2002

A fingerprint capture device using a holographic optical element

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Recommended Citation

Supper, Natacha F., "A fingerprint capture device using a holographic optical element" (2002). *Master's Theses*. 2335.
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A FINGERPRINT CAPTURE DEVICE USING A HOLOGRAPHIC OPTICAL ELEMENT

A Thesis
Presented to
The Faculty of the Department of Physics
San Jose State University

In Partial Fulfillment
of the Requirement for the Degree
Master of Science

By
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August 2002

UMI Number: 1410435

ProQuest Information and Learning Company
300 North Zeeb Road
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Ann Arbor, MI 48106-1346

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ABSTRACT

A FINGERPRINT CAPTURE DEVICE USING A HOLOGRAPHIC OPTICAL ELEMENT

by Natacha F. Supper

A converging Holographic optical element in the form of a diffraction grating combined with a prism is used to sense a fingerprint. The fingerprint is extracted using the principle of total internal reflection. The resulting device gives a high resolution image, free of trapezoidal distortion in a compact and light casing .

ACKNOWLEDGEMENTS

I would like to greatly thank my thesis advisor Dr. R. D. Bahuguna for giving me the invaluable opportunity to work with him and learn from him; it was a great experience.

I am also very thankful for the help and encouragement I received from all the professors in the Pysics Department; especially to Dr. J. Becker and Dr. G. Williams for reviewing this thesis.

Finally I would like to thank the SJSU Physics Department technical staff Pat Joyce, Duyen Nguyen and Minh Mai who were always willing to help.

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CHAPTER 1

INTRODUCTION

The perfect security system which will use biological criteria to identify a person and prevent fraud of any kind is a priority for many agencies especially banks, the CIA, the FBI and immigration. This technology could also be very useful to welfare agencies to prevent multiple or fraudulent enrollments. Nature has given us several ways to perform biometrics comparison; among these are retinal or iris scanning, fingerprints, hand geometry, and voice spectrography. The large amount of information carried in a fingerprint as well as its accessibility is the reason why fingerprint identification is considered very accurate and is preferred over the other techniques.

Scientists all over the world have been trying to find a fast, reliable, and inexpensive answer to the fingerprint identification problem. The fast and constant evolution of computer technology has opened a new door in the form of automated fingerprint comparison, i.e., a computer driven fingerprint identification system. A fingerprint matching algorithm based on minutiae was quickly made available. The remaining problem was to design a scanner with a sensor extracting a very detailed, non-distorted, aberration free fingerprint.

Such sensors have already been designed using different techniques. In our laboratory, we have previously built a scanner using a holographic sensor, but the constant need for downsizing brought up new problems, and with it, a new solution: the converging hologram. The chapters of this thesis are the following:

In Chapter 2, an introduction to the principles of holography is presented; it also includes a brief description of the use of holographic optical elements. Chapter 3 is an analysis of existing designs, their respective problems, and limitations including a detailed discussion of the Optical and Ultra sound based systems. Chapter 4 covers the description of the set up used in the new design. In Chapter 5, the various known designs are compared.

CHAPTER 2

PRINCIPLES OF HOLOGRAPHY

Holography was first introduced in 1948 by D. Gabor[1], but its techniques only became popular a decade later with the introduction of the laser. Its numerous applications such as aberration removal, interferometry, data storage, and holographic optical element (to cite a few) made holography an important part of the science of optics. The following is a study of the recording analysis for plane and volume hologram (Bragg effect), and a description of the properties of holographic optical elements. The treatment that follows is from "Methods of experimental physics[2]" which the reader may refer to for further explanation.

2.1 Basic mathematical analysis of plane holograms

A hologram is considered plane or thin if the thickness of its recording material is negligible compared to the fringe spacing. A simple recording geometry is shown in figure 2.1. The object wave front and the reference wave front interfere on the holographic plate and create a complex fringe pattern. This constitutes the hologram.

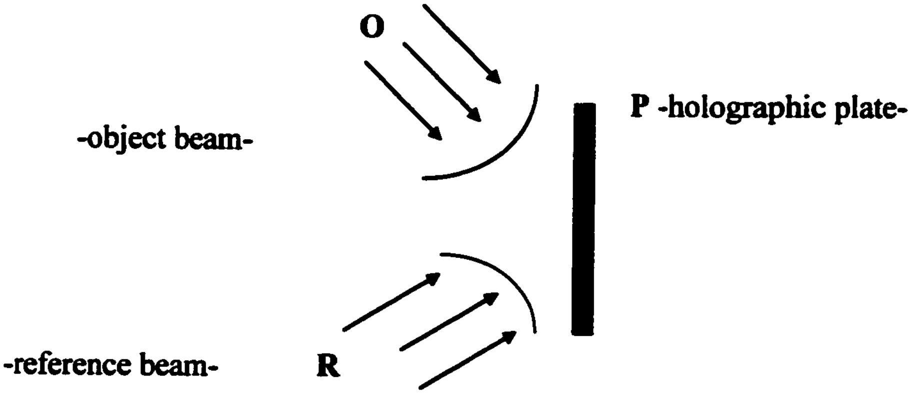

fig 2.1 Recording geometry example

The total field on the plate is: $A_{tot} = R + O$.

The irradiance I(x) is given by :

$$\begin{aligned} I(x) &= (A_{tot})^*(A_{tot}) \\ &= (R+O)^*(R+O) \\ &= |R|^2 + |O|^2 + RO^* + R^*O . \qquad (i) \end{aligned}$$

Working in the linear region of the "transmittance versus exposure" curve, the following expression can be used:

$$t_r(x) = t_r^0 + pE(x)$$

where $t_r(x)$ is the amplitude of the transmittance, E(x) is the exposure, t_r^0 is a constant, and p a parameter depending on the emulsion and the processing condition. The exposure time T and the irradiance I(x) are directly related by the expression:

$$I(x) = E(x)/T$$

Using this relation and equation (*i*), t_r can be written as:

$$t_r = t_r^0 + pT(|R^2| + |O^2| + RO^* + R^*O)$$

After the developing process, the hologram is illuminated by the reference beam O. The transmitted field $r(x)$ at the hologram plane is given by:

$$r(x) = R(x)\, t_r(x)$$

$$r(x) = Rt_r^0 + pT (R\,|O|^2 + R\,|R|^2 + O\,|R|^2 + O^*\, R^2)$$

For a uniform reference beam R, then $|R|^2$ can be considered as a constant which implies that the term $O\,|R|^2$ is just the object beam times a constant. The term $O^*\, R^2$ represents the conjugate of the object wave times R^2.

2.2 Geometric construction of the conjugate image

It is possible to draw the conjugate image of an object using the following techniques shown in figure 2.2:

- draw a line joining object point (O) and reference point (R)
- draw a perpendicular(RP) with respect to the plate
- measure the angle (RPO) = χ
- draw the line PO^C with the angle $(RPO^C) = \chi$

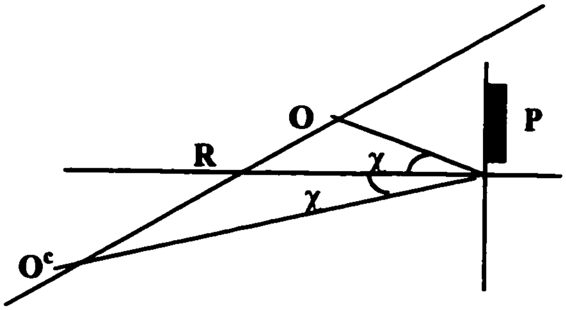

fig 2.2 Geometrical construction of a conjugate image

O^c is then the conjugate image.

The conjugate image can be either real or virtual. When the image is located in front of the hologram, it is real. The virtual image is behind the hologram.

When recording the hologram, depending on the set-up geometry, it is possible to create a pseudoscopic image that is inside out. For example, illuminating a hologram by a conjugate beam, i.e., a beam antiparallel to the original reference beam, a real pseudoscopic image is formed at the location of the object. The recording and reconstruction using normal and conjugate illumination of a hologram is illustrated in figure 2.3. It is possible however to correct this problem by using the pseudoscopic image as the object; this then creates an orthoscopic image (normal image).

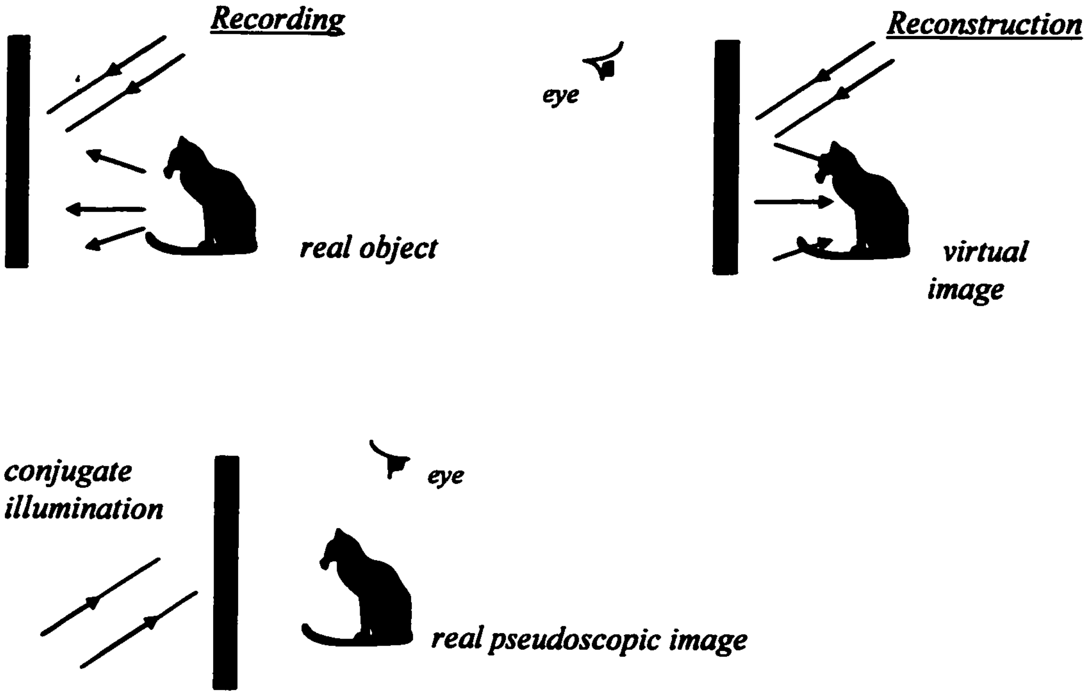

fig 2.3 Recording and reconstruction using normal and conjugate illumination.

2.3 Volume holograms and the Bragg effect

When the spacing of the interference fringes is small compared to the thickness of the holographic emulsion, the hologram is called a *volume hologram.* The interference pattern is now recorded throughout the emulsion as well as on its surface.

Volume holography can produce two types of holograms: reflection holograms which can be viewed using white light, and transmission holograms that are usually seen under laser light. The arrangement to form a volume transmission hologram is shown in figure 2.4, where R and O are respectively the reference and the object waves.

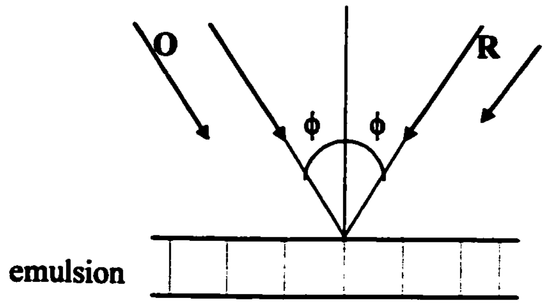

fig 2.4 Set-up to form a volume transmission hologram.

The fringe spacing is given by :

$$d = \lambda/(2 \sin \phi)$$

For a reference and object beam with an angle of 2 ϕ between them, they will produce a set of fringes perpendicular to the emulsion. When the holographic plate is illuminated at an angle θ during reconstruction, the object wave will be reconstructed if θ obeys the following relation:

$$\sin\theta \quad = \pm \lambda /2d$$

This relation is also called the Bragg condition. Depending on the value of θ, the illumination of the hologram will produce the following:

- for $\theta = \phi$, the illuminating beam is in the direction of the reference beam, the object wave is reconstructed and a virtual image is formed .
- for $\theta = -(\pi - \phi)$, the illuminating beam is in the opposite direction to the initial reference wave, a real pseudoscopic image is reconstructed and no virtual image.
- for $\theta = -\phi$, the illuminating beam is in the direction of to the object beam,

but the Bragg condition is not satisfied for all the waves coming from the object, hence the reconstructed image has aberrations.

- for $\theta = (\pi - \phi)$, the illuminating beam is in opposite direction to the object beam, the reconstructed image is virtual, partial, imperfect and with aberration for the same previous reason.

2.4 Holographic emulsion and processing*

The selection of proper holographic emulsion is very important before attempting to make a hologram. Transmission holograms with a small angle between the reference and the object waves do not require a resolution of more than 2000 lines/mm and hence Agfa 10E75 (red sensitive) is quite adequate*. For transmission holograms with a large angle ($> 30^0$) and volume holograms which need a higher resolution, 8E75 emulsion with a resolution over 3000 lines/mm is commonly used. For green laser, the corresponding plates are 10E56 and 8E56 respectively.

Depending on what types of plates are used, different processing techniques involving different chemicals can achieve the goal of making a hologram. During the development of our research, we used the exposure time given by :

$$\text{exposure time} = 200/\text{power output}$$

The power output was read using a Laser power meter (Newport model 820). The processing itself consisted of three steps: developing, bleaching and drying.

---

* The detail of the chemicals and holographic plates used in this section are given in the Appendix.

During our experimentation, we used the following method and chemicals.

1. develop for 3 minutes using CW-C2 Catechol developer.
2. rinse the plate for 10 seconds with "tap" water.
3. place in stop bath for 20 seconds.
4. rinse for 10 seconds.
5. put in Potassium Dichromate bleach until it clears out (if properly exposed, the plate should clear in approximately 30 seconds).
6. rinse for 5 minutes in running water.
7. put in Kodak photoflo for 30 seconds.
8. dry it vertically .

The following is the description of the chemical used during processing:

(a) Developer

There are several formulas of developer available on the market for holographic processing. For our needs, the CW-C2 seems to give the best diffraction efficiency. We make it in our laboratory using the following formula :

<u>Part A</u>

- Catechol	10 g
- Sodium Sulfite	5 g
- L-Ascorbic Acid	5 g
- Urea	50 g
- D.I Water	500ml

Part B

- Sodium Carbonate	30 g
- D.I Water	500ml

Mix part A and B, on a one to one ratio.

(b) Stop bath

The concentrated stop bath can be purchased from Kodak. It has to be diluted with distilled water; (Stop bath is basically 2 $^{0}/_{0}$ of acetic acid).

(c) Bleach

There are various types of bleaches. They are usually associated with a specific developer to give the optimum result. We used the Potassium dichromate bleach, its formula is given below:

- Potassium Dichromate	4.0g
- Concentrated sulfuric acid	4.0 ml
-Water (filtered)	1.0 L

This combination has been successfully tested and yields reasonably bright holograms.

2.5 Holographic optical element (H.O.E)

It is possible to use holography to replace optical elements like lenses, mirror or even prisms. By carefully choosing the reference and the object beam, it is possible to record almost any optical element on a holographic plate.

When recording a hologram with a specific object and reference beam, interference between the two wave fronts creates a specific pattern of fringes onto the holographic emulsion. The fringe planes bissect the angle between the reference and object beam. When illuminating a hologram with the same reference beam as the one used during recording, the object beam will be reconstructed; this is shown in figure 2.5.


recording:

reconstruction:

fig 2.5 Fringe geometry in recording and reconstruction of a hologram

When using an anti-parallel reference beam, the object beam will be reconstructed in the opposite direction (figure 2.6):

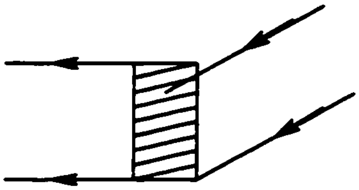

fig 2.6 Reconstruction using an anti parallel beam

In the following figures (figure 2.7 and 2.8 respectively), the geometry of the recording and reconstruction of a holographic lens, which follows the preceding rules is shown.

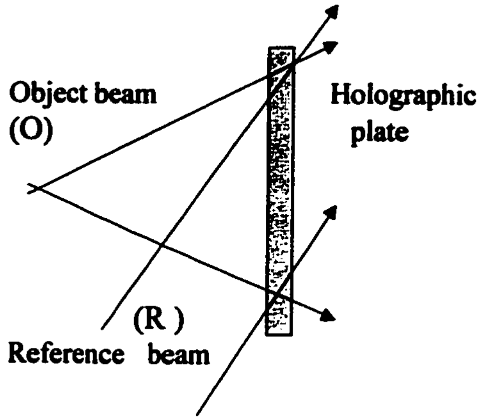

fig 2.7 Recording geometry of a holographic lens

The point source is created by expanding a laser beam, with a microscope objective. The reference beam here is a collimated beam. The geometry of this recording set-up will be discussed in more detail in chapter 4.

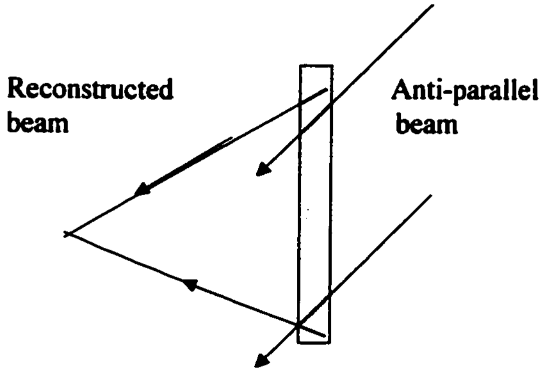

fig 2.8 Reconstruction geometry of a holographic lens

To reconstruct the hologram, it is necessary to use the same reference beam as in the recording. By doing so, the previous object beam is automatically reconstructed.

It is possible to analyze an H.O.E with regular ray tracing technique. W.C. Sweat[3] has shown that a holographic lens can be considered as a regular lens with an infinite refractive index. The use of holographic optical element is commonly used to correct aberrations which has been shown by Upatniek et al.[4]. However, a restriction applies: the light efficiency of a hologram is generally low.

CHAPTER 3

EXISTING DESIGNS OF FINGERPRINT SENSOR

The need for real time fingerprint identification created a need for a real time fingerprint sensor which would capture a high contrast, distortion free image. Fingerprint sensors have been on the market for approximately a hundred years; they can be classified in two major classes: the optical, and non-optical based sensors. In this chapter, some of the various known designs will be discussed.

3.1 Optical based designs

Most fingerprint scanners are based on the principle of total internal reflection. Using two materials with different refractive indices, it is possible to determine the critical angle at which the light will completely reflect from the interface surface as illustrated in fig 3.1 Using basics geometrical optical properties, we know from the law of refraction that:

$$n_1 \sin\theta c = n_2 \sin\theta_2$$

And with $n2<n1$, using $\theta_2=90^0$ we get $\sin\theta_c= n_2/n_1$

Then: $\theta_c = \sin^{-1}(n_2/n_1)$

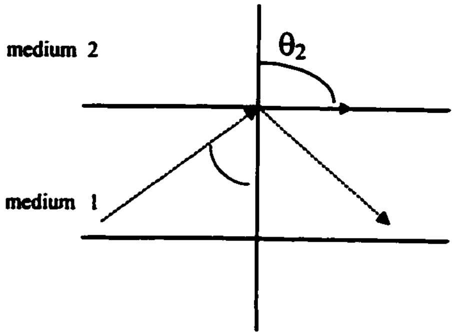

fig 3.1 Illustration of the critical angle calculation

If a finger is placed on top of a prism, because of the change in refractive index, the condition for total internal reflection will no longer be met at the ridges. The light at the ridges will be absorbed while the light at the valley will be reflected. This is how the Ridges, and the valleys of the finger, pressed on a glass surface, can be imaged. The most common geometry for a scanner is showed in figure 3.2.

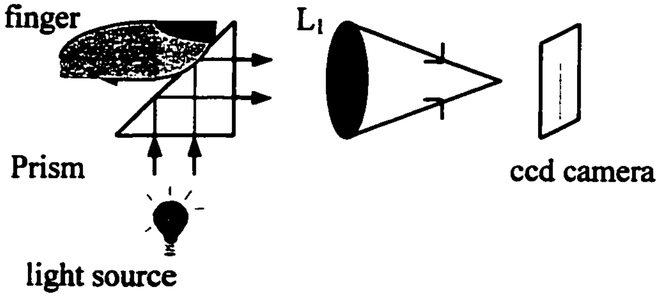

fig 3.2 Most common fingerprint scanner geometry

The set up consists of a glass prism, illuminated by a light source to capture the fingerprint image. The image is then focused onto a CCD camera with a lens (commonly used focal length is f ~ 12 to 25 cm). It is also very common, but not necessary, to use a mirror to fold the beam in a convenient way, to possibly reduce the size of the system.

When using a real time fingerprint sensor, the extracted fingerprint needs to be aberration and distortion free, and also clear of noise or "smudge " left by latent fingerprint. The above set up introduces trapezoidal distortion created by the unequal path length between different points of the fingerprint and its image. this problem can be corrected using additional optics or software which usually require additional space.

There are several variation of this design which do not suffer from these problems. We The use of holograms in the design of those sensors will be studied using in line gratings or edge lit holograms.

(*i*) "in line "grating:

A Japanese team from Fujitsu Laboratories, S.Igaki, S. Eguchi, F. Yamagishi, H. Ikeda and T. Inagaki[5] developed a holographic sensor which consists of a flat glass plate and a plain grating hologram.

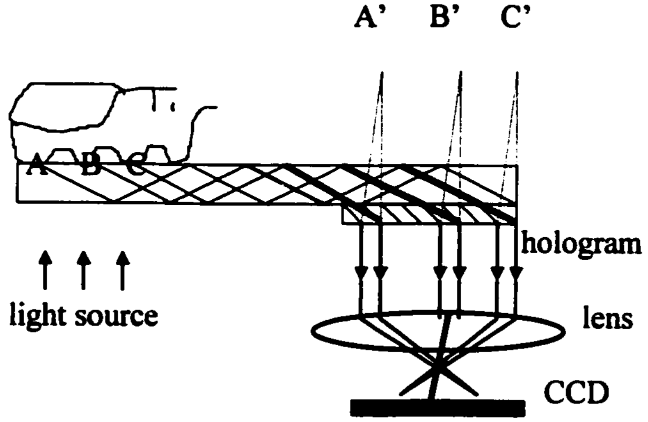

Fig 3.3 "In line"grating fingerprint sensor

This technology uses the principle of total internal reflection. The light entering the flat glass plate hits the ridges and the valley of the finger. At the ridges, the light is scattered in all direction. All rays with an angle above critical angle are reflected repeatedly, throughout the plate due to total internal reflection and are then imaged after passing through the hologram. At the valley, the light is also scattered, but no light reenters the glass at steep angle; so on the fingerprint image, the valleys will be dark figure 3.4

fig 3.4 Fingerprint image through the in line grating sensor

The use of a flat glass plate makes the optical path from any point of the fingerprint to the hologram equal. The trapezoidal distortion is eliminated

One of the major disadvantages of this design is the creation of an image with astigmatism. The light scattered from the ridges of the finger, then goes through the holographic grating and does not focus to a sharp point as illustrated in figure 3.4.

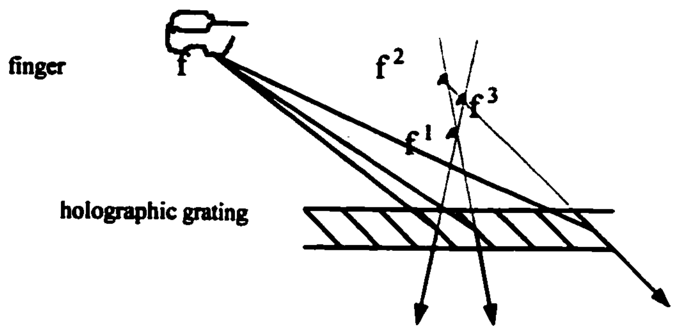

fig 3.5 Representation of astigmatism

In this design the scattered light has a diverging wavefront and produces a blurred focus: instead of having one single point reconstructed through the hologram, we have f^1, f^2 and f^3. Although it is possible to correct this aberration using several optical elements, it creates a major drawback for industrial applications because of the large size of the system. As the technology in holography keeps improving, new imaging techniques using holographic optical element will appear in the market.

(ii) Edge lit hologram:

Using holography concepts, M. Metz, C. Flatow, and a team from De Montfort University[6] developed a technique which allows a high resolution compact and inexpensive fingerprint capturing unit. The edge lit hologram is typically a structure formed in a holographic recording material with fringes at nearly 45^0. The recording geometry is shown below:

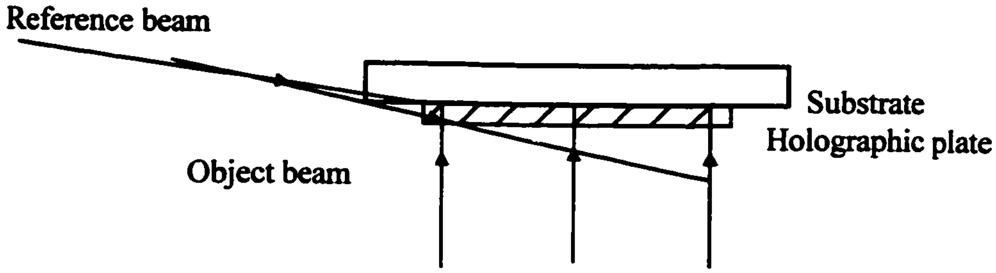

fig 3.6 Edge lit hologram recording geometry

The recording of such a hologram is made possible using a reference beam almost parallel to the holographic plate, and an object beam perpendicular to the plate. The hologram is then illuminated with the original reference beam, to create a replica of the object beam:

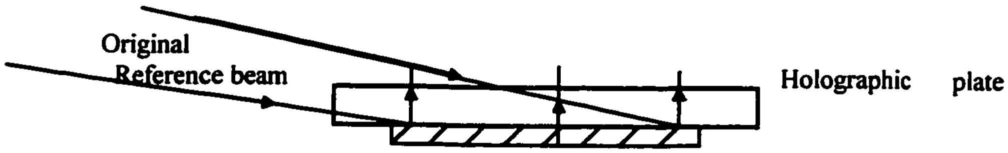

fig 3.7 Reconstruction of an edge lit hologram

This hologram is used in a fingerprint imaging device the following way:

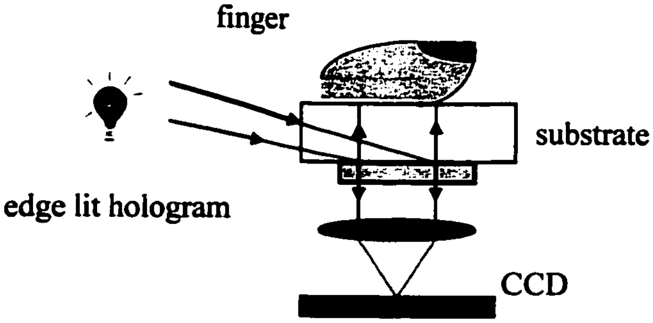

fig 3.8 Fingerprint imaging device using an edge lit hologram

The reference beam entering the substrate is reflected back towards the finger due to the fringes geometry of the hologram. The fingerprint is captured by the beam and is reflected back toward a focusing lens and a ccd camera. This set up creates a very detailed image with visible pores. Since the hologram was recorded with a 514nm Argon laser, the light source to illuminate the hologram can either be monochromatic or white light with a filter, Metz also got rid of the objective lens which allows the creation of a very compact fingerprint device as shown in the *figure 3.9*:

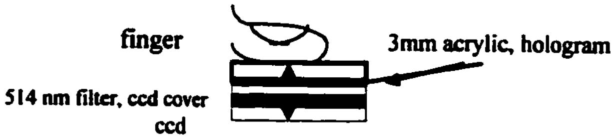

fig 3.9 Compact fingerprint design using an edge lit hologram

There are two problems associated with Metz fingerprint scanning device: the edge illumination is very hard to achieve; the image is not sharp. To be able to perfectly recreate the object beam the angle of the reference beam has to be identical to the one used during recording. Since the light is entering through the edge of the plate the recording geometry would be hard to reproduce and allows only minimum displacement margin. And, when the finger is projected on the ccd, and not imaged, the quality of the image will be poorer due to diffraction effects.

3.2 Ultra-sound based design

Optical based fingerprint scanning system are well known, but are not the only technology allowing real time fingerprint imagery. J.K Shneider describes a method[7] of imaging ridges and valley structure using ultra-sound.

The principles of ultrasound fingerprint imaging are comparable to thus of some optical systems. Ultrasonic images are obtained by reflection and transmission of ultrasound waves as they go through different media. Their respective coefficients depend on a specific property of the medium, the acoustic impedance Z defined by: $Z = \rho C$ where ρ is the density and C the acoustic phase velocity. For an optical system, this can be compared to the refractive index n. The intensity variation due to the acoustic impedance difference ΔZ, between two media (air/finger) makes it possible to pick up a gray scale image of the finger.

Like in any other system, the contrast of the image is important. To optimize it, it is needed to have a maximum reflectivity at the valley and a minimum reflectivity at the ridges. The coefficient of reflectivity depends on the acoustic impedance of the two different media:

$$R = (Z2-Z1) / (Z2+Z1)$$

Using this formula it is then needed to find the material that would satisfy both conditions. The medium was found out to be polystyrene, and the reflection coefficient for ridges and valley were respectively: $Rr = 23.2\%$ and $Rv = 99.97\%$ which enables a good contrast.

The advantage of this system resides on its non dependence on the finger texture, an oily finger will be imaged as well as a very dry finger, which is not always the case in optical scanners. The drawback comes from the amount of time needed to capture the fingerprint, which is mainly due to the fact that the speed of sound is much smaller than the speed of light. Also, this scanner unit is a lot larger than a "regular optical system".

CHAPTER 4

CONVERGING HOLOGRAPHIC SENSOR

A holographic fingerprint sensor in the form of a diffraction grating was developed by R.D Bahuguna[8] and T.Corboline. Based on total internal reflection, the sensor is free of trapezoidal distortion and gives a high detailed image with visible pores.

A fingerprint scanner was build using this sensor, which gave very good result for real time fingerprint capture. The only limiting aspect of this system was its size. The geometry of the sensor would not allow shorter distances between any of the optical elements as shown in figure 4.1 where the distance between the imaging lens and the ccd camera is dictated by the focal length of the lens.

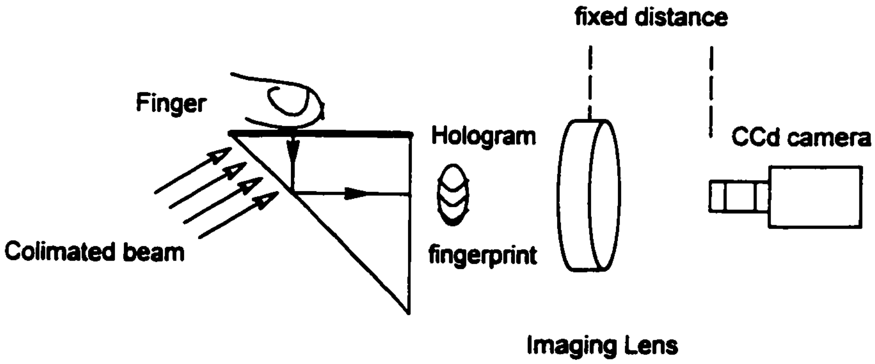

fig 4.1 optical set-up of holographic optical sensor

The constant need for smaller and lighter equipment for the industry made us research the different possibilities to reduce the size of the fingerprint scanner.

A new sensor was developed using a holographic optical element (H.O.E), which enabled us to construct a small size fingerprint scanner. The following will describe the recording geometry needed to record the hologram as well as the problems encountered and solved while building the scanning unit.

4.1 The converging hologram

In the design illustrated in figure 4.1, the size can be reduced, by using a short focal length lens, thereby reducing the object distance. However since the rays reaching the lens are parallel and since the lens has a small diameter, mostly the central rays get through the lens creating a bright center in the fingerprint image, in other words a hot spot. By incorporating a holographic lens within the previous sensor, all the rays from the fingerprint can be made to converge on the camera lens thus eliminating the hot spot. The following will describe how we successfully recorded the modified holographic fingerprint sensor.

(i) Recording geometry

In Chapter 2, the basic recording theory of a holographic lens was discussed, using a point source as an object, and a collimated beam as a reference. The ideal reconstruction for such a lens is shown in figure 4.2, where the distance between the focused point and the holographic lens is chosen at the recording.

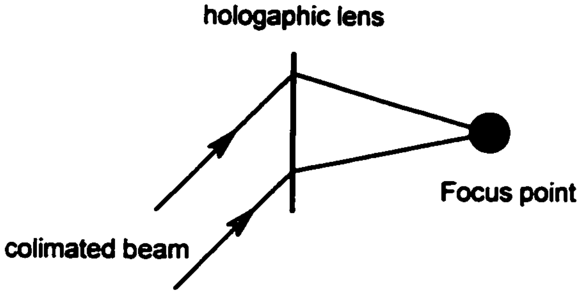

fig 4.2 Basic reconstruction of an holographic lens

One of the difficult issue to be solved is to determine how to record such a hologram where the focusing distance is to be very small to allow the construction of a very compact scanning unit. The other issue is to maintain the good image quality despite the reduction in size.

This is achieved by placing the holographic plate on a custom prism and using a surrounding recording set up in accordance with the desired reconstruction geometry. The recording set up geometry is shown in figure 4.3.

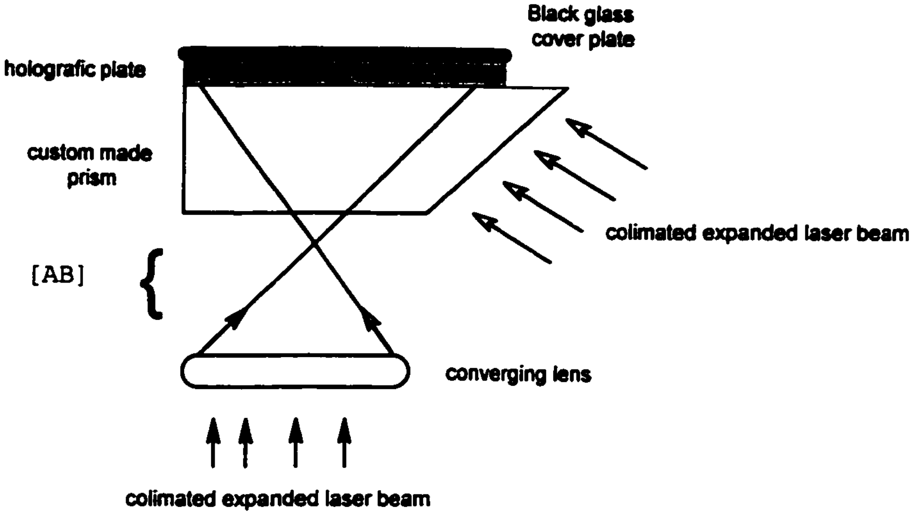

fig 4. 3 Recording geometry of the converging hologram

(ii) Making the hologram.

Once the recording geometry was set, one of the remaining problem was to adjust the distance [AB] (see fig 4.3) between the focusing lens and the custom prism, to optimize the size of the image. Our goal was to get a full size fingerprint imaged on the monitor. To achieve this goal, different available lens were tried. The hologram was made following the exposure time and development steps discussed previously; the recording geometry was achieved using the following optical set up:

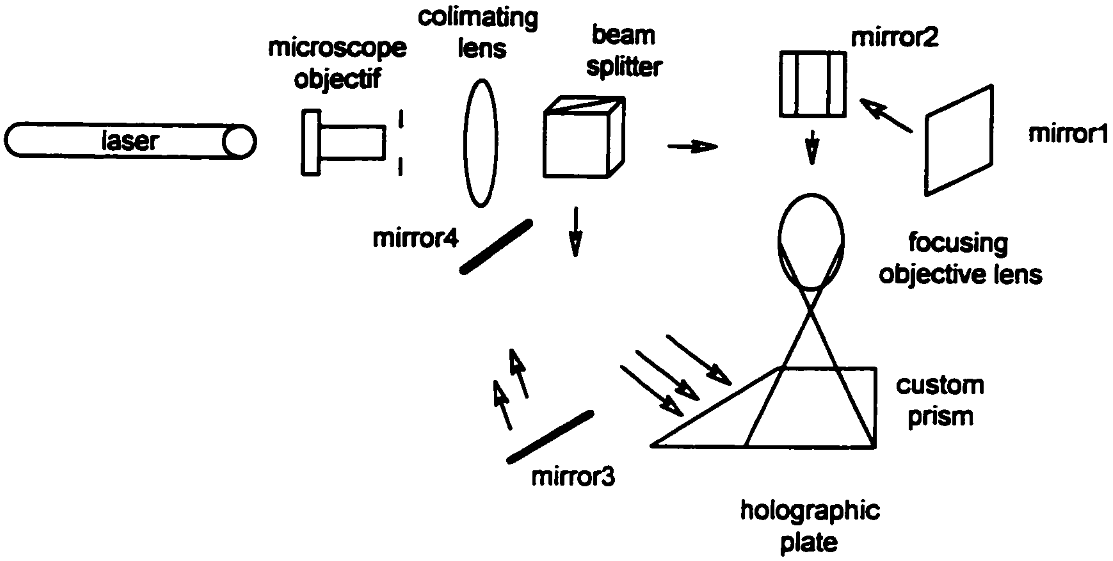

fig 4.4 Optical set-up used for the recording of the converging hologram

Using this set up, several trial holograms were made to finalize all the recording parameters, *i.e.*, illumination intensity, focusing distance, and beam ratio to get the best contrast and image quality possible. The final concern was the image quality. By flipping the holographic plate and positioning the emulsion directly onto the custom prism, separated only by a thin layer of isopropyl alcohol, a major improvement was observed in the image definition.

4.2 Building the scanner.

Once a good quality hologram was successfully made, the sensor unit needed to be build around it. The priority was to minimize the final size of the unit.

The main difficulty was the hologram illumination; since the recording was done using a collimated beam, in order to obtain a good reconstruction, a collimated beam was needed *(refer to Chapter 2).* Using a collimated light source was possible, but the size of the unit was increased by a factor of three. The solution was found using a 'jumbo' size red light emitting diode combined with a circular Fresnel lens. The idea was to form a collimated beam by placing a diverging point source at the focal point of a converging lens as shown in figure 4.5.

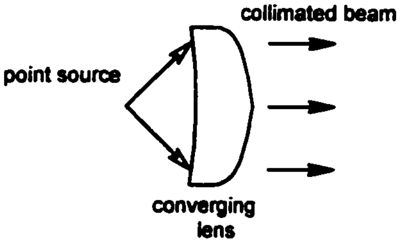

fig 4.5 Collimation using a converging lens

The optical properties of the Fresnel lens were the following: focal length: 1.3 inches and 125 lines per inches, which enabled us to place the LED very close to the custom prism surface. The LED was powered using the CCD camera transformer combined with a current limiting resistor shown in figure 4.6.

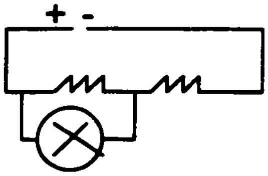

fig 4.6 Resistor circuit for the light source power supply

Using for the resistors respectively 82 and 220 ohms for the first and second one.

The results were very satisfactory, the illumination of the hologram was uniform and a very good quality fingerprint image was collected.

The mounts and holder for each components were designed to use as little space as possible as well as to allow some mobility for adjustments.

The final result was the following unit:

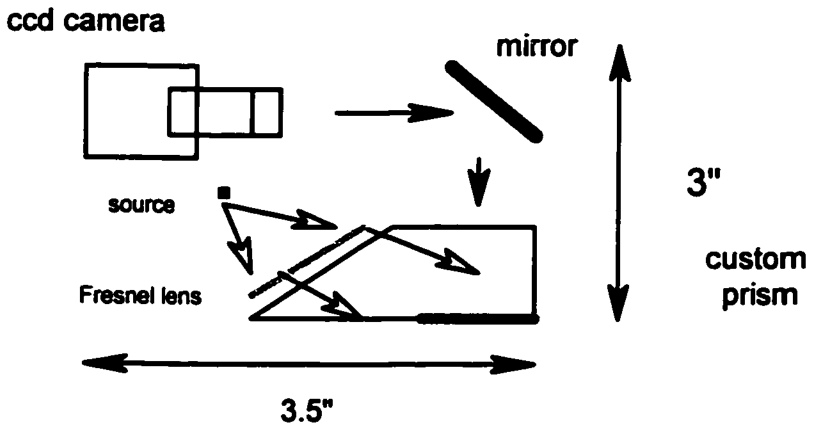

fig 4.7 Optical set up of the final scanner unit

Using a ccd camera, allows direct connection to a computer, a sample of a fingerprint capture using a frame grabber is shown in figure 4.8 :

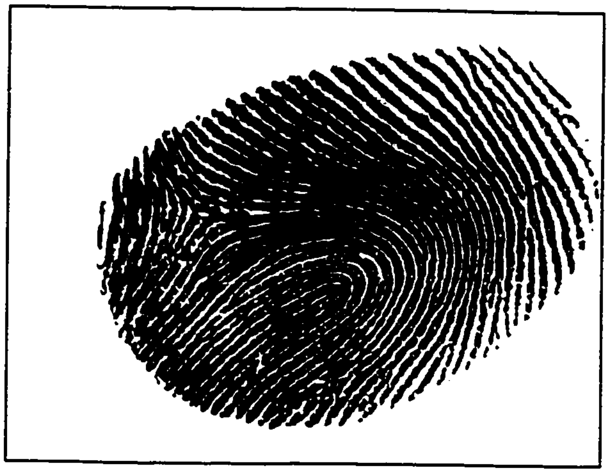

fig 4.8 Fingerprint capture using the final scanner unit

Once competed the unit was demonstrated at several security conference throughout the united states and presented at the "Biometrics consortium meeting 1996 " held in San Jose where it was very well received, shown below is the final unit:

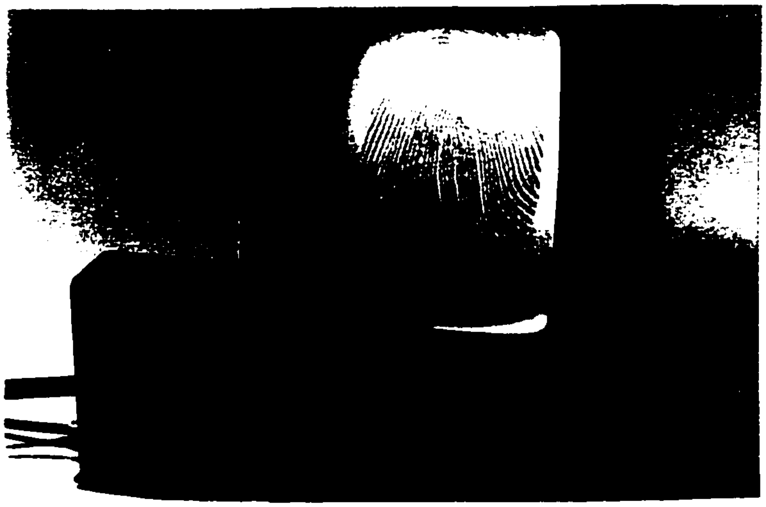

fig 4.9. Final scanner unit

CHAPTER 5

CONCLUSION

A very compact fingerprint scanner using a holographic optical element has been developed, permitting the scanning of a very high quality fingerprint image with visible pores free of trapezoidal distortion. The size of the unit as well as its cost could make it a very appealing product for the security industry or the computer industry, which could use it as an "add in" to replace the common login password if associated with a good identification software.

Nowadays, taking someone's fingerprint is no longer restricted to criminal or government agency employees all new drivers must now go through the excitement of being fingerprinted, which has greatly expanded the fingerprint business and opens new door for the commercialization of this scanner. On this unit the finger/scanner interface is glass which permits easy cleaning and good contrast for most fingers, one of the possible improvement would be to use a surface which would allow a very good contrast on very dry finger without scratching or deteriorating with time.

APPENDIX

Parts list:

Section 2.4:

- Holographic plates: Agfa 10E75, 8E75, model has been discontinued; it is possible to use Kodak TI0332, Eastman Kodak Company, Rochester, NY.
- Processing chemicals: CW-C2 Catechol developer, Stop Bath, Photoflo, Eastman Kodak Company, Rochester, NY.

Chapter 4:

Scanner Unit:

- Custom prism: BK-7 glass, 2.75" L x 1.5"W x 1.37"H, Reynard Corp., San Clemente, CA.
- Jumbo LED : 650nm, 5000mcd, Radioshack, San Jose, CA
- Ccd camera:1/3" Ccd array, 640 x 480 pixels, EM200-CS, CBC (America) Corp., Torrance, CA.
- Objective lens: CS ½" Computar,12mm focal, CBC 9America) Corp., Torrance, CA.
- Mirror: 30mm x30mm x1.5mm, FS mirror, Edmund Scientific Corp., Barrington, NJ.
- Fresnel lens: 1.5" x 1.5", 1.05" focal , Edmund Scientific Corp., Barrington, NJ.
- Prism Cover: Saphire coated, 2.75"L x 1.5"W x 0.01mm thick, Reynard Corp., San Clemente, CA.

Recording apparatus:

- He-Ne laser: 20mW, 632.8nm wavelength, Spectra physics, San Jose, CA
- Shutter: Newport Research Corp., Irvine, CA.

- Spatial filter: 20x microscope objective, 15um pinhole, Newport Research Corp., Irvine, CA.
- Collimating lens: Achromatic doublet, 5cm diameter, 10cm focal, Newport Research Corp., Irvine, CA.
- Focusing lens: 46mm filter diameter, 3 -3/8" x 4 -5/8" , Minolta Corp., Ramsey,NJ.
- Beam splitter: Broadband non-polarizing cube beam splitter, 50.8mm, Newport Research Corp., Irvine, CA.
- Mirror1, 2, 3, 4: 30mm x 30mm x 1.5mm, FS mirror, Edmund Scientific Corp., Barrington, .NJ

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