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Operational Experience of Fingermark Enhancement by Frequency Domain Filtering

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ABSTRACT: Fourier transformation of an image and subsequent filtering in the frequency domain has been found to be an effective way to improve images of fingermarks on interfering backgrounds. Examples are given of success in reducing periodic backgrounds that would otherwise have prevented fingermark identification. In addition, it has been found that better background suppression is obtained when high-resolution images are used.

KEYWORDS: forensic science, fingerprints, digital image processing, Fourier transform, charge-coupled devices

Digital image capture is becoming an attractive alternative to conventional photography in forensic science. It lends itself well to digital image processing techniques, such as smoothing, contrast stretching and convolution filtering [*1,2*], and it has already been used in document examination [*3–6*]. Forensic photographers are particularly interested in aspects of digital image processing that allow useful images to be obtained which are either impossible or extremely labor intensive to achieve using traditional photographic methods.

Fingermark examination is central in many crime investigations but there are occasions when identification is inhibited by an interfering background. Conventional filters used in photography often fail to remove such backgrounds. Interfering patterns range from simple periodic structures such as cloth weave to the more complex patterns intentionally designed into banknotes. Irregularities in a substrate surface can also reduce the lighting options and this in turn decreases the photographer's chances of obtaining good contrast. It was anticipated that digital image processing techniques could overcome many of these problems in forensic casework.

Reports of fingermark enhancement by image processing have been very few, but a recent paper did emphasize the potential value to law enforcement agencies [*7*]. Simple operations such as histogram equalization and convolution filtering have been used, but these were not applied to fingermarks with background interference problems [*8*]. Attention is specifically drawn here to Fourier transformation as a powerful image processing tool for reducing the difficulties caused by periodic patterns in a forensic context. A similar method has been reported to enhance the contrast of laser-luminescent fingermarks [*9*].

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for reducing the difficulties caused by periodic patterns in a forensic context. A similar method has been reported to enhance the contrast of laser-luminescent fingermarks [9].

In this paper we describe the application of selective filtering in the frequency domain to reduce interfering periodic patterns in fingermark images.

Since the submission of this paper a report has been published elsewhere outling the method used here [10]. A similar procedure for filtering in the frequency domain of an image was described although no details were given of specific casework samples.

Fourier Transform Image Processing

Digital images consist of a two-dimensional array of discrete intensity values that can be expressed as a sum of spatial-frequency components. The mathematical operation used to perform this conversion from spatial to spatial-frequency domains is known as Fourier transformation (FT). Typically, rapid changes in spatial intensity (sharp contrast) implies the presence of high-frequencies in the data, whereas gradual changes in contrast need only lower frequencies to be well represented. Once the image has been converted to the frequency domain, the relative contributions of the various component frequencies are easy to adjust. The process can be reversed, allowing a set of frequencies and associated amplitudes to be converted back to the more familiar spatial domain. With skilful and intelligent modification of the frequency data, an image can be achieved on reverse transformation which is easier to interpret than the original.

Many image processing techniques are easier and/or faster to apply in the frequency domain, notwithstanding the time taken to transform the data. This has caused FT to become a powerful processing tool in the functionality of most image processing software. The underlying mathematics are well covered in standard texts [8]. Appendix 1 outlines the process in terms of the data displayed to the operator.

Although a fingermark appears as a regular pattern, to the human eye it does not have sufficient regularity to produce distinct features in the frequency spectrum. It is occasionally possible to see roughly circular patterns at the lower frequencies (see Fig. 1), but a diffuse pattern of even intensity is typically observed. In contrast, truly periodic patterns in an image usually imply discrete frequencies of high amplitude and they are observed in the frequency image as intense 'spikes' of brightness distributed about the center of the display.

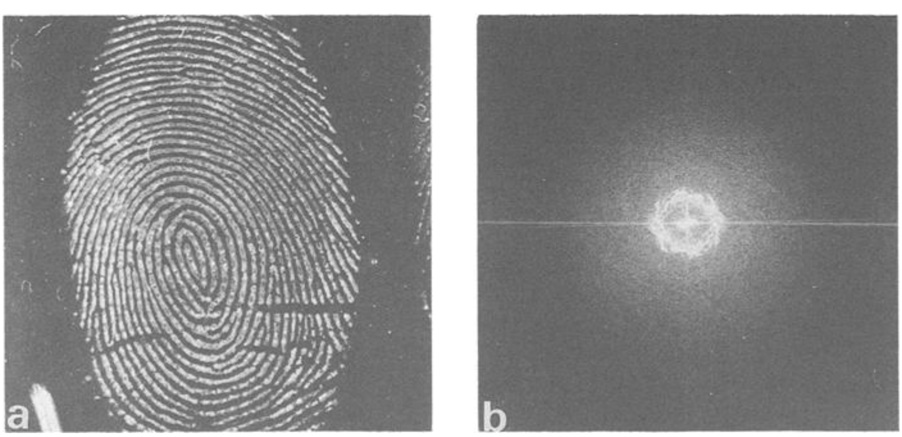

FIG. 1—(a) *An ultra violet reflection photograph of a fingermark on a plain background and* (b) *the frequency domain representation.*

Figure 2 shows an example. The periodic background pattern in the conventional image can be reduced by decreasing or eliminating the contributions of these characteristic frequencies. Figure 3 is a flow diagram of the key steps in the process. The main step is to generate a filter mask that can be used to select the frequencies to be operated on.

The first task in generating a filter mask is to identify frequencies characteristic of the background interference. This is typically an empirical process based on experience, but an understanding of the mathematical relationship between various patterns and their Fourier transforms is helpful. Occasionally the associated frequencies can be found by Fourier transformation of an undisturbed part of the periodic background. Once a mask has been generated the operator decides how much to adjust the amplitudes of the selected frequencies. The method is highly interactive and somewhat empirical, with the operator controlling many image processing parameters.

We have created masks using several methods including annular filtering, individual pixel intensity attenuation and region-of-interest cutting. Mask creation by seed-fill thresholding (described as follows) usually gave the best results.

Seed-fill thresholding is a mask creation technique in which the operator begins by selecting a pixel at the center of the spike and setting a grey level threshold. The computer then systematically checks the neighboring pixels. If any have values above the threshold setting, they too become part of the mask and their neighboring pixels are checked in turn. This process continues until a pixel is reached whose grey level value falls below the threshold setting. This typically causes a spreading out of the mask from the chosen pixel to cover the whole of the spike. The threshold has to be chosen carefully, for otherwise too many or too few pixels may be included in the final mask. This point is illustrated in Fig. 4, where a change of one grey level in the threshold value can make the difference between a correctly defined mask or excessive obliteration of the data. The process is repeated for each spike associated with the background interference.

Once a mask has been defined, the operator can then eliminate the characteristic frequencies by reducing their amplitude to zero. Thus, on application of inverse FT, the spatial amplitude variations associated with the eliminated frequencies will have been removed. However, this is usually unsatisfactory since these frequencies may contribute to the fingermark ridge detail, albeit to a small extent. It is normally better to reduce the amplitudes of the characteristic frequencies to a value comparable with those in the frequency domain as a whole. We have found the optimum extent of reduction to be image dependant but a

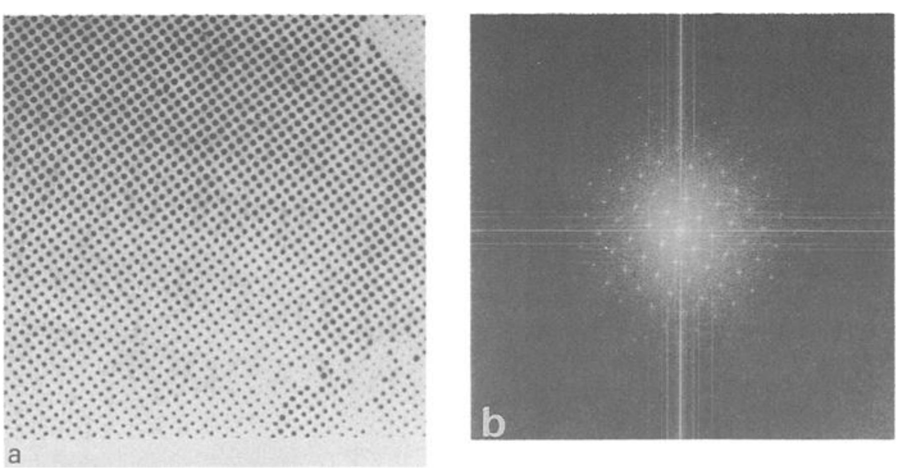

FIG. 2—(a) *An illustrative background pattern and* (b) *the frequency domain representation.*

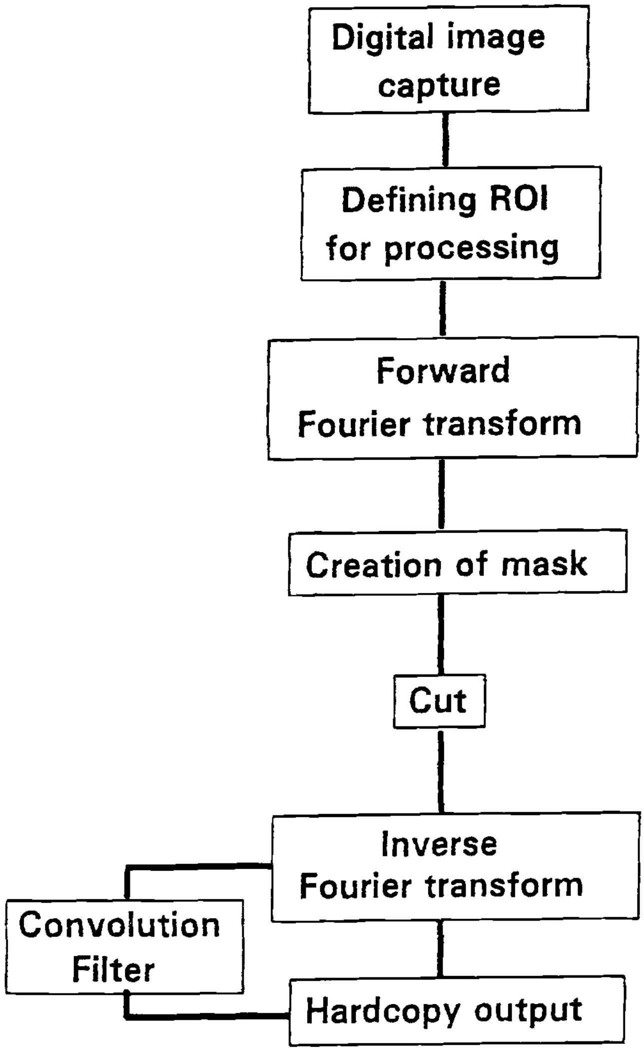

FIG. 3—*A flow diagram showing the main steps in the process of background reduction by frequency domain filtering.*

value of >75% is typical. Each spike can be adjusted individually or the mask can be applied as a whole.

Continuity of Evidence

It is essential to be able to prove the continuity of evidence after capturing and processing electronic images in forensic casework. Procedures at the Metropolitan Police Forensic Science Laboratory (MPFSL), formulated after taking legal advice, contain the kinds of safeguards outlined as follows.

Electronic image data are stored on a magneto-optical disk. The disk can be removed from the image capture equipment and is kept by the photographer. Each image is stored with a unique identifier and additional details can be stored in the image file-header. A

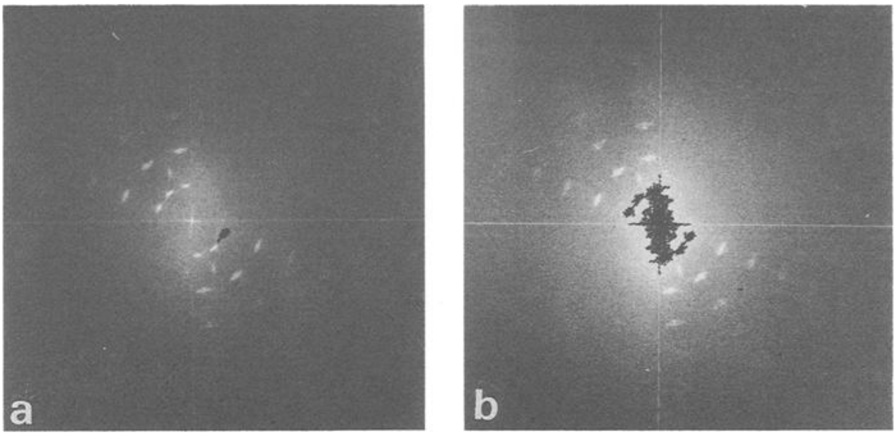

FIG. 4—*Masks created by seed-fill thresholding with set threshold values of* (a) x *and* (b) x + *1, where* x *is the grey scale value.*

magneto-optical disk is treated like any other exhibit; it is given a unique identification number and its movement is logged. The image can be copied from the disk to the image processing workstation for enhancement or hardcopy output but, irrespective of any subsequent image processing, the primary image data are always retained intact on the original disk. When full, the original disk is sealed and stored for any subsequent examination. Image processing is carried out on copies of the original data.

Processing functions applied to an image are logged and a copy of the log is retained in the case file so that the processing operations can be repeated if a further examination is required. The log therefore provides an audit trail of the processing applied to an image. The software currently used in this laboratory produces a log file of the processing commands that can be saved to disk. This log file can be recalled at any time to repeat the processing applied to an image.

An image of a known fingermark on a periodic background can be processed at regular intervals and compared with the original result to check the integrity and reliability of the processing software. This acts as an internal control in case any faults should develop.

Original and processed images can be printed onto conventional photographic film. Hardcopy production and archival storage follows conventional photography casework protocols.

Equipment

The images reported here were captured directly as digital images or indirectly by digitizing conventional photographs. Two separate capture devices were used:

1. A Photometrics CH250 CCD camera with a $2k^2$ chip
2. A Primagraphics line-scan camera with a maximum spatial resolution of 5 × 7k pixels.

The best results are obtained from image processing when care has been taken to obtain the best possible input images. Therefore, optimum photographic lighting and filtering techniques should be used to obtain the highest quality input image.

The CCD camera has a grey scale resolution of 12 bits (4096 grey levels) and the line-scan camera has a resolution of 8 bits (256 grey levels) or 24 bit color (3 × 256 intensity levels). Digital image processing was performed on a Sun Sparcstation IPX, with 32Mbyte

RAM, 700MByte hard drive and an additional 1.3G byte hard disk. The FT processing operations were from a remote-sensing image processing software package. This package was modified by the suppliers, in collaboration with the MPFSL, to produce an image processing system of more use to forensic applications. The software operates only on 8 bit images, so images from the photometrics camera were scaled before processing. The Fourier transformation software function uses the fast Fourier transform algorithm (see Appendix 1) and the input images therefore need to have dimensions of $(M = 2^n) \times (N = 2^n)$, where M and N are the number of pixels in the x and y directions respectively, and n is an integer.

A filmwriter capable of handling spatial resolutions up to $8k^2$ produced the hardcopy images. The images are written to conventional 5″ × 4″ black and white sheet film. The quality of many hardcopy images are improved by operating on them before output with a high-pass convolution filter of the type given below:

$$\begin{matrix} 0 & -1 & 0 \\ -1 & 5 & -1 \\ 0 & -1 & 0 \end{matrix}$$

This procedure is not used on images with a low tonal range, such as digitized photographs, since it has an adverse effect on quality.

Results

Obtaining photographic or near-photographic quality from digital image capture devices requires images with a high spatial resolution. In practice this means approximately $2k^2$ for an object the size of a fingermark and considerably more for complete shoemarks. In our experience a very clean, whole fingermark of good contrast, can be captured adequately at 512^2 resolution, but this is inadequate for less well-defined fingermarks on difficult backgrounds. Figure 5 shows a typical cyanoacrylate-developed fingermark imaged at 512^2 and 2048^2 resolutions.

The greater the resolution, the more specific is the elimination of the background pattern. The reason is that the more pixels there are across a particular pattern then the higher the

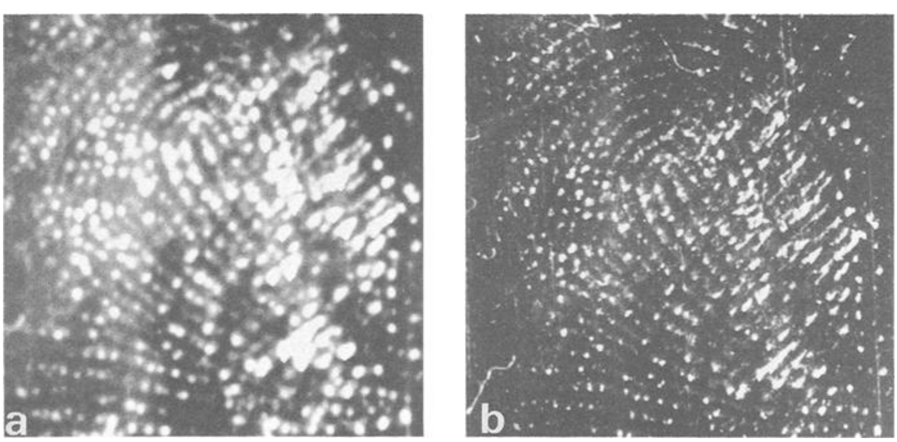

FIG. 5—*Fingerprint ridges at* (a) 512^2 *and* (b) 1024^2 *spatial resolution.*

number of frequencies available to describe the pattern, see Fig. 6. This increases the options for adjusting the relative contributions of different frequencies in order to discriminate against the background.

Casework use of seed-fill thresholding is demonstrated in this report by analogous examples. The first being a $2k^2$ image of a ninhydrin-developed fingermark on newsprint (see Fig. 7). The newspaper background was a halftone screen pattern—a series of dots of various sizes. This pattern obscured the fingermark to such an extent that it was very difficult to interpret. Applying a forward FT to this image produced a distinct pattern of spikes in the frequency domain characteristic of the spatial dot pattern. The spikes were masked and reduced in intensity by 98% using seed-fill thresholding. The frequency spectrum image after filtering is shown in Fig. 7. Inverse Fourier transformation of the processed data produced a greatly enhanced image of the fingermark.

Two casework items involving dot patterns have also been successfully processed in this manner. The first was a ninhydrin-developed fingermark on newsprint very similar to the example just described. The second was a cyanoacrylate/Rhodamine6G-developed fingermark on a plastic telephone card, which exhibits a series of evenly spaced dots of identical size. In both cases the processed mark could be identified whilst the original mark could not.

Figure 8 shows a $2k^2$ image of a fingermark in blood and on cloth. It was developed using 3,3′,4,4′-tetra-aminobiphenyl. In this example the background pattern can be thought of as a series of small irregular dots. The pattern of the cloth weave is less regular than the dots in newsprint and this consequently produced a less well-defined spike pattern in the frequency domain. Nevertheless, it was still possible to reduce the background significantly by careful masking and filtering using the seed-fill threshold method (Fig. 8). A casework mark of this type has been successfully processed.

A further example, illustrated in Fig. 9, is a fingermark on a banknote developed with ninhydrin. In a casework exhibit, as with the example shown here, it was fortunate that most of the mark lay over a periodic line pattern that produced a discrete spike array in the frequency domain. The rest of the banknote did not have a sufficiently regular spike pattern for it to be removed by seed-fill thresholding. Careful spike reduction (95% cut) and the subsequent application of an inverse FT produced a much enhanced image of the fingermark. A casework mark of this type could only be identified after processing.

One of the aims in using this technique is to improve the image quality by discarding as much irrelevant information as possible without simultaneously discarding too much of the relevant information. Broadly speaking, all frequencies contribute to all parts of the image and so the more specific the spike reduction can be the better the impact on the image as a whole. We found that excessive cutting of the data can seriously degrade an image.

Conclusion

It has been demonstrated that masking/filtering of the frequency components corresponding to periodic background interference can greatly enhance the visibility of fingermark ridge detail, thus increasing the possibility of identification. The technique proves most successful when the operator has substantial control over mask creation and cutting.

The technique works well when the periodicity in the interfering background is sufficiently well defined to give a corresponding and clearly identifiable set of spikes in the frequency domain. The best results are obtained by using high-resolution input. After processing, high-resolution images can be easily rescaled to produce input files compatible with automatic fingerprint recognition systems.

Although this paper concentrates on fingermarks the same principles can be applied to shoemarks on periodic backgrounds. Full shoemarks require considerably higher image

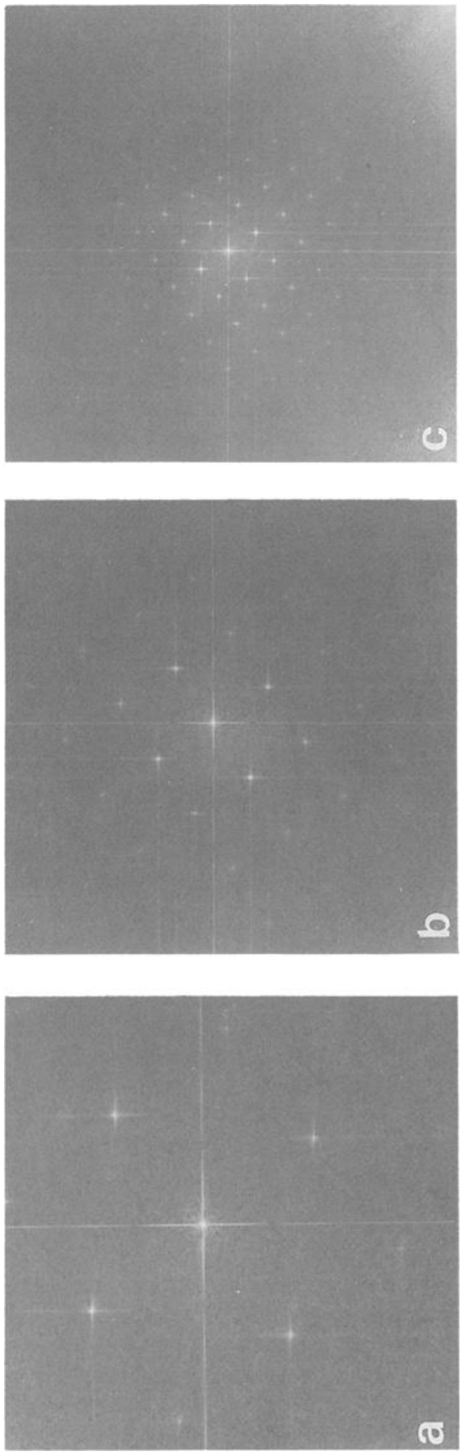

FIG. 6—*The frequency domain of a fingermark on a halftone print taken at a resolution of* (a) 250^2, (b) 500^2 *and* (c) 1000^2.

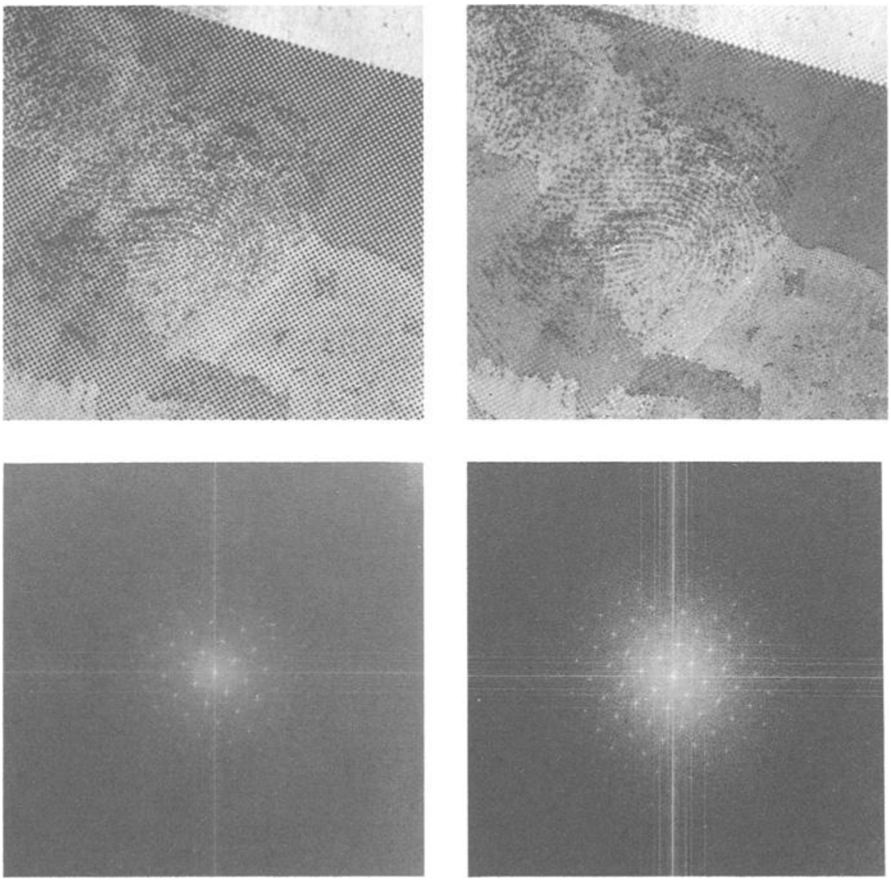

FIG. 7—*A ninhydrin-developed fingermark on halftone print* (top left) *before processing;* (bottom left) *frequency domain representation;* (bottom right) *frequency domain after masking and cutting;* (top right) *image obtained upon inverse Fourier transformation of* (bottom right).

sizes to obtain adequate resolution but areas of shoemarks on periodic backgrounds can be specifically enhanced by capturing these areas at full resolution.

Appendix 1

The Two-Dimensional Fourier Transform

A digital image consisting of $M \times N$ pixels may be analyzed in terms of its frequency components using the discrete two-dimensional forward FT function ($\mathcal{F}$) given below:

$$F(u,v) = \mathcal{F}[f(x,y)] = \frac{1}{MN}\sum_{u=0}^{M-1}\sum_{v=0}^{N-1} f(x,y)\exp\left[-i2\pi\left(\frac{ux}{M} + \frac{vy}{N}\right)\right]$$

for $u = 0,1,2,\ldots.M-1$ and $v = 0,1,2,\ldots.N-1$ and where $i = \sqrt{\sqrt{-1}}$; $f(x,y) =$ is the

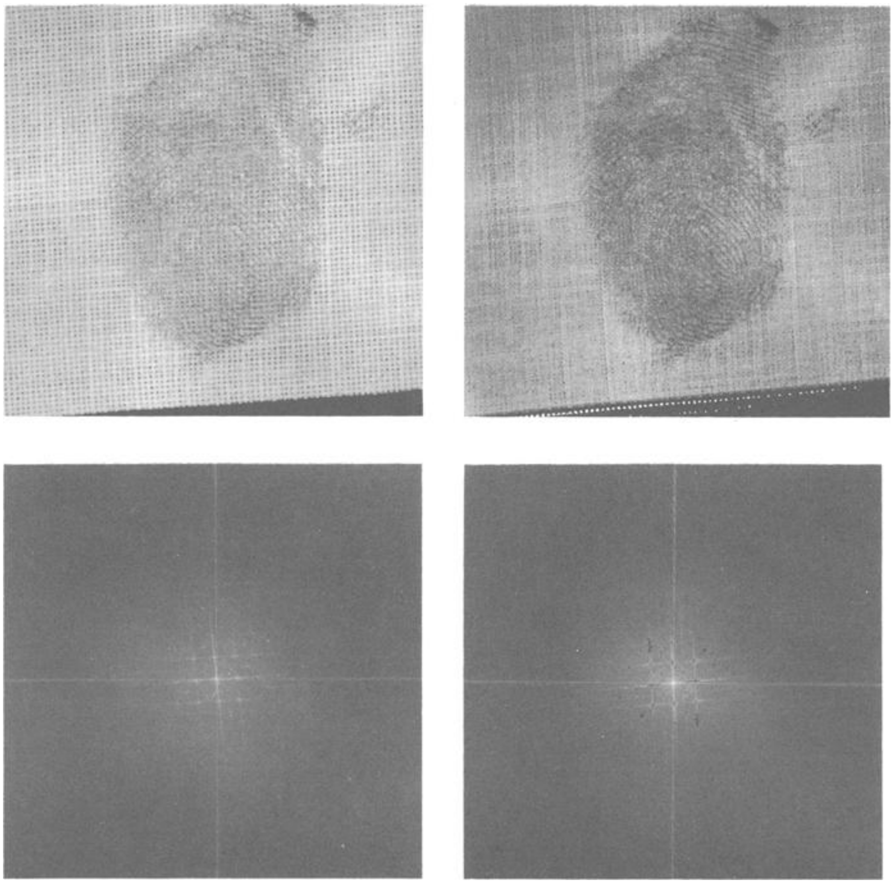

FIG. 8—*A fingermark in blood on cloth* (top left) *before processing;* (bottom left) *frequency domain representation;* (bottom right) *frequency domain after masking and cutting;* (top right) *image obtained upon inverse Fourier transformation of* (bottom right).

intensity of the image at the pixel coordinates (x,y). The frequencies u and v have the units of $(\text{length})^{-1}$.

Sampling divisions (pixels) in the spatial and frequency domains are related by the equations below

$$\Delta u = \frac{1}{M \Delta x}$$

and

$$\Delta v = \frac{1}{N \Delta y}$$

If the information is of interest these relations tell the operator what frequencies have been operated upon, but in practice the filtering is normally done through educated empiricism.

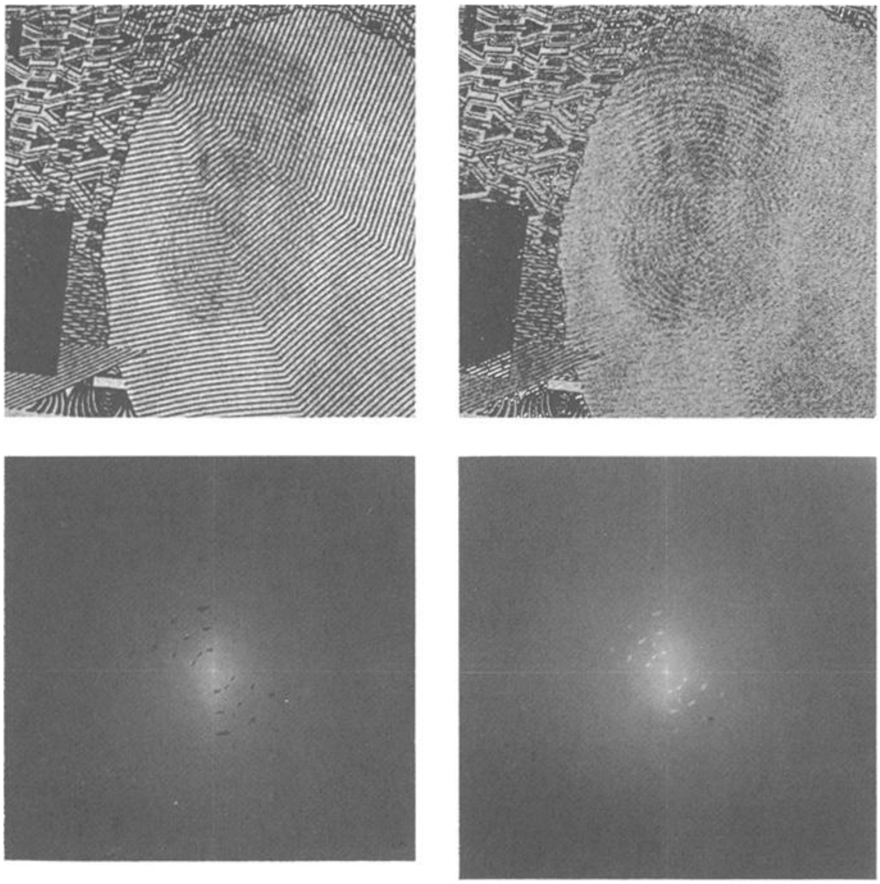

FIG. 9—*A ninhydrin-developed mark on an English banknote* (top left) *before processing;* (bottom left) *frequency domain representation;* (bottom right) *frequency domain after masking and cutting;* (top right) *image obtained upon inverse Fourier transformation of* (bottom right).

The transformed data are real and imaginary numbers but for visualization purposes they are usually represented by a grey scale image of the Fourier spectrum. The Fourier spectrum is the set of moduli of the complex numbers at the frequencies of interest.

$$|F(u,v)| = [R^2(u,v) + I^2(u,v)]^{1/2}$$

where R and I are the real and imaginary parts of $F(u,v)$ respectively. The grey scale values displayed are proportional to the amplitudes of the components spatial-frequencies.

It is convenient to shift the origin of the Fourier spectrum to the position ($M/2$, $N/2$), with a negative frequency such as $-u$ representing the frequency M-u [*8,11,12*]. Figure 10 shows the way the image data are typically displayed in both the spatial and frequency domains. This shifting of the Fourier spectrum image makes interpretation of the data much easier and consequently most image screen representations of Fourier spectra are presented in this way. The center point of the shifted Fourier spectrum is proportional to the mean grey scale value of the image.

The Fourier spectrum typically has large values near the center with considerably lower values elsewhere. It is therefore often necessary to manipulate the screen contrast to visualize

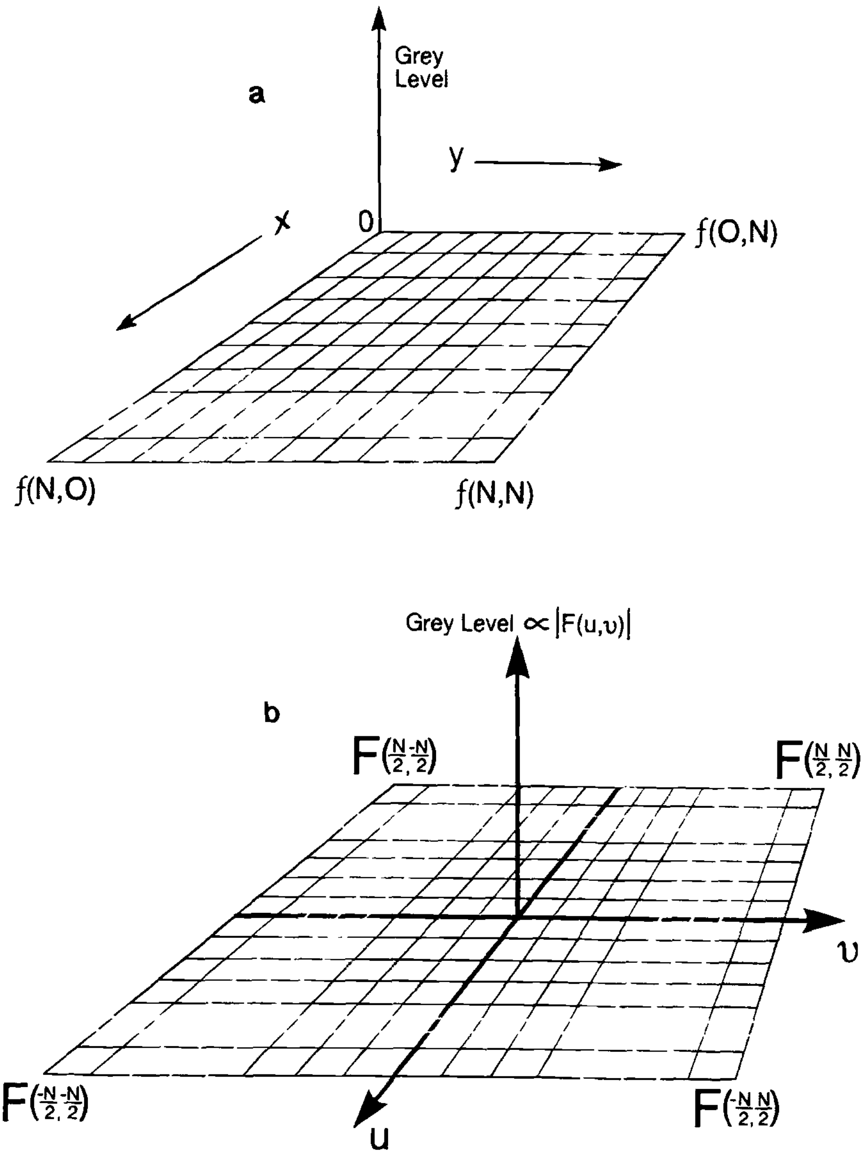

FIG. 10—*Representation of image data in* (a) *the spatial and* (b) *the frequency domains.*

the areas of particular interest in the frequency domain image. Alternatively the frequency amplitudes can be represented in a form providing a more even spread of grey scale values, using a function such as the following:

$$\log(1+(|F(u,v)|^2))$$

These representations of the frequency domain data are for display purposes only. They do not affect any subsequent computations. Nevertheless it should be realized that the frequency domain image observed on the console is not a simple representation of the raw data and in this respect it differs from the spatial image.

The frequency domain data can be recombined to give the spatial image by means of the discrete two-dimensional inverse FT operator ($\mathcal{F}^{-1}$) given below:

$$f(x,y) = \mathcal{F}^{-1}[F(u,v)] = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} F(u,v)\exp\left[i2\pi\left(\frac{ux}{M} + \frac{vy}{N}\right)\right]$$

For $x = 0,1,2,\ldots.M-1$ and $y = 0,1,2,\ldots.N-1$.

Image processing software typically uses a fast FT algorithm. It greatly reduces the number of computations necessary, but it has the restriction of requiring image dimensions of $(M = 2^n) \times (N = 2^n)$, where n is an integer [*8,11,12*]. Images not of these sizes are usually zero-filled to the next power of two before processing.

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