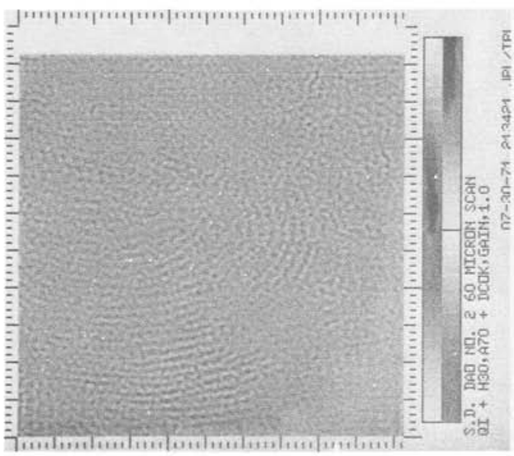

FIG. 9—*Result of applying blocking mask to Fourier transform of palm print.*

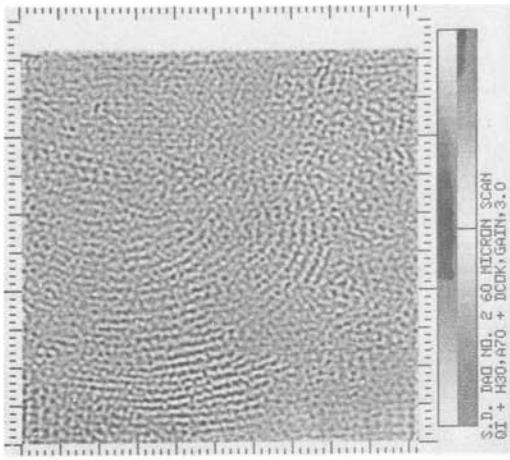

FIG. 10—*Result of applying enhancement factor of 3 to Fig. 9.*

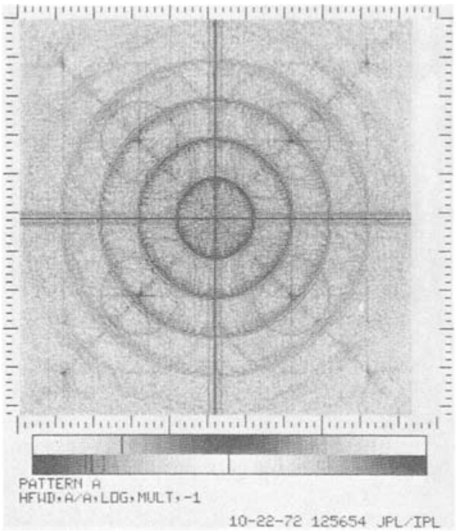

FIG. 11—*Log display of Fourier transform of Pattern A* plus *Pattern B.*

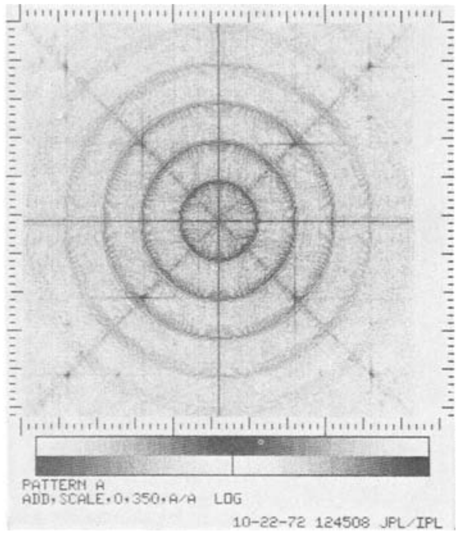

FIG. 12—*Log display of Fourier transform of Pattern A* times *Pattern B.*

contention, from the analysis of simulated test patterns and test examples using bloody palm prints on cloth, that signal and noise separation can be achieved using Fourier transform techniques for both linearly and nonlinearly combined patterns.

Before image processing will be accepted as a method in criminalistics, however, a great deal of work needs to be done with controlled experiments of known as well as unknown fingerprints. It is essential that a baseline of demonstrated use be established by *direct application* in the field of fingerprint identification. It is not enough that image processing is accepted by the scientific community of aerospace engineers. The fundamental principles are presented here and in the references. It remains for forensic scientists to apply the technology to specific problems as they arise.

APPENDIX

Controlled Tests Performed Subsequent to the Processing of the Blood-Impregnated Sheet

Tests were designed to test the feasibility of separating multiplicatively combined patterns using Fourier transform techniques. The method involves the use of logarithms.

Let:

A_S = Pattern A (real image)
B_S = Pattern B (real image)
$C_S = A_S \times B_S$ (real image)

Given an image C_S, find A_S if it is known that $C_S = A_S \times B_S$, and B_S is known.

In order to satisfy the requirements of linear relationships for subsequent Fourier manipulation, use was made of the logarithms to replace division, that is:

$$\log C_S/B_S = \log C_S - \log B_S$$

Since it is known that C_S was created as a product of A_S and B_S, we wish therefore to divide C_S by B_S. Since division is not a linear process, the log operator transforms division into a linear operator.

The creation of logarithmic images thereby satisfies this requirement. By taking the Fourier transform of log C_S and subtracting from it the Fourier transform of the log B_S, we have accomplished our goal of division of C_S by B_S.

If the only image available is a composite one (that is, C_S) it becomes necessary to find a suitable replica of B_S such as an isolated section within C_S exhibiting some singular or uncombined portion of B_S. If this procedure is unsuitable, it becomes necessary to follow the procedure used in processing the bed sheet, that of viewing the transform of the composite images and visually locating the transform spikes of the interfering pattern. In this case, elimination of specific frequencies by setting them equal to zero constitutes subtraction.

The final step in this process, after subtraction of the Fourier transform of B_S from the Fourier transform of C_S, is to take the back or inverse transform and then the antilogarithm of that resultant image to obtain A_S.

Figure 13 shows the results of multiplying A_S by B_S. In order to avoid computation problems within the computer, the elements of both A_S and B_S have been rescaled so that the product of $A_S \times B_S$ did not exceed some predetermined value. This is the reason for the very low contrast image seen in Fig. 13. Figure 13 is, in effect, a computational image. Figure 14 is a visual model of Fig. 13. It has been obtained by increasing the relative contrast of Fig. 13 to the point where the individual structural elements of the image can be seen. Figure 14 has been included for illustrative purposes. Figure 15 is the Fourier transform of the product $A_S \times B_S$, the low contrast image seen in Fig. 13. Figure 16 is the logarithm of the image seen in Fig. 13. Figure 17 is the Fourier transform of the logarithm $(A_S \times B_S)$, the image seen in Fig. 16. Compare the frequency components in this transform with those seen in Fig. 15. Figure 18, the final result of the process, shows the original Pattern A after subtraction of B_S from C_S in the Fourier domain, taking the antilogarithm of that picture and finally rescaling A_S back to the original intensity values.

A conclusion which can be drawn from this demonstration would be that multiplicatively combined image patterns can be separated using Fourier techniques. As a precautionary measure, it could be suggested that if the composite image composition is unknown, that is, it is unknown if the combination is additive or multiplicative, then the process of conversion of the composite image to logarithmic form prior to data manipulation would appear to be justified.

Conversion of additively combined patterns can also be separated via logarithmic representation and subsequent Fourier manipulation. This process can be accounted for by the relationship established, in photographic terms, between a logarithmic image and a density image, that is to say, that the logarithm of the measured light intensity transmitted through a film is proportional to the density of that film. The density or logarithmic image can now be processed by linear or Fourier processes because the structure of density images is accumulated in a linear or additive manner.

FIG. 13—*Pattern C* ($A_S \times B_S$) *with* A_S *and* B_S *rescaled to have intensity values 0 to 15. This is the computational image.*

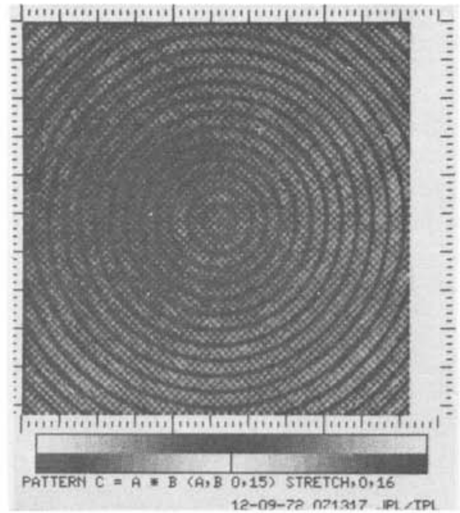

FIG. 14—*Pattern C contrast stretched for illustration purposes.*

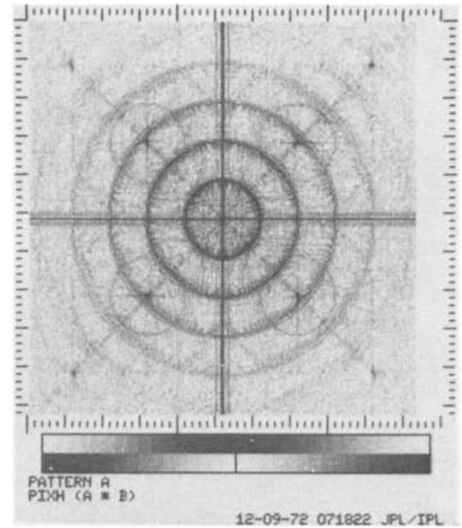

FIG. 15—*Fourier transform of Pattern C, the image seen in Fig. 13.*

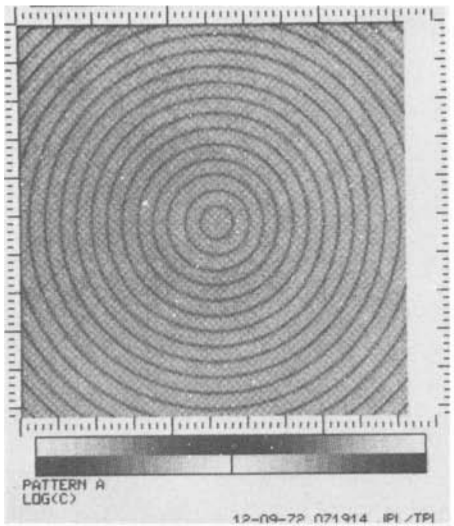

FIG. 16—*The logarithm of Pattern C, the image seen in Fig. 13.*

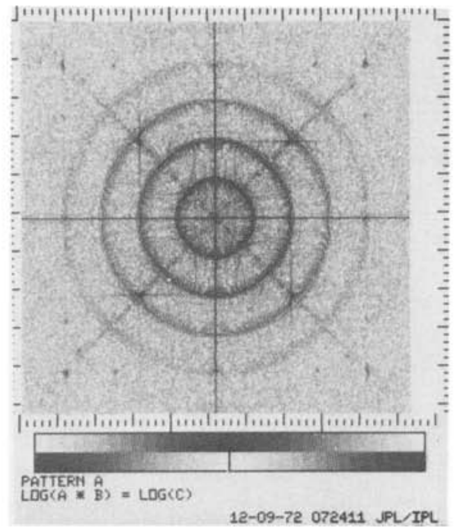

FIG. 17—*The Fourier transform of the logarithmic Pattern C, the image seen in Fig. 16.*

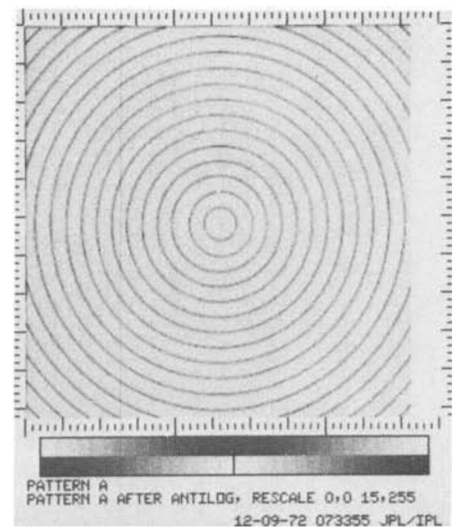

FIG. 18—*Pattern A after taking antilogarithm and rescaling back to original intensity values.*

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Erratum

Blackwell, R. J. and Crisci, W. A., "Digital Image Processing Technology and Its Application in Forensic Sciences," *Journal of Forensic Sciences,* JFSCA, Vol. 20, No. 2, April 1975, pp. 288-304. On p. 300 of this article, Figs. 11 and 12 were inadvertently transposed.

Announcement

The Twelfth International Medical-Legal Seminar will be held from 24 April to 12 May 1976 in Sydney, Canberra, and Melbourne, Australia; Auckland, New Zealand; Papeete, Tahiti; Pago Pago, American Samoa; and Honolulu, Hawaii. The seminar is sponsored by the Pittsburgh Institute of Legal Medicine, in conjunction with the Forensic Science Society of Australia, the Australian Academy of Forensic Sciences, and the New Zealand Pathology Society.

Subjects to be discussed include forensic psychiatry (XYY chromosome, legal determination of insanity, and mental disability and the law), human experimentation (medical and legal ramifications), euthanasia, organ transplants and determination of death, medical malpractice, medical expert testimony in civil and criminal cases, and official medical-legal investigation.

This seminar has been approved for Category I credit by the Division of Continuing Medical Education, University of Pittsburgh School of Medicine. For registration forms and additional information, contact Cyril H. Wecht, M.D., J.D., Director, Pittsburgh Institute of Legal Medicine, 1417 Frick Bldg., Pittsburgh, Pa. 15219 (412 281-9090).