

# Lab Report: Optical Image Processing

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## Abstract

This report describes the experimental principle, setup, results, and the discussion of optical fingerprints identification. The experimental principles and setup are based on Bahram Javidi's paper (*Optics & Photonics News*, March, 1997, p.29) with some modifications. For experimental convenience, a two-step procedure was adopted to take autocorrelation and cross-correlation images, where films were used to record images instead of CCDs. By judging the correlation peak intensity, the matching fingerprints can be clearly identified. National Institute of Health (NIH) image processing software was used to verify and prove the experiment results. Some discrepancies between experimental and theoretical results are discussed.

## 1. Background

Theoretically speaking, image processing using optics has overwhelming advantages compared to that using computers. It is totally parallel, totally real time, and supposed to be a lot cheaper. Under proper development, optical image processing can be tomorrow's superstar technique and

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it also has been applied to various areas today. In this report, we described an optical method for conducting fingerprint identification. The configurations and principles were taken from Ref.[1] with some modifications. The variations in configurations do not affect the underlying math and physics, which is based on the Fourier transform. Therefore, before going into the actual experimental setup, we will clarify the principle of this experiment by using one-dimensional Fourier theory.

To compare an original fingerprint  $o(x)$  with a standard reference, we arrange them on an object screen with a separation  $2a$ . The total information on the object screen can be expressed as

$$f(x) = o(x - a) + r(x + a) \quad (1)$$

The object  $f(x)$  is then Fourier transformed optically onto an image screen by a particular lens configuration.

$$F(v) = R(v)e^{-j2\pi va} + O(v)e^{j2\pi va} \quad (2)$$

where  $R(v)$  and  $O(v)$  are the Fourier transform of  $r(x)$  and  $o(x)$ . However, the film on the image plane does not record the Fourier transform, but the power spectrum density (PSD),  $P(v)$

$$P(v) = |F(v)|^2 = |R(v)|^2 + |O(v)|^2 + R(v)O^*(v)e^{-j4\pi va} + R^*(v)O(v)e^{j4\pi va} \quad (3)$$

For convenience, we rewrite Eq.(3) as

$$P(v) = F_0(v) + R(v)O^*(v)e^{-j4\pi va} + R^*(v)O(v)e^{j4\pi va} \quad (4)$$

where  $F_0(v)$  was used to replace the first two terms in Eq. (3). After performing the second

Fourier transform optically, Eq. (4) becomes

$$p(x) = \beta f_0(\alpha x) + \beta o(\alpha(x+a)) \otimes r(\alpha(x+a)) + \beta r(\alpha(x-a)) \otimes o(\alpha(x-a)) \quad (5)$$

where  $\otimes$  in Eq. (5) denotes correlation, and  $\alpha, \beta$  are scaling factors depending on the definition of the Fourier transform and the physical configuration to perform it. Eq. (5) is the essential part of this method. By choosing the proper separation  $a$ , we obtain the two correlation images at  $x = \pm\alpha a$  on the second image screen in addition to the 0-th order interference  $f_0(\alpha x)$ . The correlation at  $x = \pm\alpha a$  depends on the degree of similarity between the input  $o(x)$  and the reference  $r(x)$ . If the input image has high degree of correlation with the reference, two high intensity spots will appear on the second screen, and if the intensity exceeds a threshold, the finger print  $o(x)$  is treated as matching one. Otherwise, it will be rejected as a counterfeit. Since the Fourier transform is carried out on the input fingerprint  $o(x)$  with the reference  $r(x)$  at the same time, we call this method the joint transform correlator (JTC) method. In the next section, the actual optical system used to perform the joint transform correlation is discussed. Since slightly different configurations were used to perform the two Fourier transforms denoted by Eq. (3) and Eq. (5), we describe them separately, starting with the optical setup to perform Eq. (3).

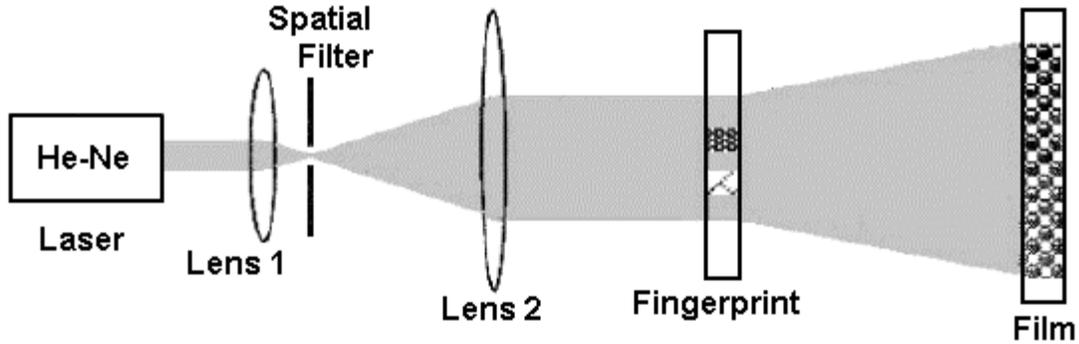
## 2. Experimental Setup

The first step of the experiment was to prepare the object. The object was made by placing the reference fingerprint and the input fingerprint together with a separation of  $2a$  in the horizontal direction, and then recording them in one film by a camera. The developed negative of the film is subsequently used as the object shown in Figure 1 to perform the first Fourier transform denoted

by Eq.(3). A certain reduction ratio was made when capturing the fingerprints. The reason will be clarified in the later part of this section.

## 2.1 The first Fourier transforms: modulation

The setup to perform the first Fourier transform denoted by Eq. (3) is shown in Fig. 1.



**Fig. 1. Optical setup for performing the first Fourier Transform.**

The Fourier transform was performed in far field fashion. In the setup, a He-Ne laser is used as light source. The laser beam is first focused by Lens 1 and collimated through the spatial filter and then expanded by Lens 2 to enlarge the illumination area. The illumination area can be adjusted by changing the distance of Lens 2 from Lens 1 to ensure the full coverage of both fingerprints shown in Fig. 1. The laser beam is subsequently modulated by the fingerprints and recorded by the film located at certain distance. In the Fraunhofer approximation, The film will record the scaled power spectrum density (PSD) of the object (fingerprints)<sup>[2]</sup>.

$$P(x, y) \approx \left| h_0(x, y) F \left( \frac{x}{\lambda d}, \frac{y}{\lambda d} \right) \right|^2 \quad (6)$$

where  $d$  is the distance from the fingerprints to the film screen, and  $\lambda = 632.8 \text{ nm}$  is the wavelength of the He-Ne laser. Since  $h_0(x) = (j / \lambda d) \exp(-jkd)$ , Eq.(6) is equivalent to Eq.(4)

scaled by the factor of  $(1/\lambda d)^2$ . This scaling factor can be disregarded after normalizing Eq. (6).

Therefore, under the Fraunhofer approximation, the film in Fig.1 records

$$P(x) = F_0 \left( \frac{x}{\lambda d} \right) + R \left( \frac{x}{\lambda d} \right) O^* \left( \frac{x}{\lambda d} \right) e^{-j4\pi \frac{x}{\lambda d} a} + R^* \left( \frac{x}{\lambda d} \right) O \left( \frac{x}{\lambda d} \right) e^{j4\pi \frac{x}{\lambda d} a} \quad (7)$$

where we use the one-dimensional case of Eq. (6) to give a simplified expression. One of special cases in Eq. (7) is when the input  $o(x)$  matches the reference  $r(x)$ . In this case, Eq. (7) becomes

$$P(x) = F_0 \left( \frac{x}{\lambda d} \right) + 2 \left| R \left( \frac{x}{\lambda d} \right) \right|^2 \cos \left( 4\pi \frac{x}{\lambda d} a \right) \quad (8)$$

Equation (8) suggests that when the input fingerprint matches the reference one, the film used to record the PSD in Fig.1 will be characterized by a periodic modulation. The fringe spacing is  $X = \lambda d / 2a$ . It should be emphasized that the appearance of the fringe for matching fingerprints is the most important feature to judge the quality of the PSD recorded on the film. It has a direct impact on the subsequent experimental results. On the other hand, it should be mentioned that the fringe is a unique feature of matched fingerprints. As we can see from Eq.(7), the cosine modulation in Eq. (8) only appears when  $R(x/\lambda d) = O(x/\lambda d)$ .

The last theoretical issue we need to address in this setup is how good is the far field approximation. For the experimental configuration in Fig. 1, the values of the parameters are as follows:

- The distance  $d$  is 1–3 m .
- The maximum diameter  $b$  of the fingerprints image is  $\sim 2\text{mm}$  (using 50X reduction).
- The wavelength of He-Ne laser  $\lambda$  is 633 nm .

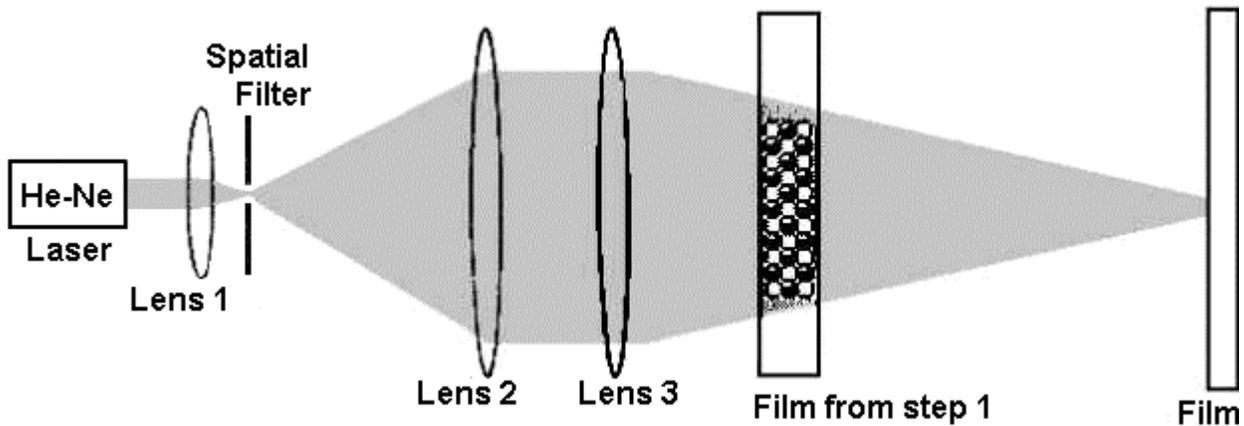
One can calculate the Fresnel number  $N'_F$  to verify the validity of the Fraunhofer approximation.

$$N'_F = \frac{b^2}{d\lambda} = \frac{4 \times 10^{-6}}{1.5 \times 0.633 \times 10^{-6}} = 4.2$$

This calculation suggests that the far field approximation doesn't work very well in this setup since the validity of Fraunhofer approximation requires  $N'_F$ .

## 2.2 The second Fourier transforms: correlation

The second setup to produce the autocorrelation or cross-correlation peak is shown in Fig. 2.



**Fig. 2. Setup to construct the correlation between the input image and the reference.**

The major difference between Fig. 2 and the first setup is the insertion of Lens 3, which ensures the validity of the Fraunhofer approximation. As in Fig. 1, the combination of Lens 1, Lens 2 and the spatial filter is used to expand and collimate the laser beam. The beam is then refocused by Lens 3 to a focal point where the recording film is located. The object (developed negative film from step 1) is put in the converging beam between Lens 3 and the recording film, and the

location of the object is chosen such that the illumination area is slight larger than the area bearing the image information.

The Fourier transform using the setup of Fig. 2 has the following expression<sup>[3]</sup>

$$E(x, y) = \frac{e^{jk\left[r_0 + \frac{x^2 + y^2}{2r_0}\right]}}{j\lambda z} p\left(\frac{x}{\lambda r_0}, \frac{y}{\lambda r_0}\right) \quad (9)$$

where

- $p(x, y)$  is the Fourier transform of the object  $P(x, y)$  denoted in Eq.(7).
- $x, y$  denote the coordinates on the recording film.
- $z$  is the distance from the object to the recording film.
- $k$  is the wavenumber
- $r_0 = \sqrt{x^2 + y^2 + z^2}$

In the experimental setup in Fig.2, since  $r_0 \gg \sqrt{x^2 + y^2}$ , we make the near axis approximation  $r_0 \approx z$ . Again, the film does not just record the Fourier transform but the PSD. Therefore, the image recorded by the film is

$$Q(x, y) = |E(x, y)|^2 = \left| p\left(\frac{x}{\lambda z}, \frac{y}{\lambda z}\right) \right|^2 \quad (10)$$

Again, the scaling factor  $(1/\lambda z)^2$  is disregarded after normalization. One of the advantages of the setup in Fig. 2 is that the size of the Fourier transform diffraction pattern can be customized without changing the focal length of the lens. For the matching case denoted by equation (8), the

output in the  $x$  direction in Eq. (10) can be written as

$$Q(x) = \left| f_0 \left( \frac{d \cdot x}{z} \right) + A_r \left( \frac{d}{z} \left( x - \frac{2za}{d} \right) \right) + A_r \left( \frac{d}{z} \left( x + \frac{2za}{d} \right) \right) \right|^2 \quad (11)$$

where  $A_r(x)$  is the autocorrelation function of the reference  $r(x)$ .

If the three terms in Eq. (11) don't overlap with each other, Eq. (11) can be written as

$$Q(x) = \left| f_0 \left( \frac{d \cdot x}{z} \right) \right|^2 + \left| A_r \left( \frac{d}{z} \left( x - \frac{2za}{d} \right) \right) \right|^2 + \left| A_r \left( \frac{d}{z} \left( x + \frac{2za}{d} \right) \right) \right|^2 \quad (12)$$

where the autocorrelation peaks can be clearly resolved.

### 2.3 Practical considerations for the experiment

The first step of the experiment is to prepare the input fingerprint and reference fingerprint on one negative. One of the sample images is shown in Fig 3.



**Fig. 3. A sample fingerprint used in this experiment. The actual size is 3.5 cm.**

Before conducting the actual experiment, we can make an initial estimation of the anticipated results. From Fig.3, the highest spatial frequency observed in the fingerprint is determined by the spacing between two adjacent lines, which was measured as  $\sim 1mm$  corresponding to a spatial

frequency of  $\sim 1\text{mm}^{-1}$ . After the first Fourier transform, based on Eq. (7), the maximum spatial frequency will be recorded on the film at a location

$$x_{\max} = v_{\max} \cdot \lambda d \quad (13)$$

Considering the actual setup, where  $d \sim 500\text{mm}$ ,  $\lambda = 633 \times 10^{-3}\text{mm}$ ,  $v_{\max} = 1\text{mm}^{-1}$ , Eq. (13) gives  $x_{\max} = 0.3\text{mm}$ . This means all the information contained in the fingerprints will be confined within an area of  $b \times b = 0.6\text{mm}^2$  on the film. A certain amount of reduction was necessary in order to enlarge the size of the PSD. After a  $N$ -fold reduction, the size of the film containing the spatial information becomes  $0.6N\text{mm}^2$ .

From Eq.(8), if an input fingerprint matches the reference one, a cosine modulation fringe appears, whose period is

$$T_x = N \frac{\lambda d}{2a} \quad (14)$$

where  $N$  is the reduction ratio and  $a = 50\text{mm}$  is the separation between the input fingerprint and the reference fingerprint. Again, from Eq. (14), the reduction is necessary to distinguish the cosine modulation on the screen. Otherwise, the period  $T_x$  will be  $\sim 6.4\mu\text{m}$ , too small to be resolved by the film.

After the second Fourier transform, the film records information represented by Eq. (11). However, we know that, in order to get clear autocorrelation peaks, we need to ensure that the three terms on the right hand side of Eq. (11) do not overlap with each other, which leads to Eq. (12). The size of the actual fingerprint shown in Fig. 3 is  $\sim 35\text{mm}$ . After an  $N$ -fold

reduction, the size becomes  $35/N \text{ mm}$ . Generally speaking, the size of the autocorrelation is about the same size as the original, therefore, each term in Eq. (11) has a size  $\sim z/d(35/N) \text{ mm}$ .

From Eq. (12), the separation between two adjacent peaks is determined by

$$s = \frac{z}{d} \cdot \frac{2a}{N} \quad (15)$$

where  $z \sim 1200 \text{ mm}$  is the distance between the object and the film in the second Fourier transform shown in Fig. 2. Therefore, the separation between two adjacent correlation peaks is  $1200/N \text{ mm}$ , and the separation between two AUTO-correlation peaks is  $240/N \text{ mm}$ . From the above calculations, generally speaking, the correlation peaks will not overlap each other. For comparison purposes, all the above calculations are listed in Table 1.

Definition of notation:

- $2a(\text{mm})$ : Distance between the input finger print and the reference finger print
- $N$ : Reduction ratio
- $c(\text{mm})$ : Size of the original fingerprint
- $d(\text{mm})$ : Distance between the object and the recording film in the 1<sup>st</sup> Fourier transform
- $z(\text{mm})$ : Distance between the object and the recording film in the 2<sup>nd</sup> Fourier transform
- $T_x(\text{mm})$ : Period of the cosine modulation for the matching case (Eq. (8))
- $\lambda(\text{mm})$ : Wavelength of He-Ne laser
- $b(\text{mm})$ : Size of the first Fourier transform
- $2s(\text{mm})$ : Separation of the two autocorrelation peaks in the 2<sup>nd</sup> Fourier transform

$N$	$2a(\text{mm})$	$c(\text{mm})$	$b(\text{mm})$	$T_x(\text{mm})$	$2s(\text{mm})$
1	50	35	0.6	0.0064	240
10	5	3.5	6	0.064	24
25	2	1.4	15	0.16	9.6
50	1	0.7	30	0.32	4.8

**Table 1. Preparatory Calculations**

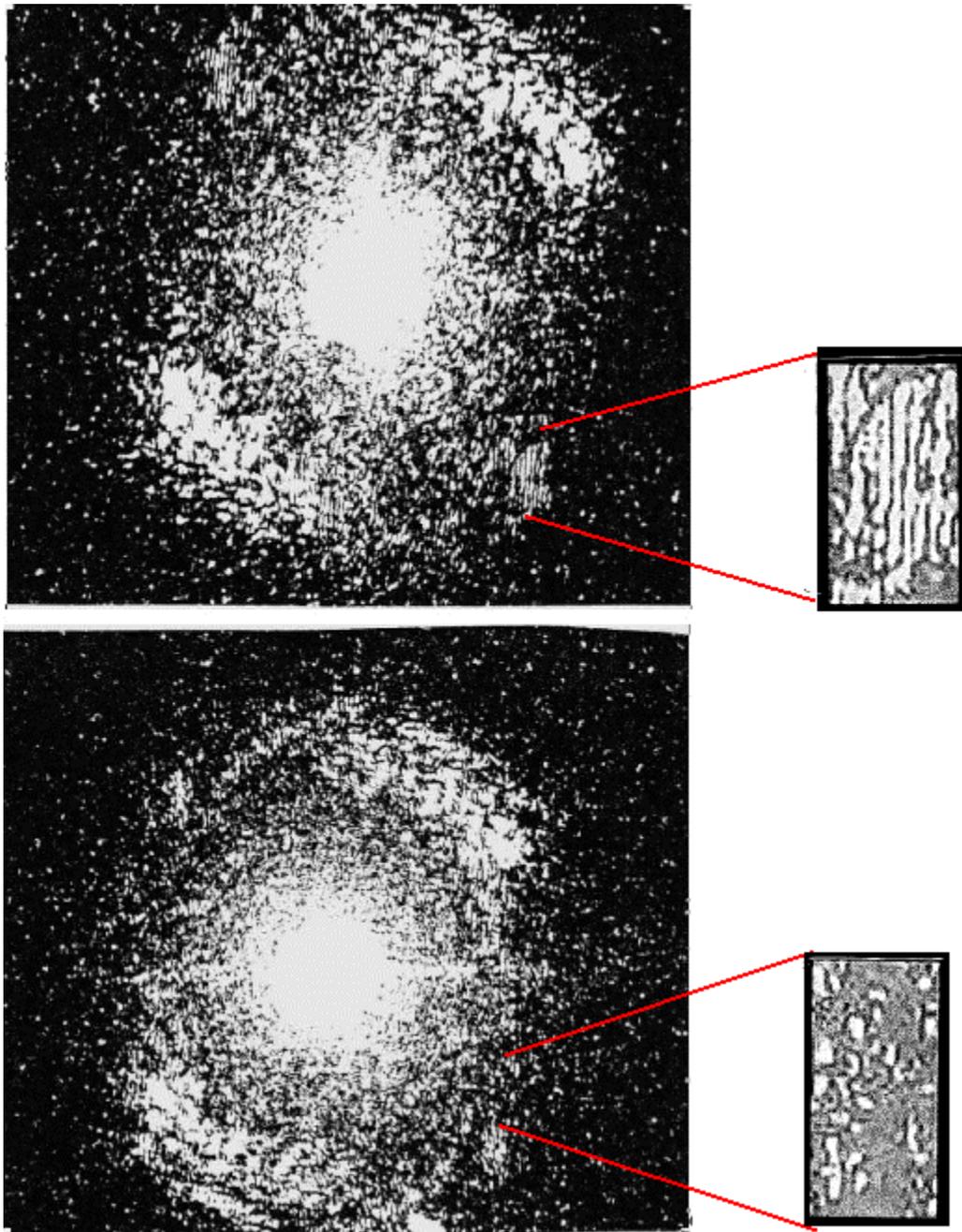
### 3. Results

The experiment started with preparing the input and reference fingerprints. For demonstration purposes, two sets of fingerprints were prepared as shown in Fig. 4. In the first set, the input fingerprint matches the reference fingerprint. The second set doesn't match. Kodak ASA-100 black and white film was used to grab the both sets of fingerprints using different exposure times while the F-number was set at 2 for the camera. Three different reduction ratios (10, 25, and 50) were used to take the pictures. After the development of the films, the negatives were checked under an optical microscope to pick up the best quality negative (1/250 sec shutter speed, 25-fold reduction) to perform the next step of the experiment.



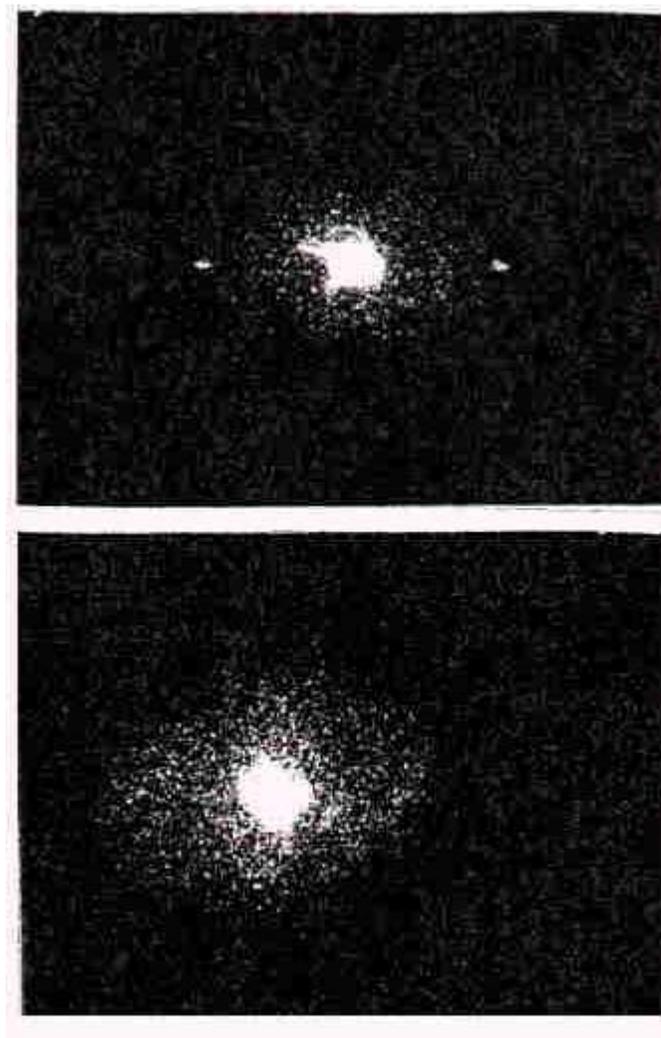
**Fig. 4.** The two sets of fingerprints used in the experiment. The left fingerprints in both sets are the reference. The fingerprints in the top set are matching, while in the bottom set, they are mismatching.

The negative of the fingerprints are then Fourier transformed. The results shown in Fig. 5. As predicted, for the autocorrelation, the cosine modulation is clearly visible around some locations, and the modulation period is  $\sim 0.14\text{mm}$ , consistent with the preparatory calculation. The cross-correlation does not have this feature.

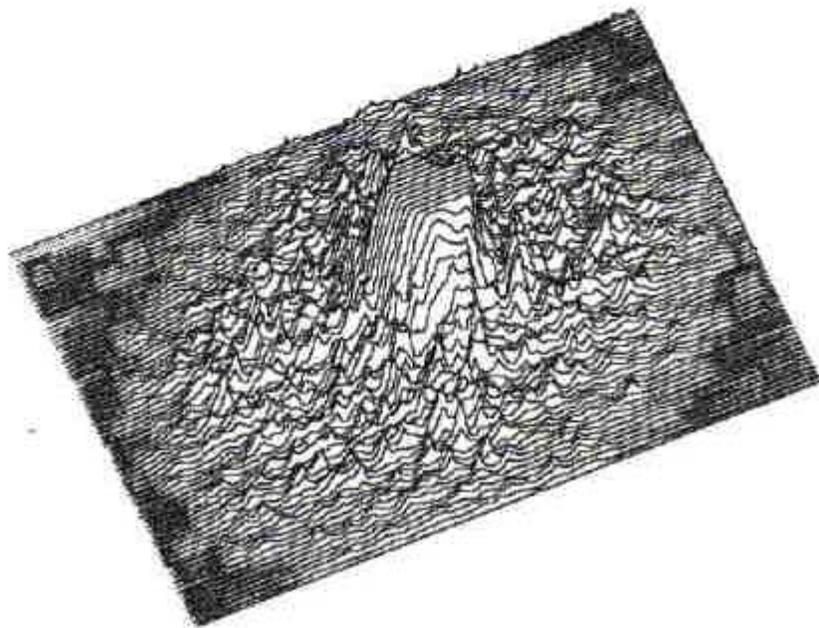
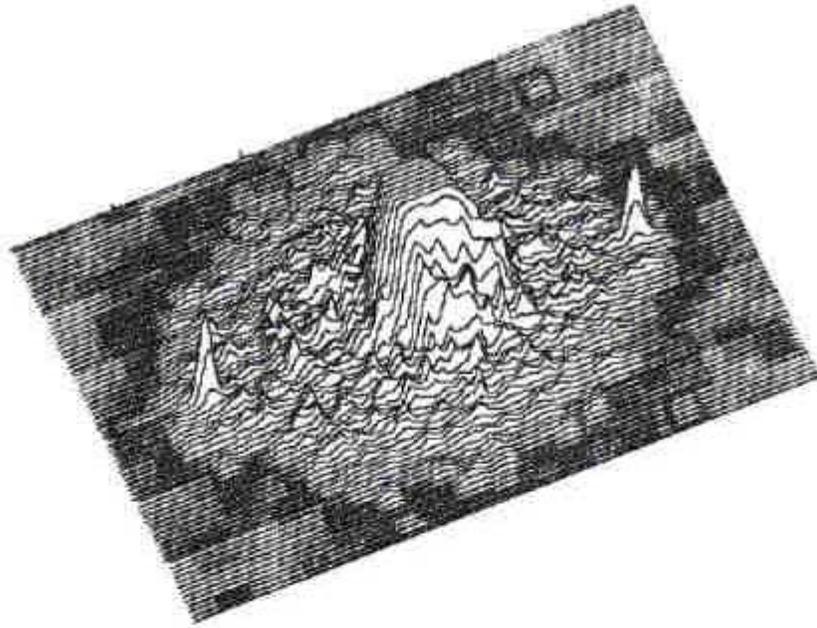


**Figure 5. Optical power spectrum density of the fingerprints. The top is for the matching set, and the bottom is for the mismatched set.**

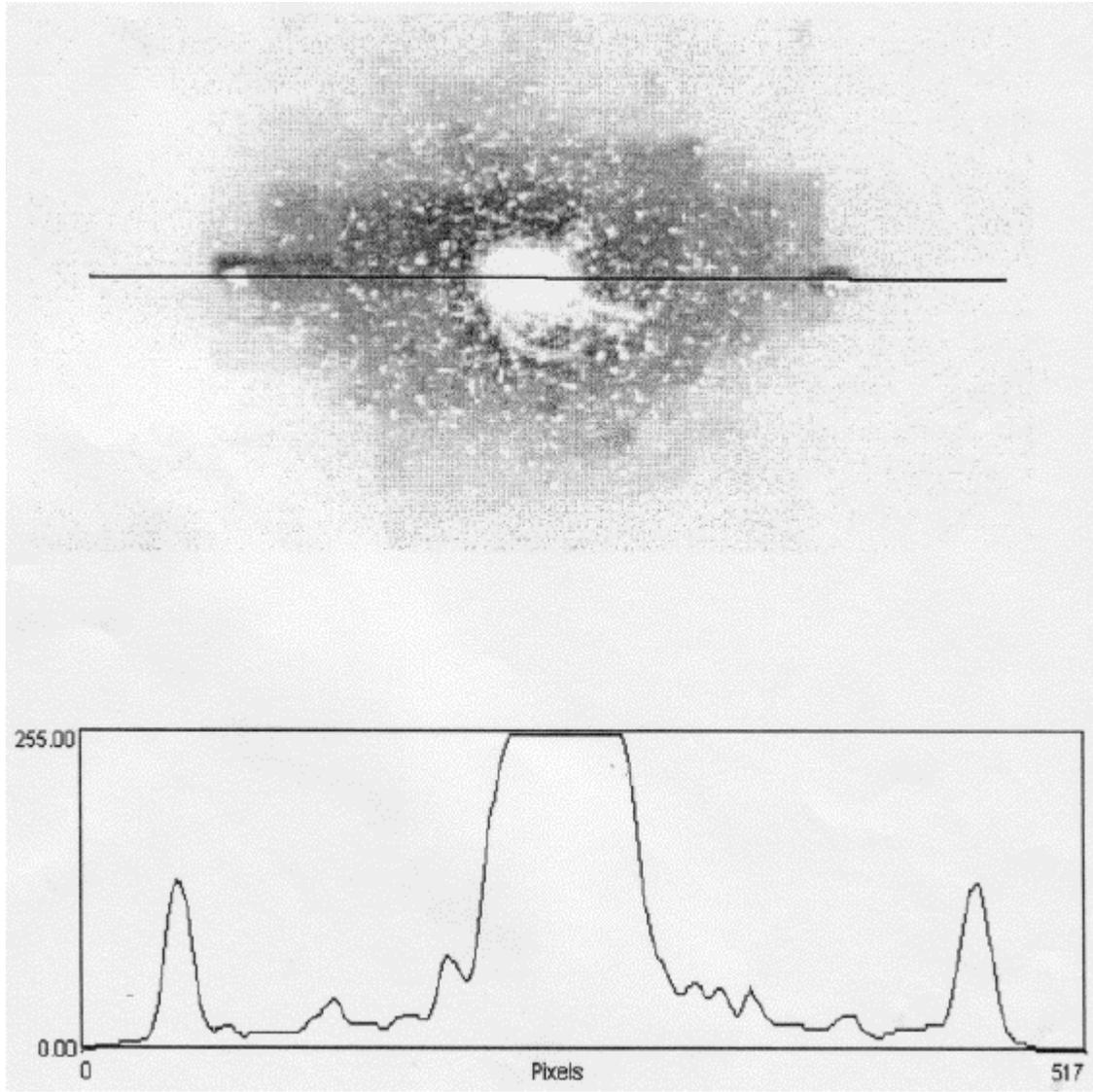
Figure 6 shows the autocorrelation and cross-correlation images from matching and mismatching fingerprints. The results show a vital difference between the auto and cross-correlation. Along the horizontal plane, two bright peaks appear for the autocorrelation image, which is the verification signal for the matching fingerprints. Figure 7 shows a 3D image of Fig. 6 generated by National Institute of Health (NIH) image processing software, and Fig. 8 is a cross-sectional analysis for the autocorrelation peak.



**Fig. 6 Autocorrelation image (above) and cross-correlation image (below).**



**Fig. 7. 3D graphs generated by NIH of the autocorrelation image (above) and the cross-correlation image (below). Image smoothing was performed before the 3D graphs were generated.**

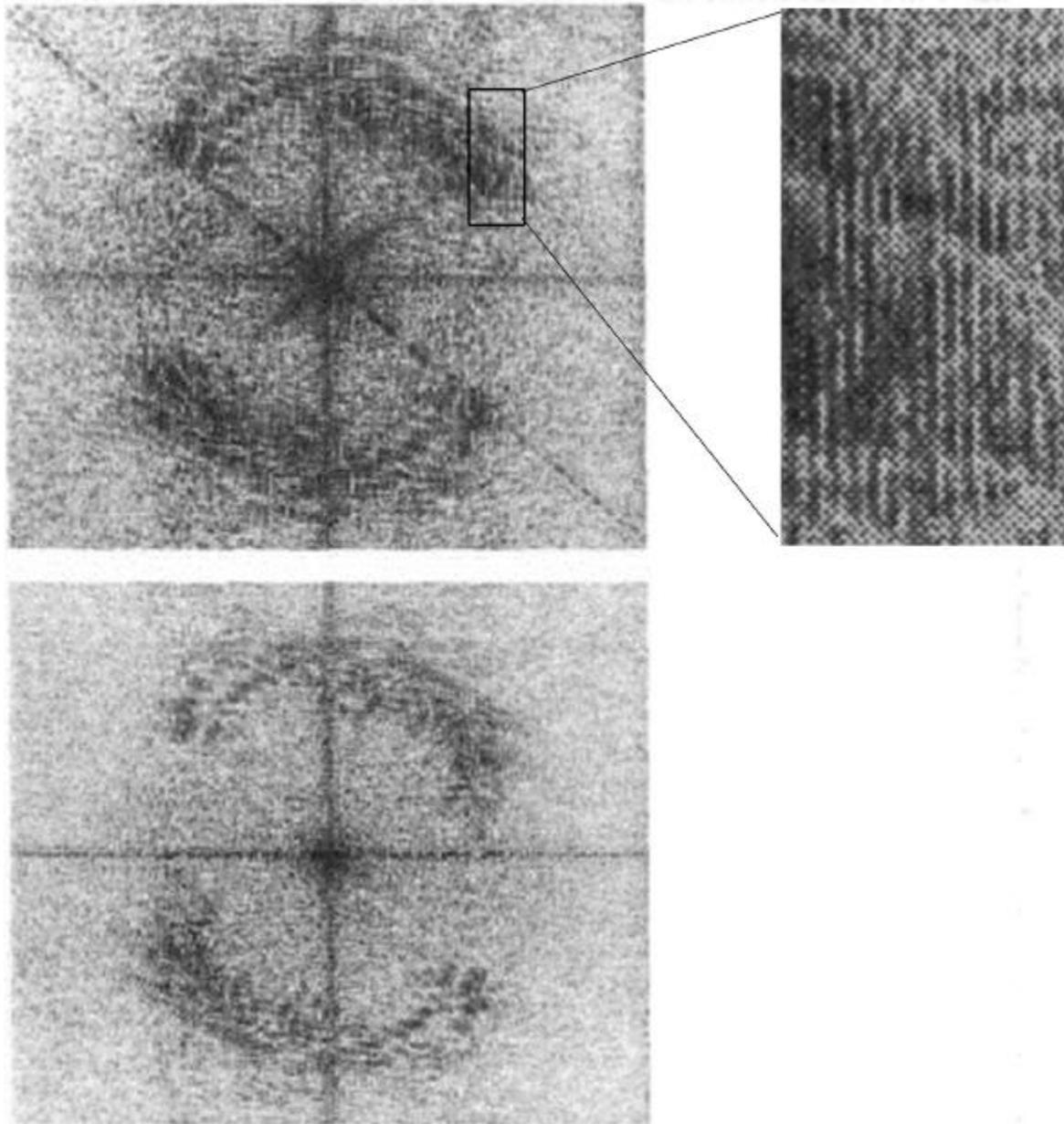


**Fig. 8. Cross-sectional analysis of the autocorrelation image. The top image is the autocorrelation image shown in Fig. 6 with the background subtracted by NIH.**

#### **4. Discussion**

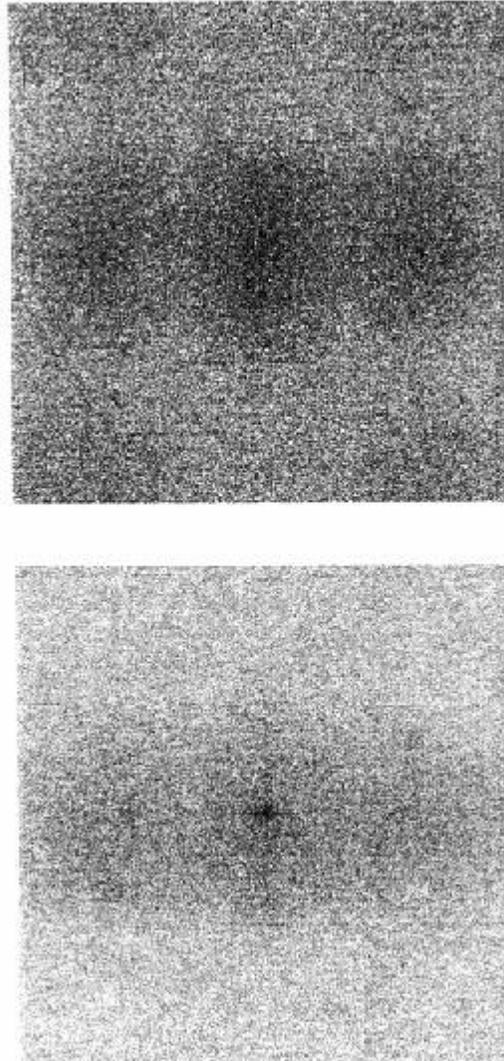
It is interesting to compare the experiment results with the results generated by computer. To accomplish that, the NIH was used to perform the Fourier transform and calculate the PSD. Figure 9 contains the computer calculated PSD images after the first Fourier transforms. As

predicted, the matching fingerprints generate significant cosine fringes in the horizontal direction, while the mismatched fingerprints do not generate such cosine fringes.



**Fig. 9. Computer calculated PSD of the matching (top) and mismatched (bottom) fingerprints. Note the uniform cosine fringes along the horizontal direction for the matching case.**

The calculated PSD from Fig. 9 is shown in Fig. 10. Again, the matching fingerprints produce autocorrelation peaks, while the cross-correlation one does not. Compared with the experimental results, the numerical results give a more confined 0-th order in the center.



**Fig. 10. Computer calculated PSD of the autocorrelation (top) and cross-correlation (bottom) images from the matching and mismatched fingerprints. Note the autocorrelation peaks for the matching case. No image smoothing was performed on the above images.**

## **5. Conclusion**

An optical joint transform correlator was successfully realized to conduct fingerprint identification. When the input fingerprints match with the reference, autocorrelation peaks were produced as a verification signal, while the cross-correlation from mismatched fingerprints did not produce the signature peaks.

## **6. Acknowledgement**

The author of this report would like to thank Miss Sandy Ng for her cooperation and constructive discussion during this experiment.

## **7. References**

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3. Keigo Iizuka, Notes for ECE1640 Advanced Topics in Photonics, 1999.