VISION SKIN: AN INTEGRATED PROXIMITY AND IMAGING SENSOR

by

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"Vision Skin: An Integrated Proximity and Imaging Sensor"

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Abstract

An integrated proximity and imaging sensor called “Vision Skin” has been fabricated and its operation is characterized in this thesis. Vision Skin is aimed at the close range (0-20 mm) robotic applications where a high accuracy proximity measurement and a low resolution image of an object approaching a robotic gripper arm is desired. The uniqueness of Vision Skin is its lensless operation. Unlike a standard non-integrated proximity and imaging sensor, it uses an array of small, closely spaced, high aspect ratio holes called a ‘Shadow-mask’ instead of a lens. The shadow mask is placed over a photodetector array such as a modified charge-coupled device (CCD). Vision Skin uses the principle of laser triangulation by employing a laser diode for proximity measurements, and a group of light emitting diodes (LEDs) for wide area object illumination for imaging applications. Three different techniques are investigated for shadow mask production - laser micromachining with polypropylene, photolithography for multi-layer thin film mask, and laser-LIGA with a photosensitive polymer. The integrated Vision Skin discussed in this thesis uses a 500μm thick laser micromachined polypropylene shadow mask with an array of 30μm holes, hence producing an aspect ratio (height/width) of 16.7 for these holes. The holes are spaced at 150μm and have an acceptance angle of only 3.4° to restrict the cone of light seen by the detector sitting underneath. The restricted light acceptance makes the location of laser spot easy and accurate to find for proximity applications. Also, it enables Vision Skin to image objects without the use of a lens. Without a lens, Vision Skin has the advantage of being small in size, and free of depth of focus and refocusing problems. Experiments show that Vision Skin has the ability to identify simple real-life objects for distances up to 10mm, and measure the proximity with errors of only ±75μm in the best case for distances up to 20mm, i.e. proximity errors of less than 1% are attained. Calibration techniques and several proximity extraction algorithms were investigated to minimize the errors for the sensor.
Dedication

To Waheguru (Almighty)
Acknowledgments

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Chapter 1

Introduction

The development of intelligent robots is enhanced by research on new sensors. Sensors play a similar role for a robot as the five senses of touch, sight, smell, sound and taste play for a human being. Sensors provide the robot with an information about the surroundings and act as a guide for its interaction with the external environment. The most studied types of sensors are vision, proximity and tactile. Proximity sensors make preliminary observation of the surroundings by detecting and sensing the presence of objects without actually touching them. These sensors give a robot a sense of the distance, shape, size and orientation of an approaching object. The challenge is to come up with an accurate proximity sensor performing its tasks in all kind of situations and surroundings, which is lacked by robotic industry at present. This thesis will focus on the creation and testing of a new kind of proximity sensor which does both proximity and imaging.
1.1 Motivation

Proximity sensing can be defined as the sensing or detecting the presence or closeness of a desired object without making a physical contact with it. With a little ingenuity, proximity sensors can provide a wealth of information to the control system [1].

A good proximity sensor provides as much information about the object and the surroundings as possible. In robotics, properties like the distance, location, size, orientation, weight distribution and surface shape, along with other parameters like temperature, color, thermal characteristics, compliance, coefficient of friction of object surface, electrical conductivity, resilience, and the force acting between the gripper and the object are needed to completely describe the object. Proximity sensor gives information on the object’s distance, size, orientation and surface shape.

Generally, the number of ways in which a proximity sensor can be used is endless. It can be used in obstacle avoidance [2-5], tactile sensing [6], space applications [7], robot control [8], nuclear reactor [9], biomedical fields [10], plasma cutting device for the edge shaping process [11], traffic control [12], precision autowork [13], scanning tunnelling microscopy (STM) [14], plasma arc cutting of contaminated waste [15], electronic control of drop distances from bulk produce conveyors [16], and bakery [17]. If a sensor also gives a low resolution range map of an object, it can be used in high resolution stereo method for 3D data acquisition in computer vision [18-21]. It can also be used for manufacturing applications [22], textured surface shape analysis [23], and underwater surface mapping and imaging [24].

Numerous proximity sensors types are available in the market today [25, 29]. They all have their own advantages and disadvantages. Desirable characteristics for a proximity sensor include: small size (good size/range ratio) and compactness; light weight, robustness and ruggedness; contamination free; simplicity of associated electronics and high speed; low sensitivity to environmental disturbances; long life and reliability; cost effectiveness.
The motivation of this research is to come up with a sensor which can generate distance measurements at several points on the object’s surface in the close range (0-20mm) and produces its low resolution image. The following section presents an overview of various types of the existing proximity sensors, followed by the technique used in this thesis.

1.2 Background

1.2.1 Various types of proximity sensors

Robots need a wide range of sensor types to obtain information. Sensors provide feedback to the robot containing information about robot’s action (internal sensors) or about its environment (external sensors). Robotic systems use four classes of internal sensors to report position, velocity, force, and acceleration of robot’s joints. Position sensors are the most common and are often used as a part of the feedback loop in a servo system. External sensors are primarily used to learn more about the robot’s environment, especially the object being manipulated. There are two kinds of external sensors - contact sensors which require physical contact with the object, and non-contact sensors which require no physical contact. Contact sensors may be further subdivided into tactile sensors and force-torque sensors. The following chart in Figure 1-1 shows the classification of robotic sensors discussed so far. Proximity sensors are non-contact sensors and their various types will be discussed shortly.

---

**Figure 1-1: Classification chart for robotic sensors**

---
The non-contact (proximity) sensors can be divided into three main categories, depending upon their mode of operation, viz mechanical, electromechanical and electromagnetic [25]. While the greatest number of noncontact sensors are members of the electromagnetic category, sensors from all the groups can be used in various robotic applications. The following chart shows the classification of various noncontact (proximity) sensors.

Figure 1-2: Classification chart for noncontact proximity sensors [25]
The operation of various sensor types along with their capabilities and limitations is presented below.

1.2.1.1 Mechanical Proximity Sensors

Classification chart in Figure 1.2 shows two types of noncontact proximity sensors which are mechanical in nature - pneumatic and ultrasonic. A brief description of these types is presented here.

(A) Pneumatic proximity sensor

This sensor has been in use for many years. It is known as the air gauge which is based upon a phenomenon that occurs when pressurized air escapes through a fixed orifice or nozzle (Bernoulli’s principle). When an object is brought into the airstream from the orifice, the free flow of escaping air is retarded and an additional back pressure (pressure change) is developed upstream from the orifice. Changes in this pressure can be related to the changes in the spacing between the orifice and the object [25].

The dynamic range of such kind of sensor is of the order of 1mm or less. If a greater range is desired, the size of the device grows significantly and also additional air flow is required. For these reasons, this approach would not be generally useful for robotic applications where accurate sensing up to larger distances is required and the size of the device is critical. The response time of these devices is generally slow.

(B) Ultrasonic proximity sensor

Several different types of ultrasonic sensors are in use in robotic industry [25-28]. Ultrasonic sensors use high frequency sound waves (about 175 kHz) to detect the presence or absence of a target. Taking into account the speed of sound in the conducting medium, range may be determined by measuring the time which elapses between transmission and subsequent return of the reflected signal. Ultrasonic sensors can detect all types of targets regardless of material, color, or transparency (except sound absorbing materials).
Ultrasonic sensors are excellent for sensing of large objects in the range of 200-250 mm and underwater applications, but their high price over inductive sensors makes them an unrealistic option in some applications [29]. Other disadvantages include slow response time due to the speed of the sound, spurious range readings due to specular reflections and ultrasonic interference noise, the need of a medium for propagation of sound waves [30] and large sensor size. Ferroelectric polymer technology produces an ultrasonic sensor with a very (compact) high size-range ratio by employing polyvinylidenefluoride (PVDF), a piezoelectric material [31].

1.2.1.2 Electromechanical proximity sensors

These sensors produce an electrical output proportional to distance, but are constrained to operate mechanically along a fixed path. The most familiar of these sensors are Linear Variable Differential Transformer (LVDT), Rotary Variable Differential Transformer (RVDT) (for fixed rotary motion), and magneto-acoustic sensor [25].

Though some of these sensors find applications in heavy electrical and hydraulic systems, e.g., within a robot to sense the location of a hydraulic piston, generally these sensors do not appear to suit well to external robotic applications because the distance sensing can only be accomplished along a fixed path.

1.2.1.3 Electromagnetic proximity sensors

Further classification of these type of sensors include the following:

(A) Magnetic proximity sensor

A simple form of magnetic proximity sensor is known as a reed switch. More sophisticated forms include magnetic proximity device involving the phenomenon of eddy currents. It usually consists of an appropriately shaped field coil driven by an oscillator, thus creating an oscillatory magnetic field around the coil. When a conductor is brought within the sensitive range of the coil, eddy currents will be electromagnetically induced in it. By
Lenz’s law, this action will oppose the field of the exciting coil thereby reducing its impedance (inductance). This impedance change unbalances a bridge circuit, which produces an output signal proportional to the proximity of the conductor [25].

Magnetic proximity sensors are quite fast (typically operating at 1,000 pulses per second), offer a larger range of uses: they are more reliable in contaminated-filled environments and harsh conditions (i.e. heavy vibration, moisture, etc.), and are relatively low cost. Drawbacks include their limited sensing range and their ability to sense only metal objects [29]. Additionally, both the size and the speed of the object being sensed will have to fall within certain parameters.

(B) Capacitive proximity sensor

A capacitive proximity sensor is essentially a simple capacitor in which one plate is contained in the sensor, and the other plate is at ground potential. As object passes in front of the sensor, the capacitance of the sensor changes which is measured electrically. An advantage of capacitive sensors is their ability to be adjusted to sense specific materials. Capacitive sensor can detect virtually any material including plastic, glass, wood, paper, metal, water, and oil.

Capacitive sensors are a viable option, but they are more expensive than magnetic sensors and have a tendency for false activation due to moisture, humidity and improper grounding [29]. The size of these sensors is proportional to the range of object detection desired. Capacitive sensors generally operate at a maximum speed of about 400 pulses per second. Different kinds of capacitive proximity sensors [4,22,32] are currently in use including NASA’s Capaciflector (capacitive reflector) [5,7-8].

(C) RADAR type

In this case, electromagnetic signals are generated and transmitted from directive antennas, and the round trip time for the signals to be reflected back from a target is measured. Examples include RADAR which is used in determining the presence and distances of commercial and military aircrafts, and analyzing local weather systems [25]. It is used for
very long range tasks in the order of tens of miles, and hence not suitable for short range robotic proximity applications.

(D) Nuclear Radiation and X-ray type

These sensors incorporate nuclear radiation effects, and measure material thickness and distance by sensing back scattered or absorbed radiation [25]. Because of its hazardous potential, it is only used for specialized applications in robotics, e.g. automatic inspection.

(E) Optical proximity sensor

As the classification chart in Figure 1.2 suggests, optical technology dominates in terms of the variety of noncontact sensor types. Various methods are used to determine the range of the target object from the sensor. Following is a brief presentation of some of those.

(a) Time of flight

Short light pulses are emitted with a high repetition rate towards an object. A small fraction of the light is reflected from the surface of the object and received by the measurement system. The distance is uniquely obtained from the elapsed time interval between the transmitted and the received light pulses [33-34].

This method works very well for longer distances, but for shorter distances of 30cm or less, a subnanosecond timing circuitry would be required which is not cost effective.

(b) Photoelectric sensor

Here, an opaque object will obscure a light beam which normally illuminates the photosensitive surface. The larger the object, the greater the degree of obscuration, which is measured in terms of electrical output [25]. Photoelectric sensors are a popular choice because of their long range detection capabilities (5 to 50 meters depending upon type), ease of use, and the variety of mounting and packaging styles available. Photoelectrics provide a variety of sensing techniques including diffuse, retroreflective, and through-beam, and can detect almost any material [28].
(c) Interferometry

This technique involves the transmission of a single coherent light source along two different optical paths by using a beam splitter. If the length of one optical path is changed, the two beams interact in such a way that when they are rejoined, clearly visible interferometric fringes, which may be counted electronically, are produced. The number of fringes counted is related to the change in the optical path length which is a direct measure of mechanical deflection [25,35].

(d) Frequency modulation

This involves detecting the phase shift associated with the transmission and reflection of modulated light beams [36].

(e) Optical Triangulation

This technique has been employed in the proximity sensor designed in this thesis, and hence will be discussed in detail in the following section.

Other types of optical proximity sensors include opto-electronic types and diffraction systems.

1.2.2 Principle of Laser Triangulation

In laser triangulation sensors, a low power laser beam is directed towards the object’s surface, as shown in Figure 1-3.
According to surface and laser properties, the beam is scattered back. The scattered laser light is focussed by an optical system to a photodetector that is often a charge-coupled device (CCD). Since the angle of the laser beam $\theta$ and the location of the photodetector element $s$ from the laser are known, the distance $d$ of the object from the sensor can be calculated using the simple trigonometric relation given in equation (1-1).

$$d = s \tan \theta$$  \hspace{1cm} (1-1)

Laser sensors are popular in inspection applications requiring high precision. They have extremely high resolution and detect variances as small as 10 microns. This makes them suitable for extremely precise measuring and gauging in quality control. Other uses include precise material thickness/warpage gauging, eccentricity/concentricity measurements, and detection of very small or thin targets. They can operate very well even in dirty environments.
Laser triangulation sensors typically use an optical system (i.e. lens; see Figure 1.3) to focus the scattered beam from the object surface to a fine spot on the sensor’s. Because of the lens, these sensors have depth of focus and refocusing problems and are bulky.

The accuracy in distance measurement of laser triangulation sensors is limited by speckle noise [37,39]. Other sources of noise are temporal and spatial fluctuations of the coherence of laser light as well as photonic and thermal noise of the CCDs and signal processing electronics [40]. Furthermore, “the shape of an object inspected and the orientation of its surface with respect to the probing laser beam” [41], “surface inclination and reflection variation” [42], and “scattering characteristics of the targets” [43] cause systematic errors in triangulation measurements. Some optical effects limit the ability of a triangulation sensor to make measurements when sudden change in surface height occur, on surfaces with significant reflectance variations and roughness [44].

Speckle noise can be reduced by certain optical means or signal processing by using lot of different available approaches [37]. Because of the various sources of measurement errors due to specular and other noises, laser triangulation can be regarded and modelled as a stochastic process [40] and principal component analysis can be used to stabilize the variance of the corrupted data [37].

1.3 Contributions

The field of proximity sensor needs a sensor which exploits all the advantages of the well known method of laser triangulation, yet eliminating all its drawbacks. Drawbacks of the proximity sensors based on optical triangulation include depth of focus problems encountered at close range applications and the large size of the sensors because of the presence of the lenses and various optics (see Figure 1.3). A lensless proximity system based on laser triangulation will retain all its advantages and eliminate most of its difficulties.

The sponsors of this research project, Canadian Space Agency (CSA), required a
small size, light weight and rugged proximity sensor which gives a high accuracy proximity measurements and a low resolution image of an approaching object. The sensor was aimed at close range robotic applications working from the point of contact to the distance of 20 mm, i.e. 0-20 mm.

The sensor, also called “Vision Skin”, used the principle of laser triangulation by employing a laser diode for proximity applications, and a group of light emitting diodes (LEDs), surrounding the sensor in a circular fashion, for imaging applications. Vision Skin gives a high accuracy proximity measurements (1-2% error) for distances up to 20 mm, and a low resolution image of simple surface profiles like checkered-board up to distances of 10-12 mm. The uniqueness of Vision Skin is its lensless operation. Instead of a lens, it uses a ‘Shadow mask’ over the photodetector array of a modified charge-coupled device (CCD). Shadow mask is a 500 micron thick sheet of polypropylene with an array of closely spaced (150 micron centre-to-centre spacing) small (30 micron) holes, fabricated using laser micro-machining. These small holes create small acceptance angles (3.4 °) thereby restricting the amount of light seen by the sensor. To measure proximity, a laser spot is projected onto the object, and the scattered beam is received by shadow-masked CCD sensor. With the restricted reception of the light only by a small group of holes under the point where the laser beam hits the object, the location of the centroid of the brightest spot can be easily obtained. By following the movement of this brightest hole on the CCD photoarray as the object changes its distance, the latter can be easily calculated using the simple trigonometric relations, since angle of the laser beam and the spacing of the holes on the photoarray is already known. For imaging, a group of LEDs are used instead of a laser diode. The surface of the object is flooded by these LEDs and the scattered light is received by the shadow masked CCD array. While the holes under the dark areas of the surface texture will receive no light, those under light areas will receive it, so as to duplicate the surface profile of the object. Hence, lensless proximity and imaging operation of this sensor “Vision Skin” is the unique contribution made by this thesis.
1.4 Thesis Outline

This thesis presents the work on the Vision Skin sensor as a follow up of the research completed in “Development of Vision Skin: A Proximity and Imaging Sensor” by Darren Bergen [45]. The thesis stresses on integrating the sensor, along with exploring various techniques for shadow mask manufacturing.

Chapter 2 describes the theory and operation of Vision Skin’s proximity and imaging capability. Chapter 3 details the equipment used in the shadow mask production, along with the laser micromachining (with polypropylene) and photolithography (for multi layer thin film mask) techniques used/investigated for the purpose. Chapter 4 discusses another shadow mask production technique called ‘Laser-LIGA’ (with photosensitive polymers) investigated in this thesis. Chapter 5 presents the integration of Vision Skin. Imaging results are elaborated in Chapter 6 followed by proximity results in Chapter 7. Chapter 8 begins with the conclusion, and then discusses the future work to be done in the area.
Chapter 2

Theory and Operation

“Vision Skin” is aimed at close range applications of 0-20 mm and has both proximity (distance measurement) and imaging capabilities. The main optical component consists of a shadow mask (a matrix of small i.e. 30 μm and closely spaced i.e. 150 μm holes) which is placed on the top of a photodetector array (e.g. a CCD) as shown in Figure 2-1.

Figure 2-1: Vision Skin proximity and imaging sensor
For proximity applications a laser diode projects one or more small spots on the surface of an approaching object, while for imaging applications a group of light emitting diodes (LEDs) surrounding the photo-array in a circular fashion illuminate the whole object surface. For clarity only one LED is shown in the Figure 2-1. The key to both proximity and imaging applications of Vision Skin is the small acceptance angle or the limited acceptance cone of light for the detectors below the holes of a shadow mask. This acceptance angle is set by the aspect ratio between the mask thickness \( t \) and the hole diameter \( D \). The expressions for the aspect ratio and acceptance angle are given in equation (2-1) and (2-2) respectively, and are explained using Figure 2-2.

\[
\text{ar} = \frac{t}{D} \quad (2-1)
\]

\[
\theta = \text{atan} \left( \frac{D}{t} \right) \quad (2-2)
\]

![Figure 2-2: Acceptance angle for shadow mask holes](image)

Typically, a shadow mask is about 500 \( \mu m \) thick and has holes of diameter 30 \( \mu m \), which gives the aspect ratio of 16.7 and the acceptance angle of only 3.4° for the holes. The spacing between the holes or the detectors is about 150 \( \mu m \). The portion of the photodetector array under each hole is referred as a detector, though in actual practice one such detector
can be a combination of many detectors, e.g. several pixels of a CCD are grouped together under each hole to make one detector. So each hole of a shadow mask correspond to a detector sitting underneath.

In this chapter, the theory behind the proximity and imaging capabilities of Vision Skin, and multi layer thin film mask, along with a brief description of CCD functioning is presented.

2.1 Proximity Measurement

Vision Skin sensor measures distances by using the principle of laser triangulation as seen in Figure 1-3. But unlike the sensor described in the figure, Vision Skin does not use lenses to focus the spot on the detector array. Instead, a matrix of small and closely spaced holes called a shadow mask is used as shown in Figure 2-3. Please make a note that the holes of the shadow mask are not shown to the same vertical and horizontal scale. In the figure, the holes are seen to be about twice as high as their diameter, but in reality the hole height is about 16.7 times the diameter (i.e. the aspect ratio of holes is 16.7 which is the ratio of the mask thickness of 500 µm to the hole diameter of 30 µm). In other words, the shadow mask holes act like pin-holes, the effect of which is to limit the acceptance angle (3.4°) for the holes. Other important considerations about the shadow mask holes are: the reflection of light from the hole walls is nil (i.e. hole walls are good absorbers) which is shown by the experiments with the mask material (polypropylene), and the diffraction effect from the hole edges is nil as the hole diameter is large enough for that to happen.
As seen in Figure 2-3, a laser-diode beam is projected on the object whose distance is to be measured. As a first approximation, the laser light is assumed to be an ideal point source. The diffused component of the light from the object is received by the detectors while the reflected component is not seen as the angle of the reflected beam (same as incident angle of laser beam on the object - e.g. 45°) is outside of their acceptance cone. As seen in Figure 2-4, for most engineering surfaces the reflection is a mixture of specular, specular-diffuse and diffuse components [38]. Because of the axial arrangement of laser diode and detector (CCD) array, the latter relies on picking up radiation from diffuse rather than specular or mirror-like reflection at the surface. For most surfaces other than metal, much of the light undergoes diffuse reflection.
Note that in the above discussion the surface of the object is assumed to be flat with respect to sensor's surface. As the object starts tilting away from the direction of laser beam from this point, more and more specular-diffuse light components will be seen by the detectors. The scattered light would follow the Lambert's Law of Cosine relationship, as given in equation (2-3).

\[ d\Omega \propto \cos \phi \quad (2-3) \]

where \(d\Omega\) is the solid angle and \(\phi\) is the angle of the scattered light from the central axis (see Figure 2-5).

If the object is tilted in a fashion shown in Figure 2-5, reflected light component will get down the hole. Since this sensor is aimed at close range (0-20 mm) robotic applications, such a tilt is highly unlikely and hence only the diffused components will be assumed to be seen by the detector array.
For proximity measurements, the precise position of the spot over the detector array needs to be located. In the simplest case, the detector which is directly under the point where the laser hits the object receives the maximum intensity of diffused light. Other detectors receive light which is far less in intensity because of the shadowing effect of the mask edges on the detector surface. As seen in Figure 2-3, since the position of the detector (L) receiving the maximum light intensity and the angle of the laser (θ) are already known, the height (Z) of the object above the sensor can be calculated using a simple trigonometry relation as seen in equation (2-4).

\[ Z = L \tan(\theta) \]  

(2-4)

If there is no mask on the detector array, a smooth change in illumination would exist, making the precise location of the centroid or the largest intensity value of the spot
difficult to locate. With the shadow mask, a greater difference in intensity would exist between detectors directly under the point where the laser hits the object and the detectors away from it as seen in Figure 2-3. For a point source of light, the detector directly under the point will be fully illuminated while those further displaced will only see a portion of their surface being illuminated and the rest being overshadowed by the top edge of the holes.

Now consider determining the position of the farthest detector which receives any light at all without being completely shadowed by the mask. Figure 2-6 shows a magnified view of two detectors being shadowed from the spot by the mask. The spot is nearer to detector 2 than detector 1, and as a result detector 1 is completely shadowed by the mask while only a part of detector 2 is shadowed.

![Figure 2-6: Magnified view of shadowed detectors](image)

 Considering the case of detector 1 in the figure will give the condition in which the detector will be totally shadowed by the mask, and hence will put limit on the farthest detector which can receive light from the spot. This condition is presented as formula in (2-5) below.

\[
\frac{Z}{x} \leq \frac{t}{D}
\]  

(2-5)

where \(Z\) is the height of the object from the mask surface, \(x\) is the distance from the
edge of the detector to the spot, D is the diameter of the hole, and t is the thickness of the mask. Referring to Figure 2-6, equation (2-5) is the condition when the angle of the diffused beam ($\phi$) is less than or equal to the angle ($\alpha$) formed by the top near to the bottom far corner of the hole of detector 1, as presented in equation (2-6).

$$\phi \leq \alpha \quad (2-6)$$

Also, the tangent of the angle $\alpha$ (i.e. $\tan \alpha$) is the thickness of the mask over the diameter of the hole (i.e. $t/D$) as given in equation (2-7).

$$\tan \alpha = \frac{t}{D} \quad (2-7)$$

This ratio $t/D$ is also called aspect ratio (see equation (2-5)) and is 16.7 ($=500/30$) for Vision Skin sensor.

Hence, equation (2-7) becomes

$$\alpha = 86.5^\circ \quad (2-8)$$

So, the other way of describing the condition of equation (2-5) can be obtained by using equations (2-7) and (2-8) in equations (2-5) and (2-6), as given in equations (2-9) and (2-10) below.

$$\frac{Z}{x} \leq 16.7 \quad (2-9)$$

In other words, the mask would shadow the spot for a particular detector if the object comes closer ($Z$ decreases), or if the object moves away from the detector ($x$ increases).

$$\phi \leq 86.5^\circ \quad (2-10)$$

i.e. as long as $\phi$ is less than or equal to 86.5°, the mask will shadow the detector 2.
So far the shadow mask has been shown with simple geometric optics but there are a few other factors which affect the performance of the mask although negligibly. These factors include diffraction and absorption properties of the hole openings of the mask. The diffraction effect can be explained by using the hole as a circular aperture. As a first approximation, diffraction of light from the edges will follow Airy formula given in equation (2-11) [46].

\[ I(\beta) = I_0 \left( \frac{J_1(\beta)}{\beta} \right)^2 \]  

(2-11)

where

\[ \beta = \frac{\pi D \sin(\theta)}{\lambda} \]

and \( J_1 = \) Bessel function of order one,

\( \theta = \) angular deviation of pattern from minimum, and

\( I_0 = \) peak intensity.

The diffraction property of the shadow mask holes can be studied by considering a light pattern composed of concentric circular rings produced by its effect. The central maximum of this pattern carries most of its intensity, and its edge can be defined by the first minimum. Equation (2-12) shows the angle of the first minimum for diffraction of a circular aperture.

\[ \sin(\theta_{min}) = \frac{2.44\lambda}{2D} \]  

(2-12)

where \( \lambda = \) the wavelength of light, \( D = \) the diameter of the hole, and \( \theta_{min} = \) the angle of the minimum. The Vision Skin sensor has shadow mask holes of the size 30 \( \mu m \) and uses a laser diode at a wavelength of 670 nm. Using \( D=30\mu m \) and \( \lambda=670\text{nm} \) in equation (2-12) gives the angle of first minimum as 1.6°. This means that the detectors would also collect the light from outside their acceptance cone (recall that the acceptance angle for
the detectors is 3.4°) but that would not contribute much to the original intensity. Now consider the case where the shadow mask holes are of the size of 20μm. If the same laser diode is used (\( \lambda = 670 \text{nm} \)), the angle first minimum would be 2.3°, i.e. the diffraction effect would be more prominent. In other words, as the holes become smaller, the diffraction effect would limit the convergence of the acceptance angle, and hence would be a limiting factor in the performance of the mask. The 30μm holes of the Vision Skin sensor are large enough for any significant diffraction effect (1.6° first minimum only) to take place, so its effect would be considered nil. Figure 2-7 shows a schematic diagram of a detector undergoing the diffraction effect.

![Figure 2-7: Light diffraction from shadow mask hole edges](image)

The second factor is that of the absorption of the light beam by the hole walls. The effect of absorption can be studied by considering the effect of reflection and scattering at the walls. The material of which the shadow mask is made of (black polypropylene) is a good absorbent. Assume that 85% of the incident light is absorbed and 15% is reflected by the holes. Since the hole walls are fairly straight (for details see Chapter 3), the light beam entering a hole at an angle may undergo multiple reflections at the same angle from the side-walls before reaching the detector sitting underneath. For light entering the top half of the hole (angles greater than 6.9°), the beam would reflect off the walls at least twice and drop down to 2% or more of the original intensity and hence its contribution will be nil. For light
entering the bottom half of the hole (angles between $6.9^\circ$ and $3.4^\circ$), the beam would reflect off the walls once and would fall to 15% of the original power. Figure 2-8 explains the effect of absorption on the light gathered by a detector. The light levels reaching the detector indirectly (by reflections) would have a small to negligible effect on the light that enters the detector straight without any reflections, thereby its effect is considered negligible.

![Figure 2-8: Light absorption by shadow mask holes](image)

The discussion of the proximity theory has been presented for a point source of light above, and the same will work for a finite size (e.g. 200 $\mu m$ in diameter) laser spot with a gaussian intensity distribution. The detailed discussion of the behavior of gaussian laser spot at various experimental heights for Vision Skin proximity measurements will be presented in Chapter 7 of the thesis. A finite size laser beam is essentially a combination of infinite number of light points which tend to follow an intensity distribution given by equation (2-13) of gaussian light distribution formula.

$$I(r) = \exp\left(\frac{-2r^2}{w^2}\right) \quad (2-13)$$
where \( r \) is the distance from the centre of the beam and \( w \) is the radius of the laser spot corresponding to its \( 1/e^2 \) value.

As with the case of point source of light, the brightest detector still qualifies as the location of the spot over the sensor as shown in Figure 2-9. Using the trigonometric relation of equation (2-4), the height of the object over the sensor can be easily determined. The only difference with a finite sized laser spot is that the spread of light over the detector array is more than that in the case of a point source, i.e the light is seen by more number of detectors around the detector with the maximum intensity. The intensity of a gaussian beam near its tail ends is very low as compared to that near the centre, and even though the light is seen by the detector further out, it does not register much intensity to these detectors.

![Figure 2-9: Proximity measurement with a gaussian laser spot](image)
As seen in Figure 2-9, in case of gaussian beam the detector under the spot receives the light from the centre of the beam as well as from other portions of the profile (though only the reception from the centre and a tail end is shown in the figure for clarity reasons). Similarly, the detectors further away from the brightest detector receive the light from all portions of the profiles including that from the centre (again only the reception from a tail end and the centre is shown for clarity).

Summarizing the above, as compared to the point source of light, the effect of a finite sized gaussian spot is to extend the horizontal distance over which detectors receive illumination, and to increase the light intensity levels of these detectors. But the detector closest to the centre of the spot still has the highest intensity and qualifies as the location of the spot over the detector array. Furthermore, as with the point source, shadow mask results in the attenuation of laser beam through shadowing more than the inverse square of distance allowing for a greater difference in intensity between the detectors under the centre of the spot and those further away. Again, if there is no shadow mask, the gaussian beam would result in the smooth distribution of intensities over the photodetector and the exact centroid of the spot would be a lot harder to find.

Using the brightest hole to find the location of the spot over the detector array is a zero order technique for calculating proximity, in which case the error is limited by the spacing of the detectors and the absolute error is plus or minus one half of the centre to centre spacing between the detectors. Better results can be obtained using various algorithms and interpolation techniques, some of which are discussed in Chapter 7 with proximity results.

2.2 Imaging

Vision Skin sensor, as shown in Figure 2-1, also has the imaging capability which is attributed to the fact that Vision Skin sensor has a limited acceptance angle (because of the high aspect ratio holes), and that each detector has the ability to gather or integrate the light
falling on it. Because of the former, each hole-detector combination acts a pin hole camera, enabling each detector to distinguish the patterns on an object lying in its field of view. A shadow mask with an aspect ratio of 16.7:1 (as currently used in Vision Skin sensor) will enable a detector to distinguish a 1 mm sized object at a distance of 16.7 mm, though a smearing effect with increasing distances is expected.

Figure 2-10 shows the Vision Skin sensor in imaging mode. Though the sensor has the ability to work under normal background illumination, it would be an advantage in some applications to add a wide area light source such as an LED illumination from below the object. Figure 2-10 shows two such LEDs though in actual practice a group of LEDs are used in a circular fashion around the sensor.

![Diagram of Vision Skin sensor](image)

Figure 2-10: Vision Skin under imaging mode [45]

Each detector has an angle of acceptance (\( \theta \)) which is dependent on the aspect ratio of the hole by the relation given in formula in (2-14). Also, the acceptance spot (S) for a detector which is the diameter of the circle on the object that can be viewed by a single detector at a specific height is given by equation in (2-15).

\[
\theta = \tan \left( \frac{D}{t} \right) \tag{2-14}
\]

\[
S = D + 2 \left( \frac{D}{t} \right) Z \tag{2-15}
\]
where D is the diameter of the hole and t is the mask thickness.

Referring to Figure 2-10, the image seen by the sensor is the one where each detector sees an average of an area of diameter S of the object directly over the detector. An object with checkerboard pattern of alternating dark and light square areas, with a boarder centered between two holes is considered in the figure. The detector under the white area will record a high value and the detector under the black a low value. Figure 2-10 is the case where the object is not high enough so that all the areas of the object are not seen by the sensor (acceptance spots of two detectors in the figure do not touch each other). As the object approaches closer, more and more areas are not seen by the sensor but at the same time finer details may be viewed, assuming that sufficient light can illuminate the detector. Applying equation (2-15) for the condition when the two acceptance spots (S) of the detectors just touch each other, i.e. S is equal to the centre to centre spacing of 150 μm between the detectors for D=30 μm and t=500 μm, Z comes out to be about 1 mm. So below the height of 1 mm some of the areas of the object will not be seen in Vision Skin sensor. Furthermore, for the circular geometry of LEDs around the sensor used for illumination as mentioned before, below the height of 2 mm the object surface is not uniformly illuminated and the areas especially near the centre remain dark. So the starting height of Vision Skin is limited to about 2 mm which is dependent more on the positioning of LEDs than on the detector interspacing or its acceptance angle. This is an important point, however, to make here. Vision Skin can see the edges of an object, illuminated from the back, down to the point of contact.

Now consider the case of Figure 2-11 where the object is at such a height that the acceptance spots (S) of the detectors overlap, and the detectors will start viewing areas also seen by their neighbors. As calculated before, this will happen for heights higher than 1 mm. As the object moves higher, more areas will be seen but with a loss of detail. If the overlapped area also involves an edge as seen in the figure, the edge intensities are seen to be more gray or blurred out. Thus, a low resolution image of the object is seen.
Hence, the resolution of the object as seen by Vision Skin is set by the shadow mask hole spacing, acceptance angle, and the height of the object. An object as small as 200\(\mu m\) (slightly bigger than the hole size of 150\(\mu m\)) up to the distances of 10mm can be mapped by Vision Skin.

Although smearing occurs as the object goes further away, the quality of the image can be considerably improved even by using simplest possible image processing techniques, as will be discussed in Chapter 6 of the thesis. Furthermore, if the shape and the pattern of the object is known, then some level of proximity information can be extracted from the amount of smearing of the image by the Vision Skin.

The ability of a detector to gather or integrate the light is also important. As a first approximation, each detector can be considered to collect all the light falling within its acceptance angle. Optical f number of a detector can be related to its acceptance angle (or hole’s aspect ratio), and as a first approximation \(f\# = t/2D\), where \(t/D\) is the aspect ratio of the hole. It implies that a hole with an aspect ratio of 16.7 is similar to a fast f8 lens. Typical camera systems for daylight levels use f11 lens for the exposure, which is close to the f8 capability of Vision Skin sensor. Thus Vision Skin’s light gathering capability is reasonable in normal light levels.
2.3 Multi-layer thin film mask

The key to the performance of sensors like Vision Skin is the aspect ratio (size/length of holes) of their shadow mask. Aspect ratio of a mask can be improved by reducing the size of the holes, and/or increasing the thickness of the mask material. But at one point this process will reach its limit, i.e. the holes can no longer be made small and the thickness of the mask can not be increased if the holes have to go through. Multi-layer mask has the advantage that the aspect ratio can simply be improved by adding additionally layers. If the masks are separated by a spacing, the aspect ratio is further improved by a factor proportional to the spacing. The only difficulty with the multi-layer masks is the alignment of various layers.

The multi-layer masks discussed here are made up of thin amorphous-silicon layers (0.2-0.3µm) supported and separated by glass slips. The 500µm thick layer masks (for which the theory of proximity and imaging has been presented in sections 2.1 and 2.2) can also be stacked one over the other (with or without a spacing) using the same principle, but the theory in this section is being presented exclusively for the thin film masks as they have the potential to be mass produced using standard photolithographic techniques.

Consider Figure 2-12 in which a ray of light passes from a medium of one refractive index \( n_1 \) into another of \( n_2 \). \( \theta_1 \) and \( \theta_2 \) are the angles made by the incident and refractive rays respectively to the normal of the material boundary.
The light ray is bent at the boundary as described by Snell’s Law in formula (2-16).

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]  

(2-16)

From the basic physics, there exists a critical angle \( \theta_c \) for the glass such that the light hitting its surface at angles greater than \( \theta_c \) bend in a manner as if the incident angle was \( \theta_c \). This is somewhat opposite to the total internal reflection principle. Assuming that the incident beam of light passes through a material with refractive index 1 (this is a reasonable assumption for air), the refractive index of the glass \( n \) determines the critical angle to be \( \theta_c = \arcsin(1/n) \). A ray of light striking the glass at any angle \( \theta \) greater than \( \theta_c \) would be bent to \( \theta_{\text{max}} = \arcsin(1/n^2) \). The implications of this terms of the mask are great - light entering a hole in the thin film will enter the mask at an angle no larger than \( \theta_{\text{max}} \) meaning that the second mask must be placed at a distance beneath the first film such that a beam of light passing through a hole of first mask at angle \( \theta_{\text{max}} \) would reach the edge but not enter the adjacent holes of the second mask. Mathematically, this can be stated in the form of equation (2-17).

\[ y_1 = L / (\tan \theta_{\text{max}}) \]  

(2-17)
where \( y_1 \) is the distance between the first and the second mask and \( L \) is the shortest distance between the edges of adjacent holes.

Figure 2-13 shows the three different layers of the multi-layer thin film mask with these parameters.

\[
\frac{(y_1 + y_2)}{(d + L)} = \frac{y_1}{d}
\]

or

\[
y_2 = \frac{(y_1 L)}{d}
\]

where \( y_2 \) is the distance between the second and third film and \( d \) is the hole diameter.

Although a fourth film could be placed in contact with the CCD surface, the aspect ratio of the holes in the mask ensures that a circle of diameter only marginally larger than that of the holes will be traced on the CCD. Heuristically, it is easily seen that successive layers would increase the aspect ratio greatly, with the spacing between layers increasing for each additionally layer. Nonetheless, the distance between the third film and the CCD
depends on the error tolerance desired. To derive the equation, let $\Delta d$ be the fraction of the diameter by which the hole diameter is allowed to be exceeded on the actual surface of the CCD. Equation (2-19) gives the formula by using law of similar triangles.

\[
\frac{(y_1 + y_2)}{d} = \frac{(y_1 + y_2 + y_3)}{d}
\]

or \[ y_3 = (y_1 + y_2) \Delta d \] (2-19)

2.4 Charge Coupled Device (CCD)

In Vision Skin sensor, charge coupled device (CCD) was used as a photodetector because of its high sensitivity to the low light levels and its ability to integrate light over a desired period of time.

In its broadest definition, a charge coupled device (CCD) image sensor is an analog integrated circuit that converts an optical image into an electronic output - in other words it is the electro-optic interface in an electronic image pickup system [47]. In a CCD, the information is represented by a charge packet that is stored in potential wells created in the semiconductor by applying appropriate voltages at the gates of an array of MOS capacitors. The charge is transported in a controlled manner across a channel formed in the semiconductor [48].

A CCD image sensor works operates in four successive steps:
- during the exposure period
  a) it converts the incident illumination into a proportional quantity of electrical charges (photocharges).
  b) it stores the photocharges from each photoelement in an associated MOS capacitor (potential well).
- after the exposure period
  c) it transfers the accumulated photocharge packets sequentially along the MOS capacitors
to a readout stage (i.e. CCD acts as an analog shift register here).

d) at the readout stage, each arriving photocharge packet is converted into a proportional signal.

Additional sampling and amplification give the low impedance output video signal.

A CCD image sensor can be considered as a “black box” which transforms an optical image, i.e. a spatial distribution of radiation, into a time-distributed voltage signal.

The cross sectional view of a basic charge-coupled device is shown in Figure 2-14. A p-type (or an n-type) silicon substrate is oxidized to form a layer of SiO$_2$ on its top. The oxide layer is deposited with closely spaced metallic electrodes, which form a MOS capacitor. These capacitors can be biased in deep depletion region situated below the oxide layer.

![Figure 2-14: Cross-sectional view of a basic charge-coupled device (CCD)]

The charge storage and transfer in CCDs can be best explained using Figure 2-15 (a) and (b) where three metallic electrodes are maintained at different potentials. The central electrode in Figure 2-15 (a) has a potential ($V_2$) which is significantly higher than the potential of the neighboring electrodes ($V_1$). As soon as the electrons are injected into the depletion region, they are accumulated under the central electrode with a higher potential level ($V_2$). The potential on this electrode is high enough to contain the electrons, and hence the charge is said to be stored.
After the charge storage stage, for the charge transfer to take place, the potential on the third electrode is raised from $V_1$ to $V_3$, which is substantially higher than the central electrode potential $V_2$. This potential variation forces the electrons previously stored under the central electrode to move under the third as seen in Figure 2-15 (b), which completes the charge transfer process.

The process of charge transfer along a linear array can be better explained by using the example of a three phase CCD. A three phase clock voltage is applied to the electrodes with each phase supplying to three different groups of electrodes, e.g. first and fourth, second and fifth, and third and sixth electrodes connected to the three phases ($\phi_a$, $\phi_b$ and $\phi_c$) of a periodic waveform, as seen in Figure 2-16. The waveform for each phase (seen on the left of Figure 2-16) has a time period $T$, with three subintervals (from $t=0$ to $t=T/3$, from $t=T/3$ to $t=2T/3$ and from $t=2T/3$ to $T$) of duration $T/3$. Note that the voltage corresponding to these subintervals is either constant at $V_1$ or $V_2$, or changing from $V_2$ to $V_1$. At the end of first subinterval, i.e. at $t=0$, the voltage for phase $\phi_a$ is $V_2$ (higher state), for $\phi_b$ is $V_1$ (lower state) and for $\phi_c$ is also $V_1$ (lower state). Consequently, all the charge is stored under the electrode $a_1$. At the end of second subinterval, i.e. at $t=T/3$, the voltage for phase $\phi_a$ is $V_1$ (lower state), for $\phi_b$ is $V_2$ (higher state) and for $\phi_c$ is $V_1$ (lower state), to force the charge to move from the potential well under the electrode $a_1$ to the one under the electrode $b_1$.
process continues and at the end of third subinterval (at \( t=2T/3 \)), the charge moves under the electrode \( c_1 \) from the electrode \( b_1 \). This completes the charge storage and transfer along a linear array. After the end of the third subinterval, the waveform sequence is repeated and the charge moves to the well under the electrode \( a_3 \) and so on. There is no loss of information carried by the signal charge from the input to the output if the time the charge takes to propagate is small in comparison to the thermal relaxation time.

![Figure 2-16: Schematic diagrams illustrating the operation of a three-phase CCD [48]](image)

CCDs are the fastest growing family of components in electro-optics. CCD arrays, and the circuits to control and read the signals from them, are readily available in the commercial market. Much of the success of the CCDs rests on the fact that they are conceptually very simple and come in the form of MOS integrated circuits. Indeed, their integrated nature
provides their best known features of unlimited lifetime, low power drain, miniaturization, ruggedness and immunity to image burn-in, to name but a few. Furthermore, CCDs facilitate image analysis in discrete elements (pixels) with exact field registration and a sampled output signal delivered at low impedance.

As compared to a photodiode, CCD has an advantage of being more sensitive to low light levels. A CCD collects the light and converts it to the charge thereby providing an integration of the light levels, while for a photodiode the light level is converted directly into the current which means that a very large light intensities are needed to produce a significant signal. When low currents are used for a photodiode, it becomes more susceptible to noise. The only disadvantage of CCDs is that they also produce dark current which gets integrated over time just like the light levels. But this can be overcome to much an extent as the circuits that control and read the signals from the CCDs have the ability to subtract the dark current from the image.

2.5 Summary

This chapter introduced the basic theory and operation of Vision Skin sensor for proximity measurement and imaging. Vision Skin used an array of closely spaced 150\(\mu m\), small holes 30\(\mu m\) in a material of thickness 500\(\mu m\) called a shadow mask, instead of a lens. The high aspect ratio (16.7) holes of the shadow mask and their narrow acceptance angles (3.4°) enabled the Vision Skin sensor to perform highly accurate proximity measurements and map a low resolution image of an approaching object. Various formulae were characterized for the sensor’s operation. The theory of multi-layer thin film mask was also given. At the end, principle of operation of CCD, which forms an integral part of Vision Skin sensor, was discussed.
Chapter 3

Shadow mask production - I (Laser micromachining)

The uniqueness of Vision Skin is its lensless operation. For the purpose a 'Shadow mask', which is an array of closely spaced (<200μm approx) small holes (<100μm approx) in a material of thickness in the range of 0.5mm, is to be fabricated. No items of such kind are available commercially. Several techniques are investigated including laser micromachining with polypropylene, photolithography with amorphous silicon for multi-layer thin film mask and laser-LIGA with a photosensitive polymer. The first two techniques are discussed in this chapter and the third in the next.

This chapter first presents the equipment used for the laser micromachining with polypropylene and the laser-LIGA with a photosensitive polymer. Then the chapter discusses the polypropylene shadow mask production in detail followed by the production of another kind of polypropylene mask used by integrated Vision Skin called a proximity mask (discussed in Chapter 5 with integration). At the end, a brief investigation of multi-layer thin film mask, which is still in the preliminary stages, is presented.
3.1 Equipment

The laser table set-up used for laser micromachining and laser-LiGFA techniques for shadow mask production is an integrated system consisting of a 5.0 W Argon-ion laser, a highly accurate X-Y positioning system, a set of mirrors and lenses, an electro-optic shutter, a camera, a microscope and an IBM PC. Figure 3-1 shows the layout of all these components/equipments of the integrated table set-up.

![Laser table set-up](image)

The laser’s specifications are: INNOVA 305 Argon-ion with a wavelength range - 457.9-514.5 nm, multiline visible power of 5 W, beam diameter at 1/e² of 1.5mm and beam divergence of 0.5 mrad. The laser operates in a continuous mode, but the system has the option to operate in pulsed-mode by turning on the KD*P electro-optic shutter which chops the beam into pulses with durations of greater than 2µs. The shutter is controlled by a function generator and has an on/off ratio of 30:1. The laser beam is divided by a series of dielectric mirrors and the electro-optic shutter to finally reach the X-Y positioning table.

The X-Y positioning table uses a linear induction motor controlled by a laser interferometry measurement system and has a repeatability of 0.1 µm. It also contains a Z-axis on which the samples (polypropylene, photosensitive polymer, etc.) can be placed. The X-
Y(-Z) table is moved so that the areas to be processed on the sample are directly under the microscope. The microscope uses infinity corrected lenses with a parallel light source. This light is focused by a lens and the sample is placed at its focal point using the Z-axis control. The reflected beam from the sample goes back into the microscope and the area viewed by the microscope is seen by a camera. The video signal is produced by the PC through a video display card which displays the image on the computer. The microscopic parallel light also passes through a dielectric mirror as seen in Figure 3-2. The backside of this mirror is optically smooth and allows only the wavelength of the laser light to be reflected and is transparent otherwise, hence not affecting the microscopic beam path at all.

Since the objective lens is infinitely corrected for parallel light, the sample is also in focus for the laser beam when it is in focus for the microscope.

All the laser table controls - X-Y table control, Z-axis control, electro-optic shutter (operated by a computer controlled function generator) and camera video display of the microscopic image on the computer - are controlled at one place by the same software on the IBM PC seen in Figure 3-3. Figure 3-4 is another view of laser table set-up depicting X-Y table, Z-axis, laser, microscope and camera.
Figure 3-3: Actual laser table set-up

Figure 3-4: Front view of laser table
The software running all the controls is an in-house product controlled under MS Windows environment, as seen in Figure 3-5. The table can be controlled manually through the program or by a set of commands in a script or text file. The control system and the camera image are displayed on the monitor at all times during an operation and are accessible for any changes by the operator.

Figure 3-5: Laser table console
3.2 Laser micromachining with polypropylene

The production of shadow mask is the most important aspect of the creation of Vision Skin sensor. Laser drilling of 50μm holes has been reported in a 25μm thick teflon [49-50] and also in 25μm polyamide [51]. The aspect ratio provided by such methods is far too low (0.5) for the demands of Vision Skin. Also an ultrasonic cleaning is required as a post-processing step to clear the holes. This method, however, explores the possibility of laser-drilling with a polymer for a high aspect ratio microstructure. Laser micromachining with polypropylene was suggested by The Laser Institute (Edmonton, Canada) where experiments on polypropylene with a 50 Watt CO₂ laser produced promising results. Experiments were conducted on black polypropylene samples of thicknesses of 0.20, 0.25, 0.5 and 1 mm, which were provided by T.S. Weeks, a graduate student at New Mexico Institute of Mining and Technology.

3.2.1 Drilling parameters

The shadow mask was fabricated by using the Argon Ion laser in the pulsed mode for drilling small holes (30μm) in a 500μm thick sample of polypropylene. Several different parameters were found to affect the laser drilling in polypropylene. They are given as follows.

3.2.1.1 Laser power

A 5W Argon-ion laser is used for laser drilling, hence a power in the range of 0-5 W is available for the processing. The combination of laser power and focussed spot size determines the power density on the sample being drilled. There exists a minimum power at which hole drilling starts, which further depends on the laser pulse width and duty-cycle (for pulsed operation), the material thickness, and the optics used (focal length of the lens). This minimum power is called threshold power. The threshold power for the shadow mask drill-
ing experiments will be given later in this chapter (Table 3-1).

### 3.2.1.2 Laser pulse width

As discussed in section 3.1 the continuous mode Argon-ion laser beam is transformed into a pulsed beam by the use of an electro-optic shutter and a function generator (see Figure 3-1). With the laser in the pulsed-mode, various pulse sizes can be used for the drilling (to be set by the function generator attached to the electro-optic shutter). In the drilling experiments to follow, different laser pulse widths between 0.1ms to 500ms were investigated. Just like the threshold power, there is a minimum pulse width (for a given laser power, duty-cycle, material thickness, and lens) below which the beam does not have the sufficient thermal energy to pierce through the material. This minimum value is called threshold laser pulse width. In the experimental discussion to follow in the next section, the threshold value was found to be in the range of 0.1ms. For this reason, the pulse widths of the size greater than or equal to 0.1ms only were investigated.

### 3.2.1.3 Laser duty-cycle

For each laser pulse, there is an ‘on’ to ‘off’ ratio, and duty cycle is the percentage of time the beam is ‘on’ out of its total pulse width. For example, for a 0.1ms with 0.025ms ‘on’ time and 0.075ms ‘off’ time (on/off ratio 1:3), the duty cycle is 25%. Duty cycles in the range of 1-50% were investigated in the polypropylene drilling experiments presented in the next section.

In a stream of beam pulses, the duty cycle (on/off ratio) is important as the ‘off’ state of each pulse allows the intermittent cooling periods between the high temperature drilling operation of the polypropylene. This off period reduces the chances of a hole being refilled by the molten material of its neighbor when the latter one is drilled. In other words, it allows the hole-interspacing to be reduced by minimizing the size of the hole crust (the spread of the digged-out material surrounding a hole). The idea is better explained using the diagram
in Figure 3-6.

Figure 3-6: Laser drilling of two adjacent holes

3.2.1.4 Optical parameters

Lenses play an important role in drilling of accurate, precise and micro-level structures. Argon-ion laser has a beam size of 1.5mm, which must be focused down to the hole size of <100μm. By changing the beam diameter, the lenses also change the power density (Watt/m²) of the beam, which varies with the square of the spot size. The effect of a lens with focal length \( f \) on a laser beam is given in equation (3-1), which is the formula for the new radius \( (w) \) of a gaussian laser beam of original beam radius at 1/ \( e^2 \) point of \( w_0 \) and wavelength \( \lambda \).

\[
  w = \frac{\lambda f}{\pi w_0}
\]  

(3-1)

Equation (3-2) presents the formula for depth of focus \( (\Delta z) \), which is the distance from the focal point at which the beam radius expands by no more than 5%, for a beam of wavelength \( \lambda \) and original beam radius of \( w_0 \).

\[
  \Delta z = \pm \frac{0.32\pi w_0^2}{\lambda}
\]  

(3-2)
Figure 3-7 depicts the concepts of beam focusing and depth of focus given in equation (3-1) and (3-2).

![Diagram of beam focusing and depth of focus from a plano-convex lens](image)

Figure 3-7: Beam focusing and depth of focus from a plano-convex lens

The Argon-ion laser has a beam of radius of 0.75mm and $\lambda=514\text{nm}$. For a lens of $f=5\text{cm}$, the radius of the new beam, $w$, would be $10.4\mu m$. The corresponding depth of focus, $\Delta z$, value is $\pm 222.8\mu m$ from equation (3-2). These values signify that if the beam is focused at the centre of material thickness (equivalent to focusing the beam at the surface of the sample and reducing the spacing between the lens and the sample by one-half the sample thickness), then for a material of thickness $500\mu m$ (about twice the absolute depth of focus value of 222.8\mu m), holes of the size of about $25\mu m$ (since new beam size is $2w = 2 \times 10.4 = 20.8\mu m$) are expected. The melting due to heat flow would cause some enlargement to these sizes.

### 3.2.1.5 Throughput

Throughput is defined as the number of holes drilled per unit time. The time it takes to drill one hole equals the drilling time for that hole and the waiting time elapsed until the next hole drilling starts. Drilling time is the laser pulse width multiplied by total number of pulses used for the drilling operation. Drilling results in an appreciable temperature rise of the material and the uncontrolled heat flow would result in burning of the material and irreg-
ular hole size and shape. During the drilling, the material of the hole itself dissociates, as seen by the thin stream of dark gas coming out of the hole. Therefore, a waiting time is allowed between the drilling of two adjacent holes to allow the material to cool down (found by experimentation). A waiting time of 2sec was allowed in the experiments discussed in the next section. Also, the drilling time was chosen to be 1sec, which means that 10 pulses were used for a pulse of 100ms, 100 pulses were used for 10msec laser pulse, and so on. This means that it would take about 3sec (1sec drilling time + 2sec waiting time) on the average to drill one hole, thereby resulting in a throughput of 20 holes/min.

3.2.2 Shadow mask production

3.2.2.1 Experimental set-up

Figure 3-8 presents a schematic diagram of laser drilling of polypropylene for shadow mask production. The laser beam is focused by a lens on the polypropylene sample placed in a holder. The holder creates an air gap under the area of the sample to be drilled. This air gap reduces the heat loss from the sample by reducing the conduction on the back side. Placing the sample directly on an aluminium or a metallic stand would increase the heat conductance and require a higher laser power. Additionally, the air gap allows the beam to defocus (as the air gap is much larger than the depth of focus of the lens used) and as a result the reflected beam from the bottom of stand has an insufficient power density to reprocess the sample.
A set number of laser pulses for a given pulse duration are used, then a waiting period (~2sec) is allowed, the drilling position is changed (by about 150μm) to the next hole location, and the process is continued. The laser pulse duration, its duty cycle and the power are preset at desired values, and the waiting time, the table movement and the drilling operation can either be given manually or using a script file where all the commands are previously written. After setting all the parameters, the operation is pretty much automated.

### 3.2.2.2 Results

Laser drilling in polypropylene was a step by step process in which all the various parameters discussed in section 3.2.1 are tested independently and in relation to each other. While the settings which did not work were eliminated from the consideration, those worked were analyzed, kept and the work was proceeded on those lines. As also discussed in the last section, a lens of focal length of 5cm was chosen because its depth of focus (±222.8μm) would suit the thickness of the sample (500μm) and would produce holes of
the size of 25-30µm (spot size 20.8µm). Samples of various other thicknesses (250µm and 1000µm) were also investigated in initial experiments with appropriate lenses, but they did not give the results as good as provided by 500µm sample. So the further experiments were performed only with the 500µm sample, and the results are provided in the following discussion. Furthermore, laser powers of 0.10-2.00 W (higher powers being unsafe/inappropriate for precise/small hole drilling), laser pulse width of 0.1-500ms and duty cycle of 1-50% were used in the experiments.

(A) Threshold power

First of all, individual holes were drilled with various laser pulse widths and duty cycles and the minimum power (threshold power) required to produce a through hole was recorded. Table 3-1 presents these threshold powers for a range of pulses.

Table 3-1: Threshold powers for hole drilling in 500µm black polypropylene

<table>
<thead>
<tr>
<th>Duty Cycle (%)</th>
<th>Pulse Width (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500</td>
</tr>
<tr>
<td>50.0</td>
<td>0.12 W</td>
</tr>
<tr>
<td>16.7</td>
<td>0.18 W</td>
</tr>
<tr>
<td>9.1</td>
<td>0.23 W</td>
</tr>
<tr>
<td>2.0</td>
<td>0.75 W</td>
</tr>
<tr>
<td>1.0</td>
<td>1.20 W</td>
</tr>
</tbody>
</table>

As seen from the table, the threshold power drops with the increase in pulse width and/or duty cycle. Blank entries correspond to the powers (>2W) found unsafe or appropriate for controlled small hole drilling process. When the power is too high, the holes are generally much bigger (200µm) than the requirement, and are also irregular shaped (not round because of uncontrolled heat flow).

As mentioned before, the number of pulses are set such that the drilling lasts 1sec, i.e. 10 pulses for a 100msec pulse, 100 pulses for a 10msec pulse, and so on.
(B) Hole dimensions versus laser parameters

It is clear at his point that the holes as small in size as possible are desired. The hole diameter becomes smaller and smaller with smaller pulse widths and duty cycles, because of the reduction in the power density of the pulse (provided the power of the laser is above the corresponding threshold power). But there is a trade-off here: with the pulse width and duty cycle becoming smaller and smaller, higher and higher powers are required to get the through holes (Table 3-1 gives some idea) and at one point (e.g. pulses of smaller width than 1ms and duty cycles than 2%; see Table 3-1), the power requirement grows so high (>2.5W) that it is unsafe and inappropriate for the material. Very high powers would result in uncontrolled heat flow which results in irregular hole shapes and limits the hole interspacing (as the digged out material spreads to the larger distance because of the heat to block the neighboring holes). Also the throughput is affected because with the higher powers, a larger waiting period between the hole drilling is required to adequately cool the material for good results.

Furthermore, even for the same power and pulse duty cycle, smaller pulse width (and more number of pulses) does not necessarily mean smaller dimensions as the pulse might not have enough thermal energy to pierce through the material. If the pulse width is very small, it digs out more material in horizontal direction than the vertical while struggling with its insufficient thermal energy to go through the material, resulting in both larger hole sizes and interspacings. Additionally, more number of pulses sometimes lead to larger hole dimensions as they keep on cutting the hole edges to make it wider.

In other words, there exist an optimum parameter setting for smallest possible hole drilling, which has a small pulse width and duty cycle but not so small that it leads to the complications stated above.
(C) Optimum setting

The above discussion leads to the conclusion that there exists an optimum setting (i.e. optimum laser power, pulse width and duty cycle) which produces the best possible hole dimensions. These optimum parameter values must not hit the extremes (e.g. too small or too large pulse widths or duty cycle or power) to avoid the complications discussed before. This suggests that these values must be those situated near the core of Table 3-1 (ignoring blank entries, of course). These are shown in bold numbers and clearly suggests that the best results must lie close to these parameters. Note that these settings have moderate threshold powers (0.25-0.60 W), moderate pulse widths (10ms and 100ms) and moderate duty cycles (9.1% and 16.7%).

(D) Tabulated results

A wide range of different parameters were experimented and the results were recorded. Table 3-2 presents the tabular results for laser pulse widths in the range of 0.1-500ms, duty cycles of 1-50% and powers of 0-2W (no data taken wherever power of >2W was required for reasons mentioned before) using a lens of 5cm focal length. Note that the powers used are slightly higher than the corresponding threshold powers to ensure the successful drilling results. As expected, the optimum parameters (from Table 3-1) gave excellent results of hole size and interspacing, and are seen in bold numbers in Table 3-2. Numbers in italic are other good results outside the optimum parameters.
Table 3-2: Complete hole size and interspacing results for 500\(\mu\)m black polypropylene

<table>
<thead>
<tr>
<th>Pulse Width (ms)</th>
<th>Duty Cycle (%)</th>
<th>Number of Pulses</th>
<th>Power (W)</th>
<th>Hole Diameter ((\mu)m)</th>
<th>Interspacing ((\mu)m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>50.0</td>
<td>2</td>
<td>0.15</td>
<td>55</td>
<td>250</td>
</tr>
<tr>
<td>500</td>
<td>16.7</td>
<td>2</td>
<td>0.20</td>
<td>45</td>
<td>200</td>
</tr>
<tr>
<td>500</td>
<td>9.1</td>
<td>2</td>
<td>0.25</td>
<td>42</td>
<td>200</td>
</tr>
<tr>
<td>500</td>
<td>2.0</td>
<td>2</td>
<td>1.75</td>
<td>45</td>
<td>200</td>
</tr>
<tr>
<td>500</td>
<td>1.0</td>
<td>2</td>
<td>1.20</td>
<td>52</td>
<td>200</td>
</tr>
<tr>
<td>100</td>
<td>50.0</td>
<td>10</td>
<td>0.15</td>
<td>35</td>
<td>200</td>
</tr>
<tr>
<td>100</td>
<td>16.7</td>
<td>10</td>
<td>0.20</td>
<td>32</td>
<td>175</td>
</tr>
<tr>
<td>100</td>
<td>9.1</td>
<td>10</td>
<td>0.30</td>
<td>30</td>
<td>150</td>
</tr>
<tr>
<td>100</td>
<td>2.0</td>
<td>10</td>
<td>0.90</td>
<td>27</td>
<td>150</td>
</tr>
<tr>
<td>100</td>
<td>1.0</td>
<td>10</td>
<td>1.50</td>
<td>30</td>
<td>150</td>
</tr>
<tr>
<td>10</td>
<td>50.0</td>
<td>100</td>
<td>0.35</td>
<td>60</td>
<td>250</td>
</tr>
<tr>
<td>10</td>
<td>16.7</td>
<td>100</td>
<td>0.50</td>
<td>45</td>
<td>200</td>
</tr>
<tr>
<td>10</td>
<td>9.1</td>
<td>100</td>
<td>0.65</td>
<td>40</td>
<td>200</td>
</tr>
<tr>
<td>10</td>
<td>2.0</td>
<td>100</td>
<td>1.75</td>
<td>35</td>
<td>150</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>50.0</td>
<td>1000</td>
<td>0.50</td>
<td>72</td>
<td>250</td>
</tr>
<tr>
<td>1</td>
<td>16.7</td>
<td>1000</td>
<td>0.70</td>
<td>60</td>
<td>250</td>
</tr>
<tr>
<td>1</td>
<td>9.1</td>
<td>1000</td>
<td>0.90</td>
<td>60</td>
<td>250</td>
</tr>
<tr>
<td>1</td>
<td>2.0</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.0</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>50.0</td>
<td>10000</td>
<td>0.60</td>
<td>72</td>
<td>250</td>
</tr>
<tr>
<td>0.1</td>
<td>16.7</td>
<td>10000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>9.1</td>
<td>10000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>2.0</td>
<td>10000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>1.0</td>
<td>10000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
By redrawing Table 3-1 for hole sizes and interspacings from Table 3-2, it is seen in Table 3-3 that the best results include the predicted optimum parameters and also include some other settings right in their neighborhood. Optimum results are shown bold, and the other best results in italic.

Table 3-3: Hole size and interspacing results for 500μm black polypropylene

<table>
<thead>
<tr>
<th>Duty Cycle (%)</th>
<th>Pulse Width (ms)</th>
<th>500</th>
<th>100</th>
<th>10</th>
<th>1</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.0</td>
<td></td>
<td>55 (250)</td>
<td>35 (200)</td>
<td>60 (250)</td>
<td>72 (250)</td>
<td>72 (250)</td>
</tr>
<tr>
<td>16.7</td>
<td></td>
<td>45 (200)</td>
<td>32 (175)</td>
<td>45 (200)</td>
<td>60 (250)</td>
<td></td>
</tr>
<tr>
<td>9.1</td>
<td></td>
<td>42 (200)</td>
<td>30 (150)</td>
<td>40 (200)</td>
<td>60 (250)</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td></td>
<td>45 (200)</td>
<td>27 (150)</td>
<td>35 (150)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td>52 (200)</td>
<td>30 (150)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Hole dimensions and interspacings (in brackets) in μm;

Settings other than optimum also give comparable or better results but are unreliable, give unsymmetrical holes (as they require much higher powers) and have other complications. For an example, for a 100ms pulse with a 1% duty cycles, holes of 30μm with a spacing of 150μm are obtained with a power of 1.50W (compare Tables 3-1 and 3-3). Same results are obtained for the 100ms pulse with a 9.1% duty cycle but for a much lower power of 0.30W. Higher powers have their own complications especially when a large array of closely spaced holes (shadow mask) is to be fabricated. For this reason, only the settings using lower powers would be considered and those are the ones corresponding to the optimum parameters discussed in the last section.

(E) Mask fabrication

For the shadow mask production, a choice of many settings was available (see Table 3-3). The setting of 100ms pulse with a duty cycle of 9.1% was the best of all as it required
a power of only 0.3W while producing the best hole dimensions and interspacings, and hence was chosen for the purpose. Two different programs were written in different script files (using software on PC controlling laser table; see section 3.1) for the shadow masks for TC211 and TC245 CCDs. The number of holes drilled for the respective masks was such that the array of holes would fully cover the CCD image areas. Also, the hole interspacing (close to 150µm) was set to be a multiple of CCD pixel sizes (different in x and y directions) to make each hole with the same distribution of pixels. Table 3-4 gives the hole interspacings and grid size for shadow masks for both the TC211 and TC245 CCDs.

Table 3-4: Hole interspacing and grid density calculations for shadow masks

<table>
<thead>
<tr>
<th></th>
<th>CCD Data</th>
<th>Shadow Mask</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of Pixels</td>
<td>Pixel Size (mm)</td>
</tr>
<tr>
<td>TC245</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>755</td>
<td>8.5</td>
</tr>
<tr>
<td>Vertical</td>
<td>242</td>
<td>19.75</td>
</tr>
<tr>
<td>TC211</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>192</td>
<td>13.75</td>
</tr>
<tr>
<td>Vertical</td>
<td>165</td>
<td>16</td>
</tr>
</tbody>
</table>

Figure 3-9 shows the cross-sectional view of a portion of a shadow mask for TC211. The centre to centre spacing between the holes is 144µm. Note that the size of the hole near the entrance point is significantly larger than 30µm, but it quickly (within 60µm into the 500µm thick material) tapers down to its size of 30µm.
(F) **Hole dimensions versus throughput**

There is a trade-off between the hole dimensions (hole size and intespacing) and the throughput (holes/min). Under most of the circumstances, hole dimensions for a particular setting can simply be improved by allowing a longer drilling time and more number of pulses for a pulse of the same width, and by dropping the power. With the additional number of pulses, the through holes are attained at a power at which they were not possible before. The advantage of using a lower power value is to obtain smaller holes. Not to mention, this is done at the cost of throughput.

To explain the concept, take an example of 10ms pulse with 9.1% duty cycle from Table 3-2. The power used was 0.65W and the number of pulses 100 (for a drilling time of 1sec). If now the drilling time is increased to 3sec to accommodate 300 pulses (200 additional pulses), a power of only 0.50 would be required and the hole size would drop from $40\mu m$ at $200\mu m$ spacing to $30\mu m$ at $150\mu m$ spacing. Although, the throughput before was 20 holes/min (1sec drilling time + 2sec waiting time for each hole = 3sec total for each hole) and now is 12 holes/min (3sec drilling time + 2sec waiting time = 5sec total for each hole). Table 3-5 compiles this information.
Table 3-5: Hole dimensions versus throughput for 500μm black polypropylene

<table>
<thead>
<tr>
<th>Pulse Width (ms)</th>
<th>Duty Cycle (%)</th>
<th>Drilling-time/ hole(sec)</th>
<th>Number of Pulses</th>
<th>Power (W)</th>
<th>Hole Diameter (μm)</th>
<th>Interspacing (μm)</th>
<th>Throughput (holes/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9.1</td>
<td>1</td>
<td>100</td>
<td>0.65</td>
<td>40</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>9.1</td>
<td>3</td>
<td>300</td>
<td>0.50</td>
<td>30</td>
<td>150</td>
<td>12</td>
</tr>
</tbody>
</table>

The improved dimensions with this adjustment is now the same as that of the best result of 30μm hole at 150μm spacing seen in Table 3-3, at the cost of throughput.

Also, the success rate and consistency in the size of the holes in the shadow mask drilling depends upon the consistency of sample material composition. The polypropylene samples used had an appreciable surface roughness and were not of the same composition from point to point. Because of that, some of the holes would found to be blocked after the operation, and their sizes significantly different from the others. For the TC245 CCD shadow mask, an array of 41x29 (=1029) holes were drilled, and on an average 2-10 holes were found blocked, thereby giving a success rate of about 99-99.8%. Also, most of the holes were within ±10% of each other’s size.

3.2.3 Proximity mask production

The production of proximity mask (the mask used for getting three laser spots from a laser diode for proximity experiments; see Chapter 5 and Chapter 7) uses the results obtained during shadow mask production discussed in last section. The only difference is that with the proximity mask, hole size and spacing is not that critical. The aim is to get holes of the size of about 150μm with a spacing of about 3000μm, which is a very simple task in comparison to shadow mask demands.
3.2.3.1 Experimental set-up

There are two kinds of proximity masks used in Vision Skin - a mask in which the three holes are drilled at 45° angle and the other in which the holes are drilled straight through (see Chapter 5 for details). The experimental set-up for both kinds is exactly the same as that for shadow mask production of Figure 3-8, except that for the former, the sample is placed at 45° angle under the laser beam, as seen in Figure 3-10.

![Figure 3-10: Experimental set-up for proximity mask with angled holes](image)

The three holes of the proximity mask are drilled in a triangular fashion such that the laser beam coming out of them makes an equilateral triangle of sides of 3mm on the CCD detector array after 45° projection at the object surface. See Chapter 7 for detailed spacing calculations for the proximity mask. Two of the three holes on the proximity mask are at 3mm apart and the third hole is at a spacing of 1.84mm from the centre of other two holes, as seen in Figure 3-11.
For the kind of proximity mask in which the holes are drilled straight through, the sample is placed flat under the laser beam and the spacings shown in Figure 3-11 are provided by the X-Y positioning table. For the mask where the holes are drilled at a 45° angle, the sample is placed at a 45° angle on the X-Y table. In that case the first two holes are drilled at a spacing of 3mm as before, but for the third hole (the line joining this hole and the centre of the first two is at 45° angle with respect to the table), the table is moved only 1.3mm (= 1.84.cos45°) from the centre of the first two holes. The actual increment on the mask surface (45° with respect to the table) is 1.84mm and the proximity mask spacings of Figure 3-11 are obtained. Hence two proximity masks with spacings shown in Figure 3-11 are fabricated, one with the holes drilled straight through and the other with the holes at 45° angle.

3.2.3.2 Results

The aim in this case is to get the holes of the order of 150-200μm in size. As with the shadow mask production, a 5cm focal length lens and a polypropylene sample of 500μm thickness were used. The following parameters of Table 3-6 were experimented for the desired hole sizes on the basis of shadow mask production results.
Table 3-6: Proximity mask laser drilling results for 500μm black polypropylene

<table>
<thead>
<tr>
<th>Pulse Width (ms)</th>
<th>Duty Cycle (%)</th>
<th>Number of Pulses</th>
<th>Power (W)</th>
<th>Hole Diameter (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>50</td>
<td>5</td>
<td>0.8</td>
<td>200</td>
</tr>
<tr>
<td>1000</td>
<td>50</td>
<td>5</td>
<td>1.5</td>
<td>250</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>10</td>
<td>0.8</td>
<td>150</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>10</td>
<td>1.5</td>
<td>200</td>
</tr>
</tbody>
</table>

For the integrated Vision Skin used for proximity experiments in Chapter 7, proximity mask has the 45° angled holes drilled by using a 100ms pulse with 50% duty cycle at a power of 0.80 W. Note that the same parameters would work both for the straight and the angled holes, but a slightly higher power would be required for angled holes as the effective thickness of the sample at an angle is more than its actual thickness of 500μm. Also, the outlook of the angled holes at the surface of the sample would be elliptical and not round, and hence their size would also be bigger than the holes (round) drilled straight through.

3.3 Multi-layer thin film mask

Although the single thick layer polypropylene shadow mask provides a good aspect ratio for Vision Skin sensor, the process (laser micromachining) by which the mask is made is relatively slow, as the masks are made one by one and they can not be mass produced. This led to the idea of using a technique such as photolithography which facilitates mass production. Though the individual layers do not have a high aspect ratio, but when they are used one over the other with a spacing in the multi-layer mode, they provide a very high aspect ratio for the holes. The only difficulty with the multi-layer masks is the alignment of various layers with respect to each other.
A thin amorphous-silicon layer (used because the irregular lattice pattern would trap light better than a regular lattice) could be deposited on glass slips (very thin $\sim 178\mu m$ sheet of glass on which samples are normally placed for microscopic observation) and patterned into a series of holes of desired diameter and centre to centre spacing using standard photolithographic techniques. The glass slips would not only serve as a support for the thin opaque film, but would also provide the required spacing between the layers of the mask. The first layer of glass would further provide the additional feature of blocking out light rays coming into the hole from large angles. This is important because the second film must be placed at a height such that the light entering one hole can not be detected by any area on the CCD except the one directly beneath the hole through which the light entered. The theory of multi-layer thin film mask is been discussed in section 2.3 of Chapter 2. Figure 3-12 gives a schematic diagram of a three layer thin film mask.

![Figure 3-12: Film spacing for a multi-layer thin film mask](image)

The sizes of the layers $y_1$, $y_2$ and $y_3$ (the distance between the bottommost layer and the CCD surface) are given by the following expressions (see Chapter 2 section 2.3 for details) where $\theta_{max} = \sin(1/n^2)$. 

$$\theta_{max} = \sin(1/n^2).$$
\[ y_1 = \frac{L}{\tan \theta_{max}} \]
\[ y_2 = \frac{(y_1 L)}{d} \]
\[ y_3 = (y_1 + y_2) \Delta d \]

The first mask prototype was designed for the TC211 CCD. The holes of diameter 50\(\mu\)m with 150\(\mu\)m centre to centre spacing were desired for a three layer mask. The design for the mask was done in a CAD program called xKic by an undergraduate student Marinko Sarunic. The hole interspacing was set to be an integral multiple pixel size, and since the pixels of the TC211 are rectangular (13.75\(\times\)16\(\mu\)m) the hole interspacing in \(x\) and \(y\) directions was different. Figure 3-13 illustrates the mask for hole interspacings and hole shape. Note that the holes were actually made octagonal whose sharp corners would get rounded out in the fabrication process.

![Figure 3-13: Multi-layer thin film mask on a TC211 CCD array](image)

A mask prototype for the TC245 CCD was also designed on the same lines.

The process begins with the deposition of 0.2-0.3\(\mu\)m thick film of amorphous-silicon on a simple microscopic cover glass slip. The cover slips are 7/1000 of an inch (approx-
imately 178µm) thick but are of an undetermined refractive index. The tools needed to
determine the refractive index of glass so thin are not available, so the value of n has to be
estimated. The refractive index for crown glass is about 1.52 and for flint glass 1.66 (at a
wavelength of 600nm) - to be conservative the lower value of n=1.52 is chosen. Also,
because this is the only thickness of the glass available as a spacer between the layers, the
actual distance between the layers will be an integral multiple of 178µm and less than or
equal to the calculated (ideal) value. If the actual value between the layers is larger than the
calculated value, light entering one hole may hit the CCD surface in a completely different
area and produce erroneous results.

Having decided upon the critical dimensions of the mask, the spacing between the
layers can now be determined. L is the centre to centre distance between the holes minus the
hole diameter (the shorter of horizontal and vertical centre to centre distances is used, i.e.
151.25). This gives $L = 151.25 - 48 = 103.25 \mu m$. Putting the values of L, n and d in equa-
tions (3-3), the values of $\theta_{max}$, $y_1$ and $y_2$ comes out to be 25°, 215µm and 383µm respec-
tively. The values of $y_1$ and $y_2$ are reduced from 215µm and 383µm to 178µm and 356µm
respectively (because spacings only multiple of cover slip thickness of 178µm can be
obtained). The distance between the third film and the CCD surface $y_3$ is dependent on $\Delta d$
which is set at 30%, about one pixel width. Again using equation for $y_3$ from equation (3-3)
gives $y_3=160\mu m$. In this case, the calculated distance is shorter than the cover slip thickness
of 178µm, so $y_3$ is forced to 178µm and $\Delta d$ is forced to a slightly larger error tolerance, i.e.
$\Delta d_{forced}=33.3\%$. Table 3-7 gives the summary of the ideal and actual spacings of the three
layers.

<table>
<thead>
<tr>
<th>Between Layers</th>
<th>Ideal Distance (µm)</th>
<th>Actual Distance (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 and 2</td>
<td>215</td>
<td>178</td>
</tr>
<tr>
<td>2 and 3</td>
<td>383</td>
<td>356</td>
</tr>
<tr>
<td>3 and CCD surface</td>
<td>160</td>
<td>178</td>
</tr>
</tbody>
</table>

Table 3-7: Distances between layers in a three layer thin film mask
The overall height of the mask above the CCD surface is $y_1 + y_2 + y_3 = 712 \mu m$, and for a hole size of $48 \mu m$ it yields an aspect ratio of 14.8. It is interesting to note that the aspect ratio of the single layer polypropylene mask described in the previous section was only marginally larger at 16.7 despite the fact that the single thick layer mask had holes (30\(\mu\)m) that were about 1.6 times smaller than the holes (48\(\mu\)m) in the multilayer mask.

Although both the prototypes for the TC211 and TC245 were ready and the amorphous-silicon film was deposited on the cover slips, the multi-layer mask could not be completed in the time for this thesis, and hence it could not be tested in the Vision Skin sensor for performance.

### 3.4 Summary

This chapter discussed the first two technologies - laser micromachining and photolithography - investigated for shadow mask production. The equipment used for the production was a high precision XYZ laser positioning table. Laser micromachining with polypropylene produced a shadow mask with 30\(\mu\)m holes at 150\(\mu\)m intesping in a 500\(\mu\)m thick sample with a success rate of well over 99\%. These holes had an aspect ratio of 16.7 and an acceptance angle of only 3.4°. A laser power of 0.30W with 10 pulses of width 100ms at duty cycle of 9.1\%, and a plano-convex lens of 5cm focal length were used for these holes. Another kind of mask called proximity mask to obtain multiple laser beams from the same diode source was fabricated. This mask also used the same 500\(\mu\)m thick polypropylene sample and contained three 150\(\mu\)m laser-micromachined holes at a spacing in the range of 3mm. At the end, photolithography technology for multi-layer thin film mask was discussed.
Chapter 4

Shadow mask Production - II (Laser-LIGA)

Laser-LIGA is another technique investigated in this thesis for shadow mask production. It involves creating high aspect ratio structures using a photosensitive polymer exposed to a powerful laser beam to solidify it - a laser writing of the structure. This chapter starts with the background of such high aspect ratio microfabrication technologies. A description of various photosensitive polymers used in the laser-LIGA process are given. This is followed by the discussion of various steps involved in the process. The experimental strategy is presented and the detailed results are analyzed. At the end, a conclusion is drawn.

This is a preliminary work accomplished in December, 1995, and its follow up was later carried out by Gilbert Wong in his Bachelor’s degree thesis [52].
4.1 Introduction

High aspect ratio micromachining processes have been developed using methods like LIGA [53], laser ablation [54], X-ray lithography [55], ultraviolet [56] and electron beam lithography.

LIGA consists of three processing steps: special lithography, electroplating and molding. First, a thick-film photoresist (up to 1mm), typically poly-methyl methacrylate (PMMA) is deposited on a substrate. The photoresist is exposed to X-ray radiation from a synchrotron source through a special mask. Since the X-rays are penetrating, they will transmit through the thickness of the mask exposing the full thickness of the layer. The photoresist is then developed to form the desired structure. Second, if the substrate is not electrically conductive, the structure has to be covered with an evaporated metal film, for instance, nickel film. Electroplating is then carried out to form a layer of metal, which fills the space in the structure and covers the photoresist. The electroplating process stops when a standard thickness of metal has reached. Third, the metal part formed is separated from the photoresist. It can now be used as a mold insert for micro injection molding to form replicas of the original photoresist structure.

Laser ablation has been used as a variant of the LIGA process. First, a thick-film polymer is deposited on a substrate. The polymer is then micromachined by laser. Using eximer laser ablation [57] is a powerful tool which can dissociate the material. This enables the sculpturing of small structures through this process. Then the structure formed is covered with an evaporated metal film, and electroplating as in LIGA process is carried out. Third, the polymer is removed and the metal part forms a mold insert for injection molding.

The ultraviolet (UV) aims at lower cost. A UV light source and suitable photosensitive polyamide replace the synchrotron X-ray source and PMMA. Usually, multiple layers of polyamide are required to form a thick structure. This process, however, has a lower defi-
inition quality than LIGA.

In this thesis, a new attempt to utilize Argon-ion laser and photosensitive polymer is carried out. This process is called ‘Laser-LIGA’, and consists of exposing a liquid polymer to the laser at wavelengths which will polymerize the material throughout its depth.

4.2 Photosensitive polymer

Three different photosensitive compounds were used - Irgacure 184, RX00727 from Radcure and RX00768 from Radcure. Most of the experiments are done on Irgacure 184.

The chemical composition by weight of the Irgacure 184 solution is: 69.3% Ebecry 600 (epoxy diacrylate, 1.202 g/ml), 29.7% OTA 480 (propoxylated glycerol triacrylate, 1.084 g/ml), and 1.0% Irgacure 184 (1-hydroxycyclohexyl phenyl ketone), i.e. Irgacure 184 makes only 1% (by weight), and is the only photosensitive curing compound in the mixture. The mixture is called ‘Irgacure 184 solution’, and is transparent, viscous and photosensitive [58]. Irgacure 184 has its best absorption of light radiation at 203nm, 242nm and 326nm in wavelength. It has low extinction coefficients at longer wavelengths (>300nm). Thus short wavelengths are good for surface cure, because light radiation is mostly absorbed at the coating’s surface. Longer wavelengths allow the light radiation to penetrate deeper into the coating and provide excellent through cure. When light of proper wavelength irradiates on the Irgacure 184 solution, it is polymerized. This process could be interpreted as solidification of the solution. The solidified portion will not dissolve in acetone, a developer used in the post-exposing step to remove the unexposed portion. The hardness of the cured Irgacure 184 is related to the residual 2-ethylhexyl acrylate (2-EHA) remaining after cure. The lesser the 2-EHA remains, the harder the exposed polymer becomes. Irgacure 184 has 0.045% through cure residual 2-EHA concentration and 0.090% surface cure residual 2-EHA concentration, thus could provide very good cure results.
Radcure’s RX00727 is a low viscosity (328 cP at 25°C) and transparent solution, which is sensitive to ultraviolet and deep-violet wavelength range of the radiation [59]. It has a wavelength sensitive edge for a wavelength of 450nm. Radcure’s RX00768 is four times more viscous (1216 cP at 25°C), and is also sensitive to ultraviolet to deep-violet wavelengths especially to 450nm [60]. Because of the lower viscosity, RX00727 can be exposed to a greater depth into the solution (up to 25mm), as it is easy for the beam at any given power to penetrate and expose deeper into the film. On the other hand, because of the higher viscosity, RX00768 can be deposited to greater thicknesses (1-2mm) on the substrate even without any confinement (if the liquid polymer is thin and less viscous, it will flow outside the substrate and will need some boundary confinement for thicker film heights). Both compounds are dissolved in acetone, hence acetone is once again used as a developer in the post-exposing development step.

The laser source used for polymer exposure is an INNOVA 305 Argon Ion laser with a power of 5W for multiline visible (457.9-514.5nm) mode. The power specifications for the additional lines is shown in Table 4-1. Note that there is considerable power (0.47W) available in the 450-460nm range.

Table 4-1: Power specifications of the Argon-Ion laser source

<table>
<thead>
<tr>
<th>Argon Wavelength (nm)</th>
<th>Output Powers for Innova 305 Laser (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1090</td>
<td>0.05</td>
</tr>
<tr>
<td>528.7</td>
<td>0.35</td>
</tr>
<tr>
<td>501.7</td>
<td>0.40</td>
</tr>
<tr>
<td>496.5</td>
<td>0.60</td>
</tr>
<tr>
<td>476.5</td>
<td>0.60</td>
</tr>
<tr>
<td>472.7</td>
<td>0.20</td>
</tr>
<tr>
<td>465.8</td>
<td>0.15</td>
</tr>
<tr>
<td>457.9</td>
<td>0.35</td>
</tr>
<tr>
<td>454.5</td>
<td>0.12</td>
</tr>
<tr>
<td>333.6 - 363.8</td>
<td>0.40</td>
</tr>
</tbody>
</table>
### 4.3 Process steps

Typically, laser-LIGA process consists of the input data, part preparation phase, layer preparation functions, laser imaging, and development step. The input data is a text file format that contains a fully surfaced CAD description. The part preparation phase uses a Cadence-to-script translator program to convert the input data into a sequence of instruction that the system uses to make a micro-structure. The layer preparation phase is a step for preparing a thick layer of photosensitive polymer on the substrate. The laser imaging step is directed by control-algorithm to draw a desired pattern on the surface of the photosensitive polymer. After the laser imaging step, the exposed micro-structure is dissolved by a solvent in the developing step. This structure can now be used to make the master mold for mass production of the structures which are replica of the original structure.

In the experiments performed in this chapter, Laser-LIGA with photosensitive compounds was a four step process as shown in Figure 4-1.

![Figure 4-1: Process steps of laser-LIGA process](image-url)
4.3.1 Preparation of a thick film

The first step in the process was to deposit a thick and uniform film on the substrate. Initially, a puddle of the polymer was formed at the centre of the substrate (silicon wafer) and was spun at various speeds. Although, the film was smoothly deposited on the substrate, it was too thin (~100μm) to produce high aspect ratio structures. Speeds as low as 500rpm were tried but made no improvement in the film thickness. Also, the spun samples were hard baked at 200°C for about 10 minutes to remove the air bubbles from the deposited film. The hard baking resulted in the melting of the polymer to make it less viscous, and hence made it flow off the substrate. The final result was a still thinner film. Considering these reasons, the steps of spinning and hard baking were eliminated from the deposition.

To improve the thickness of the polymer film, a puddle was formed at the centre of the substrate, and it was left for a few hours until the puddle got evenly distributed all across the substrate’s surface. This resulted in films as high as 1mm, which was a good starting height for the fabrication of high aspect ratio microstructures. Finally, when thicker films (2-3mm) were desired for the experiments, a confinement (ring on the substrate or putting the substrate in a small, open and shallow container such as a petri-dish) was used to contain the polymer.

4.3.2 Laser patterning

After the deposition, the sample is placed on the Z-axis of the X-Y positioning table (see section 3.1 for the set-up). The high accuracy positioning table not only allowed the sample to be accurately placed in all three axes under the laser, but it also allowed a variable speed control, i.e. the speed of the table could be made faster or slower depending upon the exposure requirements of the material. Some of the other variables/steps are discussed as under.
4.3.2.1 Optical parameters

A plano-convex lens was used to focus the laser beam to a fine spot on the polymer, as seen in Figure 4-2.

![Figure 4-2: Spot size calculations for a thick polymer film](image)

The lens was selected so that it not only focused the beam to a spot of the size of desired microstructures, but also provided enough depth of focus range to expose the whole thickness of the polymer without any significant tapering. For an example, consider two lenses of focal lengths of 5cm and 10cm. Their spot size and depth of focus calculations are presented here. Recall that the beam size of the Argon Ion laser at $1/e^2$ point before it passes through the lens is 1.5mm (diameter) and consider its wavelength $\lambda = 450\text{nm}$.

Using equation (3-1) and (3-2) from Chapter 3, and equation (4-1) give the values of new beam radius, depth of focus and spot size at different distances from the focal point, for 5cm and 10cm focal length lenses in Table 4-2.

$$w'(z) = w\sqrt{1 + \left(\frac{\lambda z}{\pi w^2}\right)^2} \tag{4-1}$$

<table>
<thead>
<tr>
<th>Lens</th>
<th>New radius, $w$ (in $\mu m$)</th>
<th>Depth of focus, $\Delta z$ (in $\mu m$)</th>
<th>Spot radius $w$ at $z$, $w(z)$ (in $\mu m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$z=250\mu m$</td>
</tr>
<tr>
<td>5cm</td>
<td>10.4</td>
<td>$\pm 222.8$</td>
<td>10.5</td>
</tr>
<tr>
<td>10cm</td>
<td>20.7</td>
<td>$\pm 882.7$</td>
<td>20.7</td>
</tr>
</tbody>
</table>

Table 4-2: Optical calculations for 5cm and 10cm plano-convex lenses
The calculations for \( w' \) clearly show that with the focal point set at the centre of the polymer film, 5cm lens would cause no significant tapering (of exposed side-walls) up to the film thickness of 500\( \mu m \) and 10cm lens would suit film thicknesses up to 2000\( \mu m \) while laser exposure of the polymer.

### 4.3.2.2 Experimented structures

Several structures based on the straight lines were exposed in the experiment. Examples include straight lines of different lengths and widths, squares and mesh-shaped structures, as seen in Figure 4-3.

![Experimental structures of laser-LIGA process](image)

Figure 4-3: Experimental structures of laser-LIGA process

Simple lines were experimented because of their simplicity in the earlier experiments. The purpose for choosing the mesh structure was to provide a thick solid support (outside frame) to the thinner lines (inside grid lines) which may not be self supporting.

### 4.3.2.3 Patterning style

Structures seen in Figure 4-3 were based on straight lines which were further comprised of several laser beam traces depending upon the width of the line desired and the lens used. These traces were scanned in a back and forth pattern such that the spacing between them (x) was about one-fourth of their thicknesses (X), i.e. each trace overlapped 3/4th of its neighboring traces, as seen in Figure 4-4.
Traces

$\delta t =$ thickness of one trace
$x =$ spacing between traces

Figure 4-4: Number of laser traces exposing a line on the polymer film

For an example, with the 5cm lens with a spot size of $20.8 \mu m$ (radius $10.4 \mu m$ from equation 3-1), the spacing between the traces would be $5 \mu m$. So with 10 traces in this case, a line of width of $70 \mu m$ ($\sim 20.8 + 10 \times 5$) or more is expected.

### 4.3.3 Development

The exposed samples were immersed in about 200ml of acetone. The unexposed areas of the polymer dissolved slowly in the acetone solution leaving behind the exposed structure on the substrate. It was required to use the agitation to speed up the process. After the first rinse for two minutes, the acetone was replaced by a fresh one. Usually, a third time acetone developing was required to completely remove the unexposed residue. Methyl alcohol could also be used in place of acetone to get the same results. Afterwards, the structure was washed in the running de-ionized (DI) water for a few minutes and was dried by dry nitrogen $N_2$.

### 4.3.4 Observation and measurement

The microstructures formed were observed under a TV camera microscope, Olympus BHZ-UMA. Magnification was adjusted between 5 to 80 times, and a careful examination of the patterns and profiles of the microstructures was carried out. The widths of the lines were measured with a displacement meter, Olympus OSM attached to the microscope. Similarly, the heights were measured. In some cases, the heights of the structures were mea-
sured using the Z-axis of the X-Y positioning table. A 50 times objective lens was used to focus the top edge of the structure, and the Z-axis was raised in small steps until the base of the structure was in focus. The displacement in Z-axis between these two foci was the height of the structure.

4.4 Experiments

A number of different variables/factors were investigated for their affect on the exposure of the polymer film by the laser. These are:

**Speed of X-Y positioning table**

The faster the table speed was, the lesser laser exposure time a polymer film would get per unit area and vice-versa. At a certain speed, the table moved so fast that the film did not get enough time to be exposed. A wide range of table speeds between $20\mu m/s$ and $192,000\mu m/s$ were experimented, and the results are discussed in section 4.5.1.

**Laser power**

A certain minimum laser power was required (also dependent on the corresponding table speed) to expose the material. For this purpose, several powers (1-5 W) were experimented and the results are compiled in section 4.5.1.

**Thickness of deposited polymer film**

The thickness of the polymer film deposited on the substrate before the exposure (provided enough laser power and other parameters are used to be able to expose it) determined the height of the final structure formed. In the earlier experiments, the deposited substrate was spun for a uniform and smooth film but the resulted thickness of the film was very small ($100\mu m$). Afterwards, films as high as 2mm were formed by manually pouring the polymer at the centre of the substrate and allowing it to smoothly settle down all across the
substrate in a few (1-2) hours. This was performed in the deposition step (see Figure 4-1; section 4.3.1) before the laser exposure of the polymer.

**Lens used**

As discussed in section 4.3.2, the lens choice was dependent on the spot size required and more importantly the thickness of the film (depth of focus limitations of a lens) to be exposed. The plano-convex lenses of focal lengths 5cm and 10cm were used. The experiments in section 4.5.1 -4.5.4 used 5cm lens, while the 10cm lens was used in section 4.5.5 - 4.5.7.

**Position of focal point in polymer film**

If the depth of focus of the lens used was comparable to the thickness of the film to be exposed, this factor had an insignificant effect. Otherwise, the position of the focal point of the lens on or in the polymer film would determine the degree of tapering on the sidewalls of the exposed structures. The results for this experiment are presented in section 4.5.3.

**Number of traces/Spacing between traces**

This would determine the thickness of the exposed structure. A number of traces (1-40) and spacings between traces (5µm and 10µm) were experiments in all the experiments (section 4.5.1 - 4.5.7). The experiments in section 4.5.2 were exclusively performed for this testing.

**Substrate used**

Finally, a substrate such as silicon wafer or glass-slide, on which the film is deposited, would determine the structure formed on it. Firstly, the laser beam after penetrating through the film hit the substrate surface and the reflected film re-exposed the film. So, the interaction of the beam with the substrate was one factor which partially affected the expo-
sure. Silicon wafer was reflective (~70%) and hence effectively re-exposed the film by con-
serving much of the original intensity of the incident laser beam. Other factor was the
adhesive properties of the substrate for the film exposed on it. If the substrate could not hold
on to the exposed film after the development, the exposed structure would float away which
was not desired. The experimental results given in section 4.5 used silicon as a substrate,
except for the section 4.5.4 where a glass substrate was used.

Considering all the factors mentioned above, an experimental strategy was designed
according to which these factors would be optimized independently and also in relation to
each other. Figure 4-5 presents a schematic representation of this scheme.

![Figure 4-5: Experimental strategy for laser-LIGA process](image)

Initial experiments worked on optimizing the table speed and laser power for film
thicknesses of about $100 \mu m$ to from the lines (the idea was to find the setting at which the
material started exposing). Once these parameters were obtained, further experiments were
performed to expose higher aspect ratio structures (mesh-structures, etc.) by changing the
other factors one by one in relation to these standard parameters (table speed and laser
power). Note that film thickness was controlled in the polymer deposition step (section
4.3.1) and was not accessed in the experiments.
4.5 Results and discussion

The results of the experiments discussed in the last section are presented here. Unless otherwise stated, the results are given for the Irgacure 184 photosensitive polymer. Radcure’s RX00727 and RX00768 polymers were received towards the end of this thesis and hence a detailed investigation on these polymers could not be completed.

4.5.1 Table speed and laser power

As a starting point, a wide range of table speeds and laser powers were experimented with a 5cm convergent lens. The thickness of the deposited film was about 100μm. A total of 11 traces with a displacement of 5μm between them were used for each line structure 5mm long. Lines were used as structures because of their simplicity. The results are compiled as under in Table 4-3.

Table 4-3: Results of laser-LIGA experiments for table speed and laser power

<table>
<thead>
<tr>
<th>Table Speed (μm/s)</th>
<th>Laser Power (W)</th>
<th>Structure Height (μm) (error ~5μm)</th>
<th>Structure Width (μm) (top/bottom) (error ~5μm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>192,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>No line structure formed</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>No line structure formed</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>No line structure formed</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>No line structure formed</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>No line structure formed</td>
</tr>
<tr>
<td>20,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>No line structure formed</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>No line structure formed</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>No line structure formed</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>No line structure formed</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>Line formed but not prominent</td>
</tr>
</tbody>
</table>

........ to be continued next page
Table 4-3: Results of laser-LIGA experiments for table speed and laser power

<table>
<thead>
<tr>
<th>Table Speed ((\mu m/s))</th>
<th>Laser Power (W)</th>
<th>Structure Height ((\mu m)) (error (\sim 5\mu m))</th>
<th>Structure Width ((\mu m)) (top/bottom) (error (\sim 5\mu m))</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,000</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>Line formed but not prominent</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>Line formed but not prominent</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>Line formed but not prominent</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>Line formed but not prominent</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>Line formed but not prominent</td>
</tr>
<tr>
<td>1,000</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>Line formed but not prominent</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>Line formed but not prominent</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>Line formed but not prominent</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>Line formed but not prominent</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>Line formed but not prominent</td>
</tr>
<tr>
<td>200</td>
<td>1</td>
<td>-</td>
<td>-60</td>
<td>Line structure formed</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>54</td>
<td>26/67</td>
<td>Best structure formed</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>62</td>
<td>16/71</td>
<td>Best structure formed</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>44</td>
<td>23/62</td>
<td>Best structure formed</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>Structure formed but not great</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>Structure formed but not great</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>Structure formed but not great</td>
</tr>
<tr>
<td>200</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>No line with 5x objective lens</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>Line formed but burnt with 5x objective lens</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>Line formed but burnt with 5x objective lens</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>No line with 5x objective lens</td>
</tr>
</tbody>
</table>

Blank entries for structure height and width mean that either the structures (lines) were not formed or were not measurable.
The results showed that the table speeds of $200\mu m/s$ and total laser output power between 3W and 5W could produce some line structures after development. This was an important part of the tests as it provided a guideline for the later experiments. A 5x objective lens was also used for best settings of $200\mu m/s$ table speed and 3-5W power, but the film burned. The reason is that the lens (5x) focussed the beam to a very fine spot resulting in increasing its power density which burnt the film. A lower power of 1W was thereby tried for speeds of $200\mu m/s$ and $20\mu m/s$ but the lines could barely be seen. Also a 5x objective lens (or any other higher power objective lens), because of its poor depth of focus, would not suit thick films of the size of 1mm. As a result, the objective lens was discontinued for the later experiments.

Figure 4-6 and 4-7 show the top view of the lines formed by using table speeds of $200\mu m/s$, and powers of 3W and 5W respectively.

**Figure 4-6:** Top view of an exposed line using $200\mu m/s$ table speed and 3W laser power; film thickness <100μm, lens - 5cm focal length and 11 traces at 5μm spacing

**Figure 4-7:** Top view of an exposed line using $200\mu m/s$ table speed and 5W laser power; film thickness <100μm, lens - 5cm focal length and 11 traces at 5μm spacing
4.5.2 Number of traces and spacing between traces

A various number of traces between 1 and 11, with spacings of 5\(\mu m\) and 10\(\mu m\) for a 5cm lens, were experimented and their results are shown in Table 4-4. The deposited film was about 100\(\mu m\) thick, and line structures (5mm long) were exposed again. Optimum table speed off 200\(\mu m/s\) and powers of 3-5W from Table 4-3 were only used.

Table 4-4: Results of laser-LIGA experiments for Number of traces and spacing between traces

<table>
<thead>
<tr>
<th>Traces per Line</th>
<th>Spacing between traces ((\mu m)) 'x'</th>
<th>Laser Power (W)</th>
<th>Structure Height ((\mu m)) (error ~5(\mu m))</th>
<th>Structure Width ((\mu m)) (top/bottom) (error ~5(\mu m))</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>5</td>
<td>3</td>
<td>60</td>
<td>5/69</td>
<td>Good height; too much tapering</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>3</td>
<td>90</td>
<td>17/60</td>
<td>Best height; significant tapering</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>Line seen but almost no height</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>Line seen but almost no height</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>Better height than last two but not enough</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>3</td>
<td>50</td>
<td>50/60</td>
<td>Fairly straight walls; good result</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

As seen, lines of aspect ratio (height/width) of 1 were formed, as height and width of the lines were both about 60\(\mu m\). Note the significant taper on one of these lines - with the base width as 5\(\mu m\) and the top as 69\(\mu m\) for a height of 60\(\mu m\). It was suspected that this
taper shape or trapezoidal cross-section was due to the reflection and scattering from the silicon substrate surface, so that the lower portion of the film was in fact exposed to the laser with a much higher intensity. The structures formed in this experiment did not show apparent difference to the experiments of Table 4-3, i.e. changing number of traces and spacing between traces did not significantly change the line dimensions. One reason is that a single trace (of size 20.8\(\mu m\)) was in fact exposed the polymer of much larger width. This may be due to multiple exposure of the film by the reflected beam from the substrate surface and also because of the better absorption properties of the film material. Thus the additional traces did not contribute much to the line width.

Figure 4-8 and 4-9 show the top view of the lines formed using 200\(\mu m/s\) speed and 3W power, and with traces of 11 and 7 respectively, spaced at 5\(\mu m\).

![Figure 4-8: Top view of an exposed line using 11 traces at 5\(\mu m\) spacing; table speed 200\(\mu m/s\), laser power 3W, lens - 5cm focal length and film thickness <100\(\mu m\)](image)

![Figure 4-9: Top view of an exposed line using 7 traces at 5\(\mu m\) spacing; table speed 200\(\mu m/s\), laser power 3W, lens - 5cm focal length and film thickness <100\(\mu m\)](image)
4.5.3 Position of focal point in the film

The beam was focused at the bottom of the film (or surface of the substrate), and then the substrate was moved downwards away from the focal points in small steps up to 500µm (the thickness of the film). In other words, the observations of Table 4-5 were taken with focal point at different heights within the film. Other parameters used were: table speed 200µm/s, lens 5cm, and film thickness ~ 500µm.

Table 4-5: Results of laser-LIGA experiments for focal point positioning

<table>
<thead>
<tr>
<th>Substrate below focal point (µm)</th>
<th>Laser Power (W)</th>
<th>Traces per Line</th>
<th>Spacing between traces (µm)</th>
<th>Structure Height (µm) (error ~5µm)</th>
<th>Structure Width(µm) (error ~5µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3</td>
<td>11</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>3</td>
<td>11</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
<td>11</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>200</td>
<td>3</td>
<td>11</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>500</td>
<td>3</td>
<td>11</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
<td>11</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>200</td>
<td>5</td>
<td>11</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>5</td>
<td>11</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>5</td>
<td>11</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0</td>
<td>5</td>
<td>11</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0</td>
<td>3</td>
<td>7</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>3</td>
<td>7</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
<td>7</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>200</td>
<td>3</td>
<td>7</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>300</td>
<td>3</td>
<td>7</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>500</td>
<td>3</td>
<td>7</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

.......... to be continued next page
Table 4-5: Results of laser-LIGA experiments for focal point positioning

<table>
<thead>
<tr>
<th>Substrate below focal point (μm)</th>
<th>Laser Power (W)</th>
<th>Traces per Line</th>
<th>Spacing between traces (μm)</th>
<th>Structure Height (μm) (error ~5μm)</th>
<th>Structure Width(μm) (error ~5μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>200</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0</td>
<td>3</td>
<td>4</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>3</td>
<td>4</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
<td>4</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>200</td>
<td>3</td>
<td>4</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>500</td>
<td>3</td>
<td>4</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0</td>
<td>5</td>
<td>4</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>5</td>
<td>4</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>5</td>
<td>4</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>200</td>
<td>5</td>
<td>4</td>
<td>10</td>
<td>460</td>
<td>150</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
<td>4</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>500</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The tapering results of Table 4-4 led to this experiment in Table 4-5. A thicker film (500μm) was experimented and the focal point was placed at various points with in the film. But no additional tapering was seen to happen with varying the focal point position. This is expected from the optical calculations of section 4.3.2, where it is seen that as far as the depth of focus of the lens is comparable to the thickness of the film, no tapering is expected. Beyond that, the beam expands by only a few microns. So, the tapering can be attributed to the reasons already given in section 4.5.2, i.e. bottom would be wider than the top as it gets exposed by the beam of much higher in intensity (because of beam reflection and scattering from the substrate surface).
An interesting observation, however, was made in this experiment. The lines formed (500μm high) did not have enough mechanical strength (as being only ~100-150μm wide) to be able to stand straight up, even though their base were firmly attached (good adhesion) to the silicon substrate, i.e. the tall structures swayed to the sides. Figure 4-10 shows the side view of one such line. This led to the conclusion that although the polymer could be exposed up to greater thicknesses by the beam for the small structural dimensions, the structures would need some solid end support to be able to stand straight. As an example, even if a thin line can not stand straight, it would have no such problem when being a part of a structure such as a mesh with solid and thick side walls.

Figure 4-10: Side view of an exposed line using lens focal point with in polymer film; table speed 200μm/s, laser power 5W, lens - 5cm focal length and film thickness ~500μm

### 4.5.4 Nature of substrate

Previous experiments used silicon substrate for polymer deposition. A glass substrate was used in the following experiment to explore the surface phenomenon such as reflection, scattering and adhesion, experienced with silicon substrates before. This substrate had half of its surface transparent, and the other half coated with a thin film of aluminium. Other parameters were: film thickness ~ 500μm, line length 2.5mm, displacement between traces 5μm, thickness of glass substrate 1mm. The tabular results are given in Table 4-6.
Table 4-6: Results of laser-LIGA experiments for substrate selection

<table>
<thead>
<tr>
<th>Table Speed (μm/s)</th>
<th>Laser Power (W)</th>
<th>Traces per Line</th>
<th>Substrate below focal point (μm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>3</td>
<td>11</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>11</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td>200</td>
<td>3</td>
<td>11</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>11</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>11</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>11</td>
<td>1500</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
<td>11</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>11</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>11</td>
<td>1500</td>
<td>Very thick line observed on the monitor while exposure</td>
</tr>
<tr>
<td>20</td>
<td>3</td>
<td>1</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
<td>11</td>
<td>1000</td>
<td>Line stayed on aluminium</td>
</tr>
<tr>
<td>200</td>
<td>5</td>
<td>11</td>
<td>1000</td>
<td>Line stayed on aluminium</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>1</td>
<td>1000</td>
<td>Line stayed on aluminium</td>
</tr>
</tbody>
</table>

While the lines were observed in most of the cases, because of their poor adhesion to the glass surface, they were washed away during development. Hence no meaningful observation on tapering, etc. could be obtained. Wherever the glass was coated with aluminium, the lines stayed (good adhesion) but were totally burnt and irregular (see Figure 4-11) and hence no meaningful data (structure width and height) could be obtained. But it definitely proved that silicon is a better substrate than glass for such kind of exposure.
4.5.5 Lens used

A convergent lens of 10cm focal length was used in this experiment. A convergent lens with a longer focal length allowed a longer depth of focus, and hence a larger working distance. Since the lens had been changed, table speeds were verified in the range of 200μm/s (optimum speed with 5cm lens) to 20μm/s, and so were the laser powers between 2.8W and 4.5W. Displacement between traces was set at 10μm, and line length 2.5mm.

Table 4-7 gives the results.

Table 4-7: Results of laser-LIGA experiments for 10cm focal length lens

<table>
<thead>
<tr>
<th>Table Speed (μm/s)</th>
<th>Laser Power (W)</th>
<th>Traces per Line</th>
<th>Substrate below focal point (μm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>2.8</td>
<td>7</td>
<td>0</td>
<td>Line formed; Height = 430μm</td>
</tr>
<tr>
<td></td>
<td>3.6</td>
<td>7</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>7</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>7</td>
<td>200</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>7</td>
<td>400</td>
<td>-</td>
</tr>
</tbody>
</table>

........ to be continued next page
Table 4-7: Results of laser-LIGA experiments for 10cm focal length lens

<table>
<thead>
<tr>
<th>Table Speed (μm/s)</th>
<th>Laser Power (W)</th>
<th>Traces per Line</th>
<th>Substrate below focal point (μm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>4.5</td>
<td>7</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>7</td>
<td>200</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>7</td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>4.5</td>
<td>7</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>40</td>
<td>4.5</td>
<td>7</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>500</td>
<td>4.5</td>
<td>7</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>7</td>
<td>200</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>7</td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td>200</td>
<td>4.5</td>
<td>5</td>
<td>400</td>
<td>Square pattern exposed</td>
</tr>
<tr>
<td>40</td>
<td>3</td>
<td>7</td>
<td>400</td>
<td>-</td>
</tr>
</tbody>
</table>

A change in lens (from 5cm to 10cm) would only make the structures look better especially for thick films (~1mm), if any change is observed at all. The 10cm lens did result in a larger spot size (41.4μm from section 4.3.2) but that was irrelevant as the structures of width no smaller than 50μm were desired. In the experiment, thin (~50μm) and tall structures (~500μm) were obtained, thereby providing aspect ratios of about 10. Figure 4-12 shows the side view of one such line.

Figure 4-12: Side view of an exposed line using a 10cm focal length lens; table speed 200μm/s, laser power 3.6W, 7traces at 10μm and film thickness ~500μm
4.5.6 Mesh structure

With all the parameters optimized for the film exposure, a mesh structure on a deposited film of thickness of about 1mm was experimented. The results are presented in Table 4-8 below. The mesh structure had the side walls relatively thick with 40 traces, and the interior mesh lines with varying number of traces (and hence widths) as seen in Figure 4-13. The number of traces for various lines are shown along with the thickness of the lines after exposure in brackets. Other parameters used were: table speed $200 \mu m/s$, laser power 3-5W, lens of 10cm focal length and film thickness $\sim 1100 \mu m$.

Table 4-8: Results of laser-LIGA experiments for mesh structure

<table>
<thead>
<tr>
<th>Traces per Side-wall</th>
<th>Traces per Grid Line</th>
<th>Structure Height ($\mu m$) (error $\sim 5 \mu m$)</th>
<th>Side-wall Width ($\mu m$) (error $\sim 5 \mu m$)</th>
<th>Grid Line Width ($\mu m$) (error $\sim 5 \mu m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>30</td>
<td>1100</td>
<td>380</td>
<td>340</td>
</tr>
<tr>
<td>25</td>
<td>20</td>
<td>10 traces ($180 \mu m$)</td>
<td>230</td>
<td>207</td>
</tr>
<tr>
<td>15</td>
<td>10</td>
<td>5 traces ($122 \mu m$)</td>
<td>180</td>
<td>122</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>40 traces ($380 \mu m$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4-13: Mesh structure exposed using a table speed $200 \mu m/s$, laser power 3-5W, lens of 10cm focal length and film thickness of $\sim 1100 \mu m$
As seen from Table 4-8 and Figure 4-13, the smallest width of the line formed (corresponding to 5 traces) was 122 $\mu m$ for the height of 1.1mm or 1100 $\mu m$, i.e. aspect ratio as high as 10 were obtained. The spacing between the lines was about 400 $\mu m$ although it could be reduced further without any difficulty. The side walls were fairly straight and smooth as seen in Figure 4-14. The tapering shape, observed in the preliminary experiments with thinner films, is not as prominent in this case. Note that this side wall used 40 traces, and it seems that with more and more number of traces (i.e. greater line widths), the degree of taper keeps falling.

![Figure 4-14: Side view of the side-wall of the mesh structure exposed using 40 traces](image)

Figure 4-15 shows the four quadrants of the exposed mesh structure. As seen, the grid lines were not found to be very straight. The reason might be that many (six) lines were exposed at very small spacings resulting in shrinkage of the polymer because of surface tension. The difference in thicknesses caused different degree of shrinkage on the lines. Also seen in the figures is the dark color for some portions of the exposed structure. The polymer in those areas was burnt because of the over-heating resulted from using many traces for the respective lines and also from the small spacings between the lines which raised the heat/temperature in the area.
4.5.7 Experiments with RX00727 and RX00768

These polymers were received late into the thesis, and hence a detailed investigation on them could not be completed. The optimum parameters from the experiments with Irgacure 184 were used once again for RX00727 for simple lines. The results are compiled as under in Table 4-9. Spacing between the traces was set at 10μm, and a 10cm focal length lens and silicon substrate was used. First five readings in the table correspond to the exposure of a ~1mm thick layer of RX00727, while the last to a ~2mm layer of RX00768.
Table 4-9: Results of laser-LIGA experiments with RX00727 and RX00768 photosensitive polymers

<table>
<thead>
<tr>
<th>Table Speed (μm/s)</th>
<th>Laser Power (W)</th>
<th>Traces per Line</th>
<th>Structure Height (μm) (error ~5μm)</th>
<th>Structure Width (μm) (error ~5μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>1</td>
<td>11</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>11</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>11</td>
<td>750</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>7</td>
<td>750</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.75</td>
<td>40</td>
<td>1700</td>
<td>550</td>
</tr>
</tbody>
</table>

The top view of the exposed line (third entry of the table above) is seen in Figure 4-16. The line has a width of about 80μm and height 750μm to provide an aspect ratio of about 10. This experiment proved that different polymers would use the settings which are not very different from each other. A mesh structure (see last entry in Table 4-8) similar to that in section 4.5.6 was also exposed with RX00727 at a power of 4W, but the structure (though was visible and exposed) was badly burnt. However, the measurements were done for the side walls which used 40 traces. The height of the walls were 1700μm and the width 550μm. Interestingly, the side wall aspect ratio in this case was about 3 which was the same for Irgacure 184 (see Table 4-8 in section 4.5.6). The side view of the side wall is seen in Figure 4-17.
RX00727 is a low viscosity material and hence considerably lower powers (than Irgacure 184) would rise the temperature (especially for closely spaced lines) high enough to cause the burning. RX00768 is a slightly higher viscosity material but is still thinner (lower viscosity) than Irgacure 184. Higher viscosity materials should be preferred in such kind of exposure because of many reasons. The thicker films would effectively withstand the turbulence effect occurred when a powerful beam hits the film surface to give fairly straight structures. The thicker films are also easy to deposit (for high aspect ratios). In other words, Irgacure 184 is a better choice in this case.
## 4.5.8 Result summary

The results obtained in the experiments above are compiled in Table 4-10.

### Table 4-10: Overall result of laser-LIGA experiments

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power</td>
<td>Higher powers between 3-5 W are generally required</td>
</tr>
<tr>
<td>Table speed</td>
<td>Slower table speeds around 200μm/s generally work well</td>
</tr>
<tr>
<td>Number of traces</td>
<td>A few (2-3) traces are enough; additional traces do not add much to the structure thickness, as just one trace exposes much more thickness of the material than expected</td>
</tr>
<tr>
<td>Spacing between traces</td>
<td>Depends upon the lens type; 10μm works well for both 5cm and 10cm focal length lenses</td>
</tr>
<tr>
<td>Position of focal point</td>
<td>Provided the thickness of film is comparable to the depth of focus of the lens, its effect is insignificant</td>
</tr>
<tr>
<td>Substrate used</td>
<td>Silicon works well while glass does not</td>
</tr>
<tr>
<td>Lens used</td>
<td>Greater the thickness of the film, the higher focal length a lens should have; 10cm lens worked well up to thicknesses of 1-2mm</td>
</tr>
<tr>
<td>Polymer type</td>
<td>Provided the polymer is sensitive to the wavelength of the radiation used (Argon Ion laser), higher viscosity helps during exposure. Therefore, Irgacure 184 is better than both RX00727 and RX00768.</td>
</tr>
<tr>
<td>Developer used</td>
<td>All exposed polymers developed well in acetone and methyl alcohol</td>
</tr>
<tr>
<td>Minimum spacing between lines (structures)</td>
<td>A spacing of only ~400μm was experimented, although it is believed that it could go down to 100μm without much difficulty</td>
</tr>
<tr>
<td>Minimum thickness of lines (structures)</td>
<td>In the range of 100-120μm</td>
</tr>
<tr>
<td>Best aspect ratio attained</td>
<td>10</td>
</tr>
</tbody>
</table>
4.6 Conclusions and Summary

A new technique for shadow mask production called ‘Laser-LIGA’ for the production of high aspect ratio microstructures (holes) was presented in this chapter. It used a 5W Argon Ion laser and a photosensitive polymer Irgacure 184. Various steps involved in the process and the factors affecting it were discussed. Experiments explored all the possible areas and the detailed results were given. A mesh structure, with the lines cutting each other at right angles, was fabricated in the process. The aspect ratio as high as 10 was obtained for these lines. This mesh structure was equivalent to a shadow mask, i.e. the spacings between the lines (hollow areas) could be considered as holes of a shadow mask, with the line thickness determining the spacing between the hollow areas or holes (centre to centre spacing between the holes would be the sum of hole size and the thickness of the line dividing the two). In the experiments, lines as thin as 122μm (see Figure 4-12) were formed. The spacing between the lines or the hole size of about 400μm was also obtained, though a lot of room for improvement exists there. Reducing the spacing between the lines or the hole size was not stressed in the experiments, but it is believed that it could be reduced to 100μm without much difficulty. If that is true, a shadow mask with 100μm holes of aspect ratio 10, spaced at 200μm (hole size 100μm + line thickness ~100μm) can be fabricated. Further research from this point onwards would only make the results better and better. The advantage of this method is its potential for mass production. Like a LIGA process, the exposed structure can be used to make a master mould to mass produce the replicas of the original structure.
Chapter 5

Integration

Previous research on Vision Skin [45] devices used separate laser sources and CCD structures. For long term applications, the creation of an integrated laser emitter and CCD system is required. The size and weight of the integrated system is also critical. There is a pressing need to reduce the size and weight of any kind of sensory system mounted on robotic end-effectors such as grippers or anthropomorphic hands [31].

This chapter will present all the components of Vision Skin sensor and describe their integration into a single system. The use of various image acquisition boards and circuits for the operation of integrated Vision Skin is also discussed at the end.
5.1 Components

The various components of Vision Skin are shadow mask, charge coupled device (CCD) sensors, laser diode and light emitting diodes (LEDs), and are described as follows.

5.1.1 Shadow mask

As was discussed in Chapters 3 and 4, three different techniques, viz laser micromachining with polypropylene, photolithography for multi-layer thin film mask, and laser-LIGA with photosensitive polymers, were employed for the production of the shadow mask. While all of them proved to be promising, in the time scope of this thesis, only laser micromachining with polypropylene produced the mask with the desired dimensions. The shadow mask used in the integrated Vision Skin has a thickness of about 500 \( \mu m \), and contains an array of 30 \( \mu m \) holes with centre-to-centre spacing of about 150 \( \mu m \).

Integrated Vision Skin used TC245 type CCD (to be discussed in the following section) for which the shadow mask has 41 (horizontal) x 29 (vertical) holes with spacings of 153 \( \mu m \) and 157.6 \( \mu m \) respectively. An outlook of a piece of polypropylene with shadow mask is shown in Figure 5-1. As can be seen in the figure, shadow mask refers to the grid of holes seen near the centre, which is cut-out and mounted on the CCD in the integrated Vision Skin sensor.

![Figure 5-1: Laser micromachined polypropylene shadow mask](image)

array of 41x29 holes

500 micron thick polypropylene
5.1.2 Charge Coupled Device (CCD) sensors

Two types of CCD sensors from Texas Instruments were employed: the TC211 and TC245. The TC211, which is a smaller array of 192x165 pixels, was used for the development of Vision Skin concept. The larger array of 755x242 pixels of TC245 was used in the integrated Vision Skin. One of the main reasons for choosing these CCDs was that the image acquisition boards were easily available commercially for their designs.

The TC211 is a full-frame CCD image sensor designed specifically for industrial applications requiring ruggedness and small size. A schematic diagram of the TC211’s physical package is shown in Figure 5-2. As seen, it contains only six terminals which makes its operation easier. It has a square image area of 2640 μm by 2640 μm and has 192 (horizontal) by 165 (vertical) pixels, i.e. size of each pixel is 13.75 (horizontal) by 16 (vertical). Twelve additional pixels are provided at the end of each line to establish a dark reference and line clamp. The TC211 uses only one clock to transfer charge row by row through an array. Each clock pulse applied to the image area gate causes an automatic fast clear of the 192 image pixels and 12 dark pixels of the serial register before the next image line is transferred into the serial register. The automatic fast clear feature can be used to initialize the image area by transferring all 165 image lines to the serial register gate under dark conditions without clocking the serial register gate.

Figure 5-2: TC211 mechanical data; units in mm (inches) [64]
The TC211 needs to be used in conjunction with some type of shutter to stop any light falling on the sensor when the charge transfer is taking place. An alternative would be to use a pulsed light source for its illumination.

On the other hand, the TC245 is a frame-transfer CCD image sensor which has a larger image area of 6417.5 μm by 4779.5 μm. It has 755 (horizontal) by 242 (vertical) pixels with each pixel of 8.5 μm by 19.75 μm. Twenty-nine pixels are provided in each line for dark reference. A schematic diagram of the TC245’s mechanical data is shown in Figure 5-3.

Figure 5-3: TC245 mechanical data; units in mm (inches) [64]

In contrast to TC211, the image or charge in TC245 is rapidly shifted to an array of identical size that is covered and not exposed to light. In transferring an image in CCD arrays, the most important stage is not the row transfer but the serial shift of columns of each row into the charge-to-voltage converter. In case of the TC245, this is alleviated by transfer-
ring the image rapidly to a temporary storage area and more slowly to the serial shift register. Because the temporary array is protected from light, there is no light contamination or smearing of the image, which is seen with the TC211. Also, using the TC245 does not require any shuttering device as the shutter exists in electronic form on the array.

Both types of CCDs have their own advantages and limitations. While the TC211s are low in cost ($70 each), their small image area and requirement of shutter makes the operation difficult. So they were only used for the development of Vision Skin concept for testing various shadows masks and experiments, and were treated as throwaway test structures. On the other hand, the TC245s cost much more (about $340 each) but have a much larger image area (more than four times the TC211’s). They are much more light sensitive than the TC211s, and require no shutter. However, their image area is situated at the centre of the package and is about 6 mm away from the ceramic end near which a laser diode is used. This makes the proximity detection capability of the sensor near the point of contact nearly impossible. For initial and near contact proximities, the TC211s have the edge as their image area is only about 2 mm into the ceramic package from all sides. The situation is better explained using Figure 5-4. Overall, the advantages of the TC245s outweigh their limitations and hence they are used in the integrated Vision Skin sensor. A real device, however, could use a different package which allows the laser beam to come closer to the image area of the CCD (photodetector array).

![Figure 5-4: Effect of CCD packaging on initial proximity detection](image)

\[
x = \text{~2mm for TC211} \\
= \text{~6mm for TC245}
\]

Figure 5-4: Effect of CCD packaging on initial proximity detection
5.1.3 Laser diode

Several types of laser diodes were used as the source for the proximity measurements. Initially a 3 mW, 670 nm wavelength laser diode from Melles Griot (model 56DLV101) was used. This diode came with an integrated collimating lens in one package to collimate the beam to a 1x3 mm spot that expands at only 1.5 milliradians. Though this 9 mm diameter, 16 mm long, and 1 gram diode worked perfectly for the integrated device, it costed $250 and hence was expensive, and was also difficult to obtain.

So a cheap alternative was considered which involved using separate diode and lens units. The lens assemblies were available at a very low cost from Melles Griot (06GCL002 or 04-501-A01), and 3 mW, 670 nm wavelength bare diodes were available from Toshiba (TOLD9230) for only $40 a piece. The diodes could easily be mounted inside these lens cases, and the lens was adjustable to place the diode at its focal point to produce a collimated beam of about 6 mm in size with less than 0.5 mrad divergence. Figure 5-5 shows this laser diode along with the lens case in which it was mounted. These lens cases were somewhat bigger (14 mm diameter and 20 mm long) than the integrated diode used previously, but were successfully implemented in the integrated version at a much lower cost.

![Figure 5-5: Laser diode with the lens case](image)

A higher power 30 mW, 670 nm Toshiba TOLD9150 laser diode was also tried for the possibility of sensor operation in the normal daylight. The same lens case from Melles Griot could be used for this and all other diodes of different power levels available from
Toshiba (TOLD9200 series) and hence they could easily replace each other in the integrated sensor. But at its normal lasing current of about 95 mA (typical), it saturated the CCD pixels. Hence no meaningful data could be extracted from the sensor. Also, the 30 mW diode was expensive and costed $421 each. So, the 3 mW laser diode was used in the integrated Vision Skin and for the proximity experiments discussed in Chapter 7.

5.1.4 Light Emitting Diode (LED)

LEDs were introduced in the Vision Skin integrated sensor for wide area illumination of the objects for imaging purposes. The LEDs were chosen to be of the same wavelength (670 nm red) as the laser diode to keep the possibility open for the use of a filter which filters all the wavelength except this to enable the sensor to work in the normal ambient light.

An array of LEDs were embedded in a 4 mm thick wooden plate in a circular fashion with a slot at the centre for the CCD sensor as shown in Figure 5-6. The diameter of the slot (about 20mm) was selected such that the larger CCD (TC245) would easily fit in. In the advanced design (will be discussed in the next section), the LEDs were mounted in an aluminium plate which also made the top cover of the Vision Skin integrated sensor. The circular slot at the centre was replaced by a sapphire window for the protection of sensor from dirt, contamination and scratches. The same aluminium plate had two screw threads on one of its edges to be attached to the robotic gripper arm. As seen in Figure 5-6, the tops of the LEDs were chopped off (by using a fine hack-saw) to the level of the plate to enable an object to come in contact with it. A very fine file was used to smoothen out the chopped off surface of the LEDs for better light quality.
Typical voltage drop across an LED is about 2 V for currents between 10 and 50 mA. As seen in the figure, a set of LEDs were used in series with a net voltage drop of about 25 V, which was supplied by an ordinary 30 V variable DC power supply. These 5mm LEDs (55-552-0) were obtained from Mode Electronics with a brightness rating of 3.2 MCD at 10mA.

5.2 Integration

The integration of Vision Skin was a step by step process. First, the CCD was modified by removing the glass cover so that the shadow mask could be mounted on its image array. After the integration of the CCD and shadow mask, laser diode and LEDs were also assembled into the system to make a complete integrated package of the Vision Skin sensor.

5.2.1 Modifying the CCD sensor

The CCDs available from Texas Instrument were covered by a thin piece of glass to protect the CCD from moisture and dirt. To mount the shadow mask on the CCD image array, this glass cover had to be removed. Since this glass cover was firmly glued on the edges of the CCD by the epoxy, the only safe way to take the cover off without damaging
the CCD was to use the Argon ion laser and the XY positioning table set up (as discussed in Chapter 3). The edges of the CCD were exposed by the continuous laser beam, at a maximum power of 5 W focussed using a 50 mm focal length lens to a 20 micron spot, in a back and forth pattern which melted the epoxy. A total of about 20 traces spaced at 50\(\mu\)m were required at a table speed of 192,000 \(\mu\)m/s. Sometimes, the process had to be repeated as one time exposure was not enough. Afterwards, the glass cover was lifted from the surface using a simple leverage such as the tip of a tweezer. The trapped fumes and the heat resulted from the high power laser exposure caused some of the areas on the CCD array to turn dark. So as a final step, the CCD image area was carefully wiped by the acetone using a cotton-swab to clean any dark areas which might have resulted in the process.

5•2•2 Integrating CCD and shadow mask

After the glass cover removal step, the shadow mask (as seen in Figure 5-1) was carefully cut out of the piece of polypropylene, by using a pair of scissors, to the size of the CCD image area. The mask was then placed on the CCD image area and then held at three of its corners by micromanipulator probes. These probes allowed X, Y, and Z positioning with the resolution of a few microns. The probes were moved slowly such that the mask’s position could be adjusted for both X and Y translations as well as for rotation \(\theta\) about the central axis. At the same time, the CCD was plugged to the image acquisition board (to be discussed in the following section) so that a live image from the CCD is seen as an aid in mask alignment. A view of this live image as seen on the computer monitor is seen in Figure 5-7.
Once the holes of the mask are aligned to the edges of the CCD image area, the four corners of the mask were glued to the CCD by using superglue applied with a syringe. The tip of the hypodermic needle allowed only tiny droplets of the glue to be applied thereby reducing the chances of glue spreading on the mask. The probes were then kept in position for about two hours to guarantee proper bonding. In the earlier attempts when the injection method was not used, this glue spread resulted in the blockage of holes near the mask corners reducing the net image area on the CCD.

Figure 5-8 shows the unmodified TC245 CCD with the glass cover (left) and modified version after glass cover removal and shadow mask gluing (right).
5.2.3 Integrating shadow-masked CCD and diode laser

The integration of shadow-masked CCD and the diode laser provides for precise alignment of the laser beam with respect to both the rows of the shadow mask holes and the vertical angle to the mask plane. The idea was to mount the shadow-masked CCD and the diode laser in a common mounting block such as plexi glass. Plexi glass had the advantage of being a soft and transparent material which made the things like drilling, fault detection, alignment and trouble shooting easier, yet with enough strength to withstand forces and impacts encountered in such an application.

The integration started with the machining of a small slab of plexi glass for the desired dimensions of the TC245 sitting in a 20 pin socket, the other end of which was connected to the image acquisition board through wires, and the laser diode, as seen in Figure 5-9. Note that while laser diode and CCD socket are seen in the figure, CCD is not.

The slots were made slightly bigger so that the components could be inserted and removed easily, but the bolts were used to hold them in place. Additional bolts were used to rotate and position the CCD in x and y axis for alignment with respect to the laser beam. The
slot for the laser diode was drilled at 45 degree in two different diameters - one for the diode itself and the other smaller path hole near the top for the laser beam (about 6 mm in size with less than 0.5 mrad divergence). Figure 5-10 shows the cross-section of the integrated sensor shown in Figure 5-9.

![Cross-section of plexi glass version of integrated Vision Skin](image)

To restrict the size of this beam, another mask called ‘Proximity mask’ was used. This mask has one hole for one-spot proximity and three holes for three-spot proximity mode (to be discussed in Chapter 7). Proximity mask uses the same 500 μm thick polypropylene as shadow mask, with holes of about 150 μm drilled at 45° to produce spots of the size of about 200 μm on the sensor array (see Figure 3-11). The one advantage of using these holes instead of a lens was that the beams coming out of these holes were also gaussian in nature. Also, the size of the proximity spot desired on the sensor could easily be obtained by using a spot of about that size on the mask. The CCD mount was placed in its respective slot such that the surface of the mask was level with the Plexi Glass surface. The laser beam (as it comes out of the proximity mask hole/holes) was aligned to just miss the top near edge of the CCD so that the closest possible proximity measurement can be made.
on the objects. In case of integrated Vision Skin sensor using TC245 CCD, this is about 7 mm because of the way the CCD image area is packaged inside its body as explained earlier.

For the alignment, first of all it is made sure that the plexi glass mount and the CCD surface are leveled in both x and y axis. The socket of the CCD is then plugged into the image acquisition board and a live image of the CCD is seen on the PC monitor. The laser diode power supply is turned on and the current is raised to the maximum operating value of 80 mA for the laser action. Then an object, which is also in level with respect to the CCD and the plexi glass mount, is placed over the CCD. The leveling was done using an accurate carpenter's level. A smooth piece of glass slide which is sprayed by a thin film of flat white paint, with the ability to diffuse light falling on it, is considered an object as described in Chapter 2. The laser beam hits the object and the diffused beam is received by the sensor. This is exactly the way Vision Skin would be working for the proximity measurements of Chapter 7. The idea is to focus the spot over a desired row of the sensor and to make sure that the spot stays for its peak value on the same row as the object moves from the minimum to the maximum height (proximity) range of the sensor. If this is not the case (not properly aligned) as seen on the live image of the camera, the CCD position is fine tuned using the adjustment bolts (by rotating and/or moving in xy axis) until the desired effect is achieved.

In case of three-spot proximity mode of the sensor, the same procedure is used. The only difference is that there are now three different spots to align for three different rows. This is equally simple as making sure one of them is aligned will automatically guarantee the same for the other two spots. It, of course, assumes that the three holes of the proximity mask make a triangle whose altitude is in line with the rows of the proximity mask on the CCD. The spacing of holes in this triangle is adjusted such that after its 45° projection on the object and hence on the sensor array, it will be seen as an equilateral triangle of sides 3 mm. The sensor after this process is assumed to be aligned and ready for proximity measurements.
5.2.4 Integrating shadow-masked CCD, diode laser and LEDs

While the integrated sensor from plexi glass was a good design and worked well, an improvement in design came later which especially enhanced the imaging capability of Vision Skin by the addition of the broad area light source of light emitting diodes (LEDs). Figure 5-11 shows the cross-section of final version of integrated Vision Skin sensor.

A total of nine LEDs were used in the design (though only two are shown for clarity in this figure) in a circular fashion around the circle to form a ring. In addition, a sapphire window was also added above the sensor to protect it from dirt, scratches and contamination. This version was intended for three-spot proximity mode, and for that matter the proximity mask had three holes with the same dimensions and spacing as before, but in this case the holes were drilled straight and there was no angle involved. Rather, the proximity mask containing these straight holes was elevated at 45° to produce the same effect, as seen in the figure.
The other difference in this case was the choice of integrating assembly - machined aluminium block. Figure 5-12 shows the top view of the sensor before the installation of the face plate (the plate with LEDs and sapphire window). Figure 5-13 and 5-14 depict two different views of the final integrated Vision Skin.

Figure 5-12: Top view of integrated Vision Skin without face plate

Figure 5-13: Final integrated Vision Skin (side view)
As noted in section 5.1.4 earlier, the LEDs have their top flushed-out to be in level with the sensor’s face plate, so that the objects can come in contact with it. Also seen in Figure 5-13 and 5-14 is that the face plate has four screw threads on the corners for the attachment to the robotic gripper arm at Kinetic Sciences Inc. Furthermore, the CCD socket is embedded in a rectangular piece of plexi-glass for firm support and electrical insulation, and the socket is connected by a ribbon cable to the image acquisition board. The socket assembly is held in the air by the use of adjustment bolts of aluminium block. Rest of this aluminium integrated sensor, including the alignment procedure, is the same as that of Plexi Glass integrated version.

5.3 Operation

5.3.1 Power supply

In the proximity mode of Vision Skin, the laser diode power supply is turned on, and the current is slowly raised to the operating value of 80 mA for a 3 mW laser for a true laser action. During the imaging mode, the diode supply is turned off and the LED supply is turned on. Typical voltage drop across an LED is about 2 V for currents between 10 and 50 mA. As seen in Figure 5-13, a total of nine LEDs are used in series with a net voltage drop
of about 18 V which is supplied by an ordinary 30 V variable DC power supply. The intensity of the light from these LEDs can be varied by varying the voltage, but a care is taken not to drag the voltage into the breakdown levels. A function generator can also be used in conjunction with the power supply to generate a pulse of light of desired time period. This is especially helpful in case of TC211s were a shutter is required while exposure, e.g. if an exposure time of 1 sec is desired, the CCD exposure time is set somewhat higher like 2 sec, and during this interval of 2 seconds, an already programmed 1 sec time period pulse is triggered using a function generator, so the CCD is exposed only for an interval of 1 sec. In case of TC245s and hence in integrated Vision Skin, this is not required because of the CCD’s ability to integrate light without the need of a shutter.

5.3.2 Image Acquisition Board

One reason for using the TC211 and TC245 from Texas Instruments was the availability of the image acquisition boards to control and read the images from the CCDs. Two different useful approaches were considered: a non real time approach in which the signal is captured and slowly converted to a digital format, and a digital approach in which an analog-to-digital conversion is done directly at high speed on the output of the CCD. While the former had an advantage of outputting an NTSC television signal that can be displayed on any TV, it had typical noise problems of the analog format. The latter approach should have less noise as the AD conversion is done directly on the output of the CCD. Also, these boards could do subframe scanning, where they only look at a subset of all the CCD pixels (e.g. every second pixel, every fourth pixel, etc.). This would allow faster Vision Skin operation by looking only at the areas where the need for proximity measurements occurs.

For the first approach, the boards were created from the CCD Camera Cookbook [61]. The book gave step by step instructions for the construction and debugging of the boards. The printed circuit boards were obtained from University Optics. A total of three boards, two for the TC211 and one for the TC245, were built by Darren Bergen [45] in the
early stages of Vision Skin development. The boards could be easily interfaced to an IBM PC, and were controlled by the programs for image grabbing, displaying, etc. running in MSDos environment, which were also included in the book. Since the boards were external to the computer, parallel port cables were used to interface boards and the PC to transfer the data. These acquisition boards allowed the image exposure time to be set from 0.1 second to 15 minutes, but were capable of taking only one image at a time. So, the system was used for taking single frame images instead of real time video signals. The fastest displayed image, using a reduced view of the camera, was one frame per second. These boards also required a power supply of ±15 V. A complete set up is shown in Figure 5-15, where a power supply of ±15 V feeds a TC245 board which is controlled by a software installed in a PC.

The advantages of these board were the ease of availability of parts, simple assembly, low cost ($100) and the availability of software to grab and store the images. Because of the relative simplicity of boards and programs, older models of 80x86s could be used. Both 80486 and 80286 PCs were used in image acquisition.
The images acquired from these boards have a 12 bit accuracy and can be stored on a hard drive or diskette. These images are transferred to Sun Spark workstations, where the programs are written in Matlab to translate to the standard ‘tiff’ format, parse into pixel areas (to be discussed in the following section), display, and analyze the results. These Matlab routines are presented in Appendix II.

The second digital approach involved using fully digital EDC-1000 series cameras (EDC-1000TE for TC211 and EDC-1000L for TC245) from Electrim Corporation [62-63]. While both the cameras were used in Vision Skin project, integrated Vision Skin used EDC-1000L which is designed for the TC245s. The camera consists of three parts: camera head assembly, an interface card and a connecting cable. Figure 5-16 shows connecting cable, one end of which is connected to the camera head, and the other end has to be connected to the interface card sitting in a slot in an IBM class PC.

![Electrim camera head and interface card connecting cable](image)

Figure 5-16: Electrim camera head and interface card connecting cable

The camera head contains an amplifier section which reads the signals directly from the CCD and converts them into an 8-bit digital form. The data is read by the interface card which stores the data in a memory map. The software to view and capture the images are also given by Electrim Corporation, which is given in Appendix III for EDC-1000L camera. Under software control, the system can set the exposure time from 1 msec to several hun-

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dred seconds, and can store the images in ‘.tiff’ format. To display and analyze this format in Matlab on Sun Spark stations, routines were written to convert this format to ‘.pnm’ and to display it, which are given in Appendix IV.

To read a complete TC245 array, the camera converts about 1,000,000 pixels per second. Thus the EDC-1000 series will capture a TC211 image at a 30 Hz rate, and a TC245 image at a 10 Hz rate. Note that a subset of the CCD (e.g. every second pixel, every fourth pixel, etc.) can be read at a much faster rate as the system is analog-to-digital speed limited.

5.3.2.1 Image Parsing

One important fact to consider while using an integrated CCD-shadow mask combination is that the CCD detectors (pixels) tend to be smaller (13.76 $\mu m$ by 16 $\mu m$ for TC211 and 8.5 $\mu m$ by 19.7 $\mu m$ for TC245) than the holes (30 $\mu m$) of the mask, and that most of the CCD detectors are covered by the mask and are not used, as depicted by Figure 5-17 for a portion of the array. The challenge is not only to ignore the detectors not needed, but also to combine the information from the pixels situated under each hole. Hence a virtual detector is created, which is nothing more than summing all the detectors that exist under each hole. From Figure 5-17, it is seen that a total of eight CCD detectors exist under each hole, and by adding the light received by these detectors, the total light falling on each hole can be calculated. The group of these eight detectors under each hole is called a virtual detector, and the CCD image is considered to be having these virtual detectors only (which is equal to the number of holes), while the rest are ignored. The dark current from the ignored detectors may still cause a problem, but subtracting the dark image from any given image would take care of it. For the dark image, the sensor is covered from the ambient light (room light, etc.). With the sensor in dark, a full frame image of the CCD is taken and saved under a separate file. This image record the intensity value (noise) of each pixel under dark conditions, which is subtracted from each image taken later on.
However, to determine whether a detector (pixel) lies under a hole and to identify the position of these detectors is a memory consuming task. For example in case of the TC245, this would amount to either storing 755x242 (=182710) pixels with the corresponding hole values or storing all the pixels under a certain hole. An easier way is to parse areas of the image that correspond to a certain hole. The parsing area is just a rectangular range which contains all the detectors under a hole (i.e. virtual detector). The values are summed in this range and then stored in an array whose index is the virtual detector location. Thus only one value is needed for each virtual detector. Figure 5-18 demonstrates parsing method for a portion of the image involving two holes (and hence two virtual detectors). As seen, parsing might also cover detectors which are not a part of a virtual detector and are totally covered by the mask, but they only contribute dark current which is again eliminated by dark current subtraction from the image. With dark current subtraction, the parsing areas can be larger than the holes with no additional errors, as long as the areas do not overlap as seen in Figure 5-18.
Parsing code for Matlab is given in Appendix II. Note that this code is specific to each CCD-shadow mask combination depending upon the orientation (alignment, etc.) and position (exact location of holes over the pixels) of the mask over the CCD.

5.4 Summary

The chapter presented a description of all the components of Vision Skin: shadow mask-CCD combination, laser diode and LEDs. The steps involved in the integration of Vision Skin were presented. The Plexi Glass mount and the more recent aluminium block version of the integrated sensor were presented. Finally, the use of image acquisition boards for image capturing was detailed, along with the process of image parsing, displaying and analyzing. The capabilities of the two types of boards used for the purpose were also discussed.
Chapter 6

Imaging results

Vision Skin has a low resolution imaging capability at close range, as explained in section 2.2. The uniqueness of Vision Skin imaging is its lensless operation. Vision Skin uses a shadow mask to create the image on the detector system, which means that it contains no refractive elements such as lenses or fibre optic bundles. Unlike any refractive element, the Vision Skin shadow mask is wavelength independent. More importantly, in contrast to lenses shadow masks are always in focus. In the close working range (smaller than the thickness of the shadow mask i.e. 0.5mm), the Vision Skin retains the same resolution independent of the distance of the object [46]. In case of a lens system, an object may not stay in focus while being closer than the lens’s focal length f. Furthermore, a simple lens of focal length f=1mm (say) is a very small, highly curved piece of glass, which has a depth of focus of only 0.08 mm at that distance. clearly for such a close range operation, a lens system must be continuously refocused. Lastly, lens systems tend to be more bulky. Therefore, Vision Skin has the advantage of being a small and wavelength independent system, which always stays in focus and has no depth of focus (refocusing) problems.
This chapter will present Vision Skin imaging set-up, results and calibration. The results are compared to the ideal simulation results. Imaging of some real life objects is also presented.

6.1 Experimental set-up

The experimental set-up for Vision Skin lensless imaging is shown in Figure 6-1 below. For experiments, a simple checkerboard pattern with alternate black and white squares of 1mm were used. The piece of paper with this checkerboard pattern was mounted on a flat white spray painted glass slide, the back side of which was painted black. Figure 6-1 presents the schematic diagram of the set-up for the imaging experiments.

![Figure 6-1: Lensless imaging set-up](image)

Figure 6-2 shows the actual set-up with the checkerboard mount (the pattern is not seen as it is facing downwards) raised and rotated to the left, though during experiments it is placed directly over the CCD. This mount was equipped with a micrometer which was moved in a well defined increments to slowly increase the height of the pattern from the sensor. The LED mount shown in Figure 5-6 earlier was used for the experiments and is shown in Figure 6-2 with the shadow-masked CCD sitting in the hole at the centre. Note that for imaging experiments, none of the integrated Vision Skin sensors were used because with the
integrated version, the minimum height at which the object could be placed was about 7mm. With the set-up shown in Figure 6-2, object could also come in contact with the sensor. The purpose of this test was to explore the imaging behavior of the sensor for heights below 7mm. As noted in the earlier chapters, because of the geometry of the TC245 CCD, the minimum proximity height could only be 7mm, and the hardware in Figure 5-13 and 5-14 was designed accordingly.

![Figure 6-2: Actual set-up for imaging experiments](image)

The surface of the pattern was flooded by a group of twelve LEDs, and the scattered light was received by the sensor. While the holes under the black regions of the pattern would receive little light, the holes under white areas would. As the pattern moves away, the blur in the image is expected as more and more holes even under the black regions receive some light. Note that although the shown set-up allows the pattern to come in contact with the sensor, the whole area of the pattern was not uniformly illuminated for heights below 2 mm. So in the following section, the imaging results from the height of 2 mm onwards will be discussed.
6.2 Simulations

To better understand the functioning of the sensor and to compare ideal versus actual results, formulas and simulations were created in Matlab and C code [45]. The simulations were based on the formulas given in Appendix IV and those given in section 2.2. The simulation code is given in Appendix V and VI.

Appendix V contains the C-code of the functions for simulating one detector. In this simulation, an ideal point source of light passes from left to right over the centre of the detector. This light sweep produces a view of the response of one detector with the shadowing taking place. Figure 6-3 shows the graph of a simulation where the spot of light is at different heights from the surface of the mask.

![Simulation result of a point source of light moving across a detector with 30μm hole of aspect ratio 16.7 [45]](image)

Figure 6-3: Simulation result of a point source of light moving across a detector with 30μm hole of aspect ratio 16.7 [45]

As seen from the figure above, for all three heights there is a flat portion around the zero displacement point, because for that portion the spot is over the hole and not shadowed by the mask. The intensity is reduced by the inverse square law which is not shown here. The flat area corresponds to a distance of 30μm (i.e. ±15μm) which is the size of the hole. The intensity from the edge of the hole (±15μm) to the cut off region (I = 0) on the either side is attenuated somewhat linearly by the shadowing.

Before going any further, let us consider equation (2-15) again for the acceptance
area (S) of each detector at a height Z. Recall that the S is the diameter of the circle on the object viewed by each detector at a specific height. Table 6-1 gives the S values for all the heights Z tested in the experiment. Also, one half of S is the radius of the circle viewed by the detector, i.e. the farthest displaced point source of light seen by the detector. This value is represented by R, and will be used in the following discussion.

Table 6-1: Acceptance spot of a detector for various imaging heights

<table>
<thead>
<tr>
<th>Object Height Z (in mm)</th>
<th>Acceptance Spot diameter D (in micron)</th>
<th>Acceptance Spot radius R (=D/2) (in micron)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>366.0</td>
<td>183.0</td>
</tr>
<tr>
<td>3.78</td>
<td>483.6</td>
<td>241.8</td>
</tr>
<tr>
<td>4.75</td>
<td>600.0</td>
<td>300.0</td>
</tr>
<tr>
<td>5.7</td>
<td>714.0</td>
<td>357.0</td>
</tr>
<tr>
<td>8</td>
<td>990.0</td>
<td>495.0</td>
</tr>
<tr>
<td>10</td>
<td>1230.0</td>
<td>615.0</td>
</tr>
</tbody>
</table>

In section 2.2 of imaging theory, more and more holes under the black squares were supposed to receive light from the white areas at larger distances according to the large R values from Table 6-1. But somewhat fewer holes were actually receiving any appreciable light in comparison to the bright holes directly under the white areas. This behavior can be explained from the graph of Figure 6-3, where a hole displaced by a distance of 600μm from the light source for a height of 10mm receives almost no light even given the fact that the light point lies at the limit of its acceptance spot. Once again, the advantage of using a shadow mask for imaging becomes clear.

Appendix VI shows the C-code for the simulation of the checkerboard pattern seen by the sensor at various heights. The pattern was represented by a light square of size 996μm with a light spot every three microns, i.e. the square was an array of light points. The values in the simulation were close enough to the approximate 1mm size of checkerboard pattern squares used in experiments of section 6.3 and 6.4. The size used in the simu-
lation was a multiple of three and hence could be centered to represent a value for the true centre of the square. These squares were laid out in the simulation in a manner as the actual checkerboard pattern. The simulation was then carried out for all six experimental heights. The simulated image at the height of 2.8mm (one of the six heights) is only seen here in Figure 6-4. The images at all the heights (including the one in Figure 6-4) will be shown with the experimental images in section 6.4.

Figure 6-4: Simulation of 1mm checkerboard pattern at a height of 2.8mm for 16.7 aspect ratio holes of size 30μm and interspacing 150μm

6.3 Results

The images shown in this section used the set-up of Figure 6-2 and the image acquisition board by Electrim Corporation discussed in section 5.3.2. The board integration time was set to 100 msec to obtain the desired exposure. The LEDs were in continuous ON mode, as the TC245 has its own electronic shutter mechanism. A dark current image was also substrates from each of these images. The dark image was taken with the sensor under dark conditions (no surrounding light) and was saved in a file. The integration time for all the images including the dark image was set to be the same (100ms).

As mentioned earlier, the side of each square on the checkerboard pattern is 1mm, which corresponds to about 6.7 hole-interspacings (~ 150μm x 6 = 0.9mm) of the shadow mask. So, one should see alternate black (dark) and white (bright) squares of size 7 holes
(six hole spacings) by 7 holes on the mask with boarder area of reduced intensity in between. Obviously, this is expected only when the pattern is in contact with the mask. As the pattern moves away, more and more holes under the black region start receiving light and become a part of white (bright) square on the mask, with the net reduction in the size of the black (dark) square. For example, for \( Z = 2.8 \text{mm} \), \( R \) has a value of 183\( \mu \text{m} \) (about one hole spacing) from Table 6-1. This means that one additional hole on each side under the dark square will receive light from the white square of the pattern (though at reduced levels), hence a pattern of 9x9 white (bright) holes and 5x5 black (dark) holes on the mask is expected. Note that the additional holes though receiving light would not be as bright as other holes which are receiving far more light being under the white region of the pattern. This is exactly what is seen at a height of 2.8mm by Vision Skin, as seen in Figure 6-5 below. The bright squares are 9x9 holes with the boarders being dimmer and the dark 5x5. The holes on the edges (of the bright squares) are barely receiving any light as compared to the other holes, hence a checkerboard pattern of alternate dark and bright squares of size 7x7 holes is still seen on the mask.

Figure 6-5: 1nm checkerboard pattern at a height of 2.8mm with TC245, and 16.7 aspect ratio shadow-mask of 30\( \mu \text{m} \) holes at 150\( \mu \text{m} \) spacing
Figure 6-6 shows the same image as Figure 6-5, but is parsed with the code given in Appendix II. An array of 29x40 dark and bright pixels (squares) is shown, which correspond to the light gathered by the corresponding virtual detectors created under each hole (as discussed in section 5.3.2.1). Again, a checkerboard pattern is clearly seen in the picture. Note that the pattern is at 2.8mm from the mask surface, which is equivalent to 5.6 mask thicknesses (the mask being about 500\(\mu m\) thick).

The image of the pattern at a height of 3.78mm along with its parsed image is seen in Figure 6-7 and 6-8 respectively. The pattern is now at a height equivalent to 7.56 mask thicknesses. As seen, the outlook of the image is more or less the same as the previous one except that the dark square appear somewhat rounded in space.
Figure 6-7: 1mm checkerboard pattern at a height of 3.78mm with TC245, and 16.7 aspect ratio shadow-mask of 30μm holes at 150μm spacing.

Figure 6-8: Parsed image of 1mm checkerboard pattern at a height of 3.78mm with TC245, and 16.7 aspect ratio shadow-mask of 30μm holes at 150μm spacing.

Figure 6-9 and 6-10 presents the images at a height of 4.75mm (9.5 mask thicknesses). From Table 6-1, the value of R for this height is 300μm, which is equivalent to two hole spacings. So two additional holes on each side of the original dark square on the mask is expected to receive some light of lower levels. Again these holes do not register much light, but sufficiently more than before to enlarge the bright square to 9x9 holes and reduce the dark square to 5x5, as seen in the figures below.
Figure 6-9: 1mm checkerboard pattern at a height of 4.75mm with TC245, and 16.7 aspect ratio shadow-mask of 30µm holes at 150µm spacing

At a height of 5.7mm, the trend continues and the dark square continue to shrink though not much over the last height (as the R value also changed a little in the process). The pattern is now at a height of 11.4 mask thicknesses. Figure 6-11 and 6-12 presents the images.
Figure 6-11: 1mm checkerboard pattern at a height of 5.7mm with TC245, and 16.7 aspect ratio shadow-mask of 30μm holes at 150μm spacing

Figure 6-12: Parsed image of 1mm checkerboard pattern at a height of 5.7mm with TC245, 16.7 aspect ratio shadow-mask of 30μm holes at 150μm spacing

The corresponding value of R for a height of 8mm (16 mask thicknesses) from Table 6-1 is 495μm, i.e. about three additional holes on each side of the square on the mask should receive the light. As seen in Figure 6-13, there is definitely a lot of light intrusion in the dark area which is reduced to only a few hole spacings each side. Nevertheless, the checkerboard pattern is still seen with an increasing blurriness, as also demonstrated by Figure 6-14.
Figure 6-13: 1mm checkerboard pattern at a height of 8mm with TC245, and 16.7 aspect ratio shadow-mask of 30μm holes at 150μm spacing

Figure 6-14: Parsed image of 1mm checkerboard pattern at a height of 8mm with TC245, and 16.7 aspect ratio shadow-mask of 30μm holes at 150μm spacing

Figure 6-15 and 6-16 show the image at a height of 10mm (20 mask thicknesses). The corresponding value of R from Table 6-1 is 615μm, i.e. four additional holes on each square side would receive light. As a result, dark squares are now reduced to islands of only a few holes surrounded by a flood of bright holes. The checkerboard pattern is barely recognizable at this point, and hence Vision Skin has reached its imaging capability limit.
Figure 6-15: 1mm checkerboard pattern at a height of 10mm with TC245, and 16.7 aspect ratio shadow-mask of 30µm holes at 150µm spacing

Figure 6-16: Parsed image of 1mm checkerboard pattern at a height of 10mm with TC245, and 16.7 aspect ratio shadow-mask of 30µm holes at 150µm spacing

In the discussion above, a fewer number of holes were actually receiving any appreciable light (in comparison to the bright holes directly under the white areas) than expected from the R values given for particular heights given in Table 6-1. The reason can be explained using the graph in Figure 6-3. The intensity received by the holes away from the
light source decreases almost linearly. The farthest holes, even while having the light source within their acceptance spots (with in the value of R from the holes), barely register any light to be seen in the images. This explains why Vision Skin can see the object further than expected.

6.4 Calibration

As seen in all the six parsed images presented in section 6.3, the checkerboard pattern as seen by the sensor does not have the expected constant intensities for the white areas. Rather a varying intensity levels are seen. The reason is that the sensor array is uncalibrated, and the virtual detectors under the holes are registering different intensity values because of difference in hole size, CCD sensitivity and hole position from one hole/detector combination to the other.

This calls for a calibration of the shadow-masked CCD for these differences. Figure 6-17 shows a set-up for this purpose. The shadow-masked CCD sits in level under a parallel uniform light source such as microscope light. A diffuser (glass slide painted by a flat spray white paint on the side facing the CCD) which is also in level with the surface of the mask is placed between the parallel light source and the CCD at a height of 1cm above it. Note that the same kind of glass slide was used for imaging experiments (also for proximity experiments discussed in the next Chapter). The height of 1cm was chosen because it was near the middle point of sensor’s range, and would provide a well diffused light source.
The parallel light was shone from above and the scattered light from the diffuser was received by the sensor. If all the holes have the same size and sensitivity, all the virtual detectors should have the same light intensities. But as seen in Figure 6-18, it was not the case.

This parsed blank image was then used to calibrate all six parsed images seen in the last section. The intensity values of the virtual detectors from this blank image were inverted and stored in a matrix. This matrix was then separately multiplied by the corresponding val-
ues at six different experimented heights, and the resultant images are shown in Figures 6-19, 6-21, 6-23, 6-25, 6-27 and 6-29 to create the calibrated images. The simulated images (see section 6.2) for all the experimented heights are also shown with the corresponding calibrated images for one-to-one comparison between the two. Note that only a small position of the actual size of the TC245 grid is simulated in these simulated images. The idea is to show the behavior of dark and bright squares and their boundaries with increasing distances. Whatever applies to these squares will also apply to the larger grid of more squares.

Figure 6-19: Calibrated image of 1mm checkerboard pattern at a height of 2.8mm with TC245, and 16.7 aspect ratio shadow-mask of 30μm holes at 150μm spacing

Figure 6-20: Simulation of 1mm checkerboard pattern at a height of 2.8mm for 16.7 aspect ratio holes of size 30μm and interspacing 150μm
Figure 6-21: Calibrated image of 1mm checkerboard pattern at a height of 3.78mm with TC245, and 16.7 aspect ratio shadow-mask of 30\(\mu m\) holes at 150\(\mu m\) spacing.

Figure 6-22: Simulation of 1mm checkerboard pattern at a height of 3.78mm for 16.7 aspect ratio holes of size 30\(\mu m\) and interspacing 150\(\mu m\).
Figure 6-23: Calibrated image of 1mm checkerboard pattern at a height of 4.75mm with TC245, and 16.7 aspect ratio shadow-mask of 30\(\mu m\) holes at 150\(\mu m\) spacing

Figure 6-24: Simulation of 1mm checkerboard pattern at a height of 4.75mm for 16.7 aspect ratio holes of size 30\(\mu m\) and interspacing 150\(\mu m\)
Figure 6-25: Calibrated image of 1mm checkerboard pattern at a height of 5.7mm with TC245, and 16.7 aspect ratio shadow-mask of 30$\mu$m holes at 150$\mu$m spacing

Figure 6-26: Simulation of 1mm checkerboard pattern at a height of 5.7mm for 16.7 aspect ratio holes of size 30$\mu$m and interspacing 150$\mu$m
Figure 6-27: Calibrated image of 1mm checkerboard pattern at a height of 8mm with TC245, and 16.7 aspect ratio shadow-mask of 30μm holes at 150μm spacing.

Figure 6-28: Simulation of 1mm checkerboard pattern at a height of 8mm for 16.7 aspect ratio holes of size 30μm and interspacing 150μm.
A comparison of the calibrated images with the uncalibrated ones of last section clearly shows a lot of improvement. It is still not perfect because there might be more parameters (e.g. speckle noise in the CCD) than those considered while calibration, and/or the position of diffuser at one fixed height for calibration might not be enough for these six different heights. Nevertheless, the outlook of the images is a lot sharper and more recognizable than before.
More importantly, the comparison of calibrated and simulated images show a clear correlation between the experimental and the ideal data. It shows how close Vision Skin works in actual circumstances to its ideal conditions. Moreover, this behavior proves the theory on which Vision Skin operation is based.

6.5 Image processing

All the images shown so far were raw images, i.e. no image processing was done on them. The aim of this section is not to introduce some standard or advanced image processing techniques for these kind of images, but to show that the images given in the last two sections would improve even with simple image processing. The more advanced and sophisticated the technique is, the clearer the image will get. The outcome of this is better image quality and object recognition, and overall improvement in the range and imaging capability of Vision Skin sensor.

Just to prove this point, one of the simplest possible filtering method is used. A 5x5 averaging filter shown in equation (6-1) was used for the purpose.

\[
\text{filter} = \begin{bmatrix}
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
\end{bmatrix} \times \frac{1}{25}
\]

(6-1)

This filter was applied to the images shown in Figure 6-27 and 6-28, and the resultant images are shown in Figure 6-31 and 6-32 below. This filter allowed values at the lower end of the gray scale to have less difference in brightness. Also, the areas in which the pixels seem overly bright were reduced.
Figure 6-31: Image correction of checkerboard pattern at a height of 8mm with TC245, and 16.7 aspect ratio shadow-mask of 30\(\mu m\) holes at 150\(\mu m\) spacing

Figure 6-32: Image correction of checkerboard pattern at a height of 10mm with TC245, and 16.7 aspect ratio shadow-mask of 30\(\mu m\) holes at 150\(\mu m\) spacing

As seen in the figures, the pattern is now much more recognizable. This filter can be applied to all the images taken by the sensor, and especially prove helpful for images taken at large distances. As stated earlier, better image processing techniques would only make the images look better and better.
6.6 Imaging with real-life objects

After proving the Vision Skin imaging principle of operation with simple patterns like checkerboard, some real-life objects e.g. paper-pins, screws, washers, etc. were tried for imaging with Vision Skin. A set-up similar to one described in section 2.1 was used, except that the objects were held by a pair of tweezers over the CCD sensor. The height at which these objects were held was 6 mm. Some of the images are shown in Figure 6-33 - 6-36.

Figure 6-33: A 400μm (dia) paper-pin with 1mm head at a height of 6mm with TC245, and 16.7 aspect ratio shadow mask of 30μm holes at 150μm spacing

Figure 6-34: A 1.5mm wide screw with 3mm head at a height of 6mm with TC245, and 16.7 aspect ratio shadow mask of 30μm holes at 150μm spacing

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Figure 6-35: A 1.5 mm wide screw with 2.5 mm head at a height of 6 mm with TC245, and 16.7 aspect ratio shadow mask of 30 $\mu$m holes at 150 $\mu$m spacing.

Figure 6-36: A screw washer (outer dia 6 mm, inner dia 3 mm) at a height of 6 mm with TC245, and 16.7 aspect ratio shadow mask of 30 $\mu$m holes at 150 $\mu$m spacing.
The same images after parsing, calibration (see section 6.3) and filtering (see section 6.4) are shown in Figure 6-37 - 6-40.

Figure 6-37: Parsed image of 400μm (dia) paper-pin with 1mm head after calibration and filtering at a height of 6mm with TC245, and 16.7 aspect ratio shadow mask of 30μm holes at 150μm spacing.

Figure 6-38: Parsed image of 1.5mm wide screw with 3mm head after calibration and filtering at a height of 6mm with TC245, and 16.7 aspect ratio shadow mask of 30μm holes at 150μm spacing.
As seen in this Chapter, Vision Skin demonstrates its ability to recognize simple objects for distances up to 1cm from the surface of the mask, which is equivalent to 20 times the thickness of the shadow mask.
6.7 Summary

This Chapter demonstrated Vision Skin’s imaging ability to recognize simple objects, such as checkerboard pattern, up to distances of 1cm from the surface of the mask, which is equivalent to 20 times the thickness of the mask. Noise and intensity variation caused by differing hole sizes and CCD sensitivities was reduced and compensated to much an extent by calibrating the sensor using a flat image. A simple averaging filter was also used to improve the quality of images at larger distances to demonstrate how much an image processing technique can enhance the quality of Vision Skin imaging and hence its range of operation. The experimental results at various heights were also compared to the simulated results based on the ideal conditions. The comparison showed the close resemblance of two types of data and proved that the theory on which Vision Skin is based is correct. At the end, some real life objects were imaged for good results.
Chapter 7

Proximity results

Vision Skin is designed to produce accurate proximity measurements (errors of the order of ±75μm) in the close range (0-20mm). This is made possible by the use of a high density, high aspect ratio shadow-mask placed over a TC245 charge-coupled device (CCD), and a laser diode. This chapter first uses a simulation to indicate how a laser proximity spot would be seen by the sensor. Then it discusses two types of proximity modes - single-spot and three-spot - of Vision Skin. Formulae used for the interpolation of data to obtain the centroid of the proximity spot has been developed. Experimental results are presented along with the sources of error. At the end, the accuracy of the results has been improved by the error compensation and calibration.
7.1 Modeling of operation

In Vision Skin, proximity measurement makes use of a laser spot which is gaussian in nature. As opposed to a point source of light, gaussian spot is seen by the detectors further away from the centroid due to emission in the gaussian tail, though the light intensity from the tail is much lower than that from the peak. There are two ways to look at the situation - the intensities seen by an array of detectors from a stationary laser spot, and intensity seen by one detector as a laser spot moves across it. Both of them produce the same effect and explain the same concept. In actual proximity operation, a combination of both is realized, i.e. a laser spot moves across the array from one side to the other (as the object's height is incremented or decremented) but for any given position, the spot is considered stationary and its intensity profile seen by a group of detectors is considered.

A gaussian laser spot can be considered an infinite number of point sources with intensity that varies with the position from the centre of the spot. Equation (7-1) gives a gaussian intensity profile as a function of distance from the centre of the spot.

\[ I(r) = e^{-\frac{2r^2}{w^2}} \]  

(7-1)

where \( r \) is the distance from the centre of the beam and \( w \) is the \( 1/e^2 \) beam radius.

In the simulation presented in [45], instead of calculating an infinite number of points, a finite number was used. A range of 804 by 804\( \mu \)m was simulated for a beam radius (\( 1/e^2 \)) of 200\( \mu \)m. Every 3\( \mu \)m was a simulated source point, with an intensity matching the formula for equation (7-1). The total number of points calculated for one laser spot was 71824. The code for this simulation os given in Appendix F of [45].

The graph shown in Figure 7-1 is a simulation of a 200\( \mu \)m beam as it moves across the centre of a detector with the laser spot at varying heights from the surface of the mask, which has 30\( \mu \)m holes with an aspect ratio of 16.7. Instead of a \( 1/e^2 \) radius of 200\( \mu \)m, the
new value at a height of 1mm is $207 \mu m$, thus the beam has the radius expanded by only $7 \mu m$.

Figure 7-1: Simulation results of a $200 \mu m$ laser spot moving across a detector of $30 \mu m$ hole of aspect ratio 16.7 [45]

In Figure 7-1, the intensities were simulated at every $3 \mu m$. In Vision Skin employing the TC245, holes are separated by $153 \mu m$ (in x-direction) and hence intensities only at those are seen. Also, as seen in the figure, with the increase in height there is an apparent increase in the beam spread. A good way of measuring the width is with the Full Width Half Maximum (FWHM). FWHM is the width of the gaussian plot at the half way between the maximum and minimum intensity values, and gives a close measure of the apparent spot size. Note that by $Z = 10000 \mu m$, the apparent spot size (FWHM) has grown to $650 \mu m$, i.e. by $400 \mu m$ over $Z = 1000 \mu m$. If the aspect ratio of the shadow mask holes is increased, the curves at higher heights would tend to converge to those at lower heights. For example, doubling the aspect ratio would move the curve corresponding to $Z = 10000 \mu m$ to the one for $Z = 5000 \mu m$ [46]. When heights $Z$ are large enough that negligible part of the laser spot is directly above the detector at the half intensity point, the FWHM appears to be about $ZD/t$. Thus for $Z=10000 \mu m$, FWHM is about $600 \mu m$ (for $D=30 \mu m$ and $t=500 \mu m$).
7.2 Proximity modes of Vision Skin

As seen in section 7.1, the image from a spot covers only a limited number of detectors. Thus several laser spots can be used to gain multiple proximity measurements on the same Vision Skin. As mentioned earlier, first models of Vision Skin operated in single-spot proximity mode while the recent models used three-spot mode. The difference lies in using a single hole and three holes respectively in the proximity mask (see Figure 5-10 and 5-11) of the sensor.

7.2.1 Single-spot proximity mode

The first Vision Skin models used only one hole in the proximity mask of the integrated version (see Figure 5-10). The proximity mask rested flat on the surface, and since the laser diode was at a 45° angle, the hole in the proximity mask was also drilled at 45°. The drilling procedure and parameters for proximity mask hole is given in Chapter 3 along with shadow mask production.

At the time when Vision Skin used single-spot proximity mode, image acquisition boards from Cookbook (see section 5.3.2) were employed. All the images shown in this section are taken by that system. Figure 7-2 and 7-3 show raw unparsed image and parsed image converted to contour plots of the laser spot respectively, as the spot fully enters the TC245 CCD image array at \( Z = 8 \text{mm} \). The \( x, y \) axis numbers on these images show the actual CCD sensor address. Figure 7-2 is a raw unparsed image, and hence the axes represent the actual number of CCD pixels/detectors, which is 242 pixels by 753/3 or 151 pixels (Cookbook camera groups three horizontal pixels into one). After parsing (section 5.3.2.1), the virtual detectors are created which gather the light collected by a group of CCD pixels under each hole. Each virtual detector correspond to one shadow-mask hole, i.e. number of holes and virtual detectors is the same. Figure 7-3 represents the contour plot of the parsed image of the hole seen in Figure 7-2. The axes address now correspond to the hole position,
or the virtual detector position. As seen, the spot is centered near hole number 21 (vertical) and 7 (horizontal). This way, the movement of the spot on the array is followed as the object changes in height. Since the hole spacing is known and the angle of laser beam is also known, by using simple trigonometric relations, the height change can easily be calculated.

Figure 7-2: Vision Skin in single-spot proximity mode at Z=8mm: Unparsed (raw) image of laser spot entering the detector array

Figure 7-3: Vision Skin in single-spot proximity mode at Z=8mm: Contour of parsed image of a laser spot entering the detector array
Figure 7-4 shows the intensity profile of the same spot seen in Figure 7-2 and 7-3 at Z=8mm, as seen by all the detectors on row#21, the detector row about which the laser spot centroid is centered. Note that the relative width of the peak, which is best measured by the Full Width Half Maximum (FWHM), is about 6 hole spacings wide or 900μm. From the simulation plot in Figure 7-1, the expected FWHM at this height is about 600μm for a 200μm laser spot. The spot size used in the single-spot proximity was about 300μm and its FWHM of 900μm is somewhat larger than the 700μm estimated by applying the distortion of section 7.1 to this larger spot.

Figure 7-4: Intensity profile for detectors on row 21 of a laser spot entering the detector array (Z=8mm) in single-spot proximity mode; Uncalibrated

Figure 7-5, 7-6 and 7-7 show the corresponding images for the same spot as it is about to leave the CCD image array, i.e. at a higher height of about 12.5mm.
Figure 7-5: Vision Skin in single-spot proximity mode: Unparsed (raw) image of a laser spot leaving the detector array

Figure 7-6: Vision Skin in single-spot proximity mode: Contour of parsed image of a laser spot leaving the detector array
From Figure 7-7, it is seen that the FWHM has increased to about 8 hole spacings or 1200\(\mu m\). The spot has gained about 300\(\mu m\) with a height gain of about 4.5mm. Again this is somewhat larger than the expected 270\(\mu m\) because of the shadowing limit of \(ZD/t\). Also note that the intensity of the spot is now reduced to 800 (see Figure 7-7) in comparison to 1700 before (see Figure 7-4), which is obvious as the object draws further.

Another interesting point to note in Figure 7-4 and 7-7 is the noise seen near the peak of the profiles. This will be discussed in detail later in the chapter because it illustrates the calibration required for each detector.

**7.2.2 Three-spot proximity mode**

Final versions of Vision Skin used three holes in the proximity mask to obtain three laser spots on the object and three illuminated areas on the detector array. In the plexi-glass version (Figure 5-9 and 5-10) the holes were drilled at 45\(^{\circ}\) angle and the mask was placed flat on the sensor, while in the final aluminium block version (Figure 5-11 and 5-12) the
mask itself was at 45° on the sensor surface with the holes drilled straight through it. The
details of proximity mask drilling procedure and parameters are given in Chapter 3.

The holes were drilled in a triangular fashion with a spacing such that after 45° pro-
jection on the detector array, an equilateral triangle with sides of 3mm is seen, as shown in
Figure 7-8 below

![Proximity Mask](image)

Figure 7-8: Proximity mask hole spacing

With the holes spaced as shown above, the proximity mask was placed such that the
side 2-3 is parallel to the height of the detector array (shadow-mask hole columns) and the
holes themselves are aligned with three different rows (in this case rows 5, 15 and 25) of the
shadow mask, as seen in Figure 7-9 (top-view).

![Shadow mask](image)

Note: Masks not to scale

Figure 7-9: Alignment of proximity mask holes with respect to shadow mask holes
After 45° projection on the objects’ surface (the object is at 45° with respect to the laser beams), the side 2-3 sees no change, i.e. it remains 3mm, while the altitude L is elongated by a factor of $\sqrt{2} \cos 45°$, i.e. to 2.6mm ($L'$), as seen in Figure 7-10 and equation (7-2).

$$L' = L \times \cos 45° = 1.84 \times \sqrt{2} = 2.6mm$$ (7-2)

Sides 1-2 and 1-3 elongates; side 2-3 does not

Figure 7-10: Projection of laser beams from proximity mask on object surface at 45°

With the altitude L elongation to $L'$, the sides 1-2 and 1-3 are also elongated to 3mm. With the side 2-3 already 3mm, an equilateral triangle of sides 3mm is seen on the detector array, as seen in Figure 7-11.

Figure 7-11: Laser spots forming an equilateral triangle on the detector array after 45° projection at object surface
Before presenting the outlook of actual laser spots on the detector array, a blank image illuminated by a parallel light displaying all the holes in the array is shown in Figure 7-12 (raw unparsed version of same image used for image calibration in Figure 6-15). As seen, not all the holes appear to have the same intensity because of differing hole size and sensitivity. Also, some holes (two in this case) are blocked, and that has to be compensated if the rows containing those holes are used for proximity measurement. Note that only two out of a total of more than 1200 holes are blocked, hence giving a success rate of more than 99.83%.

Figure 7-12: Detectors under uniform illumination from a parallel light source (image used for calibration)

In the proximity mode, the appearance of the three laser spots on the array is shown in Figure 7-13 captured with EDC-1000L camera system. This is a raw unparsed image, and as mentioned in section 7.2.1, the axes in Figure 7-13 correspond to CCD pixels. The difference here is that on the x-axis all the 753 pixels are seen as opposed to only 251 seen with Cookbook Camera in Figure 7-2. It is because Electrim image acquisition board (see section 5.3.2) reads each single pixel. Figure 7-14 is the parsed image and its contour plots is seen for all the 29x40 virtual detectors (holes).
Figure 7-13: Vision Skin in three-spot proximity mode at Z=12mm: Unparsed (raw) image of three laser spots on the detector array

Figure 7-14: Vision Skin in three-spot proximity mode at Z=12mm: Contour of parsed image of three laser spots on the detector array
As seen in Figure 7-14, three spots are centered on rows 5, 15 and 25. Hence these three rows will be used for proximity measurements to be discussed later in the chapter. Also observe that one spot leads the triangle on the array. The other two enter the array a little later and exit after the leading spot leaves the other side. This adds to the range of proximity detection by the height of this triangle, which is 2.6mm as seen in Figure 7-11.

Figure 7-15, 7-16, 7-17 show the uncalibrated intensity profiles for rows 5, 15, and 25 chosen for proximity detection. Note that the three spots are so well spaced that the effect of the centre spot (row 15) is not seen on other profiles (of row 5 and 25). However row 5 and 25 do add a plateau area on row 15 image near their peak points (column 35).

![Intensity profile for detectors on row 5 in three-spot proximity mode](image)

Figure 7-15: Intensity profile for detectors on row 5 in three-spot proximity mode
Figure 7-16: Intensity profile for detectors on row 15 in three-spot proximity mode

Figure 7-17: Intensity profile for detectors on row 25 in three-spot proximity mode
Again, note the noise near the peak of these plots (to be discussed later in this chapter).

The advantages of using three-spot proximity mode over single-spot are obvious. These are:

1. Increased proximity range, e.g. with single-spot mode, the range was 7.5-13.5 mm which was improved to 7.5-16 mm by three spot mode.

2. Improved accuracy, e.g. with the three-spot mode, there are three independent proximity measurements, and the information from these can be averaged for reduced errors.

3. The differences in height Z extracted from the three spots can be used to give the surface slope of the object, i.e. the orientation vector of the surface.

Three-spot proximity mode is simply using the CCD detector array efficiently. With the single-spot mode, most of the detector array remain unused. Two additional spots in three-spot mode utilize most of this unused space.

7.3 Centroid of gaussian

Part of the research was to find ways to extract the centroid of the gaussian laser spot on the detector array for proximity measurements. Two methods were derived theoretically and a third developed from the experimental results.

7.3.1 Brightest detector

This is the simplest way to estimate the centroid of a gaussian spot on the detector array, and it does not need any formula. The detector with the brightest intensity is considered the centroid of the spot. The problem with this method is that the accuracy is limited by the detector (hole) spacing, and is only plus or minus one-half the hole interspacing on the X-Y plane. The error in height measurement would be this error multiplied by a factor of \( \tan \theta \), where \( \theta \) is the angle of the laser beam. In Vision Skin with hole interspacing of about
150\mu m and \theta=45^\circ$, this creates an error of $\pm75\mu m$. This error is not acceptable considering the accuracy desired for such an application. Furthermore, at large distances $Z$ the intensity changes slowly at the peak, making this method very sensitive to noise in the signal.

### 7.3.2 Three point interpolation

This method looks at the intensities of three holes (brightest hole and two holes on its either side) instead of just one. Simulation plot of Figure 7-1 shows the intensity profile seen by the detectors to be continuous and smooth. In reality, the detectors are placed at every $153\mu m$, and the intensity values only for these detector positions are available. Hence, the outlook of the intensity plot actually registered by these detectors resembles a triangular more than a gaussian intensity profile. Also by that simulation when $ZD/t < 300\mu m$ (i.e. for $Z<5mm$ with shadow mask of $D=30\mu m$ and $t=500\mu m$), only three detectors (separated by two hole spacings, i.e. $\sim300\mu m$) have any significant signal.

The detector (hole) with the largest intensity value is called 'max', the adjacent with the lowest intensity as 'min', and the intermediate value as 'mid'. Detectors 'min' and 'mid' lie on either side of 'max'. In the case when the spot is exactly over the 'max', both 'min' and 'mid' have the same value and there is no intermediate value. If the plot is perfectly triangular, the centroid is easy to find. A line is drawn from 'min' to 'max', and another line of same slope but negative is made to pass through the mid. The point where the two lines intersect is the centroid, as seen in Figure 7-18. The intensities of detectors 'max', 'min' and 'mid' are $I_{max}$, $I_{min}$ and $I_{mid}$ respectively. As seen in the figure, point B is the new centroid, whereas point A would be the same if only the brightest detector is considered. The displacement between the two points A and B ($\delta x$) is given by equation (7-3), where $p$ is the pitch or the spacing between hole centres.

$$
\delta x = \frac{p (I_{mid} - I_{min})}{2 (I_{max} - I_{min})} \quad (7-3)
$$
The above equation assumes the plot to be triangular, but the same would also apply to the kind of profile seen by the Vision Skin from a gaussian laser spot. The accuracy using this formula would be a lot better than that obtained using only a brightest detector. In fact, this formula gives zero error for two specific positions even for a gaussian laser spot. These two positions are - when the spot is directly over ‘max’ detector, and when spot is in the middle of ‘max’ and ‘mid’ with both having the same intensity values.

For this formula to work, the radius of laser beam should be at least the size of one hole to hole spacing. In that case, at least three detectors would see the light from it even for a height of zero when it is not possible for the diffused light components to get into the holes not directly under the spot. Thus, using a beam radius of 150\(\mu m\) or a beam size of 300\(\mu m\) makes a lot more sense, and hence is realized in Vision Skin where hole interspacing is about 150\(\mu m\). It should be noted that this formula was developed when it was assumed that the Vision Skin proximity mode would work for small ZD/t ratio [45]. Subsequently the range of operation was found to approach ZD/t near 1.

A code for this centroid detection using this method of interpolation was written in Matlab, and is given in Appendix VII.
7.4 Experimental set-up

Since the Vision Skin proximity accuracy is near that of a micrometer, a very precise standard is required for experiments. Thus for high accuracy proximity comparisons, the X-Y positioning table (presented in Chapter 3) with a repeatability of 0.1μm was used. Table’s Z axis could only move with in a couple of millimeters, but a larger range of motion of an object was desired. So, instead Y-axis was used for changing the distance between an object and the sensor, and X and Z-axis were kept stationary. The Vision Skin sensor was mounted on the table on one side such that the detector array was perfectly perpendicular to the direction of Y-axis. To give the object a very smooth surface, a glass slide was used. It was spray painted by a smooth layer of flat white paint at the front and black at the back, and was placed in a stationary mount such that its surface was perfectly parallel to the sensor’s detector array. A schematic diagram of the set-up is shown in Figure 7-19.

![Integrated Vision Skin](image)

Figure 7-19: Set-up for proximity experiments

Instead of object moving away from the sensor, the sensor was made to move away from the stationary object to realize the same effect. The distance between the sensor and the object was increased in steps of 76.5μm, which is one-half the hole to hole spacing on
detector array rows on which a laser spot is followed. From the starting distance (height) of about 8mm, when only the leading laser spot was fully into the array, one hundred images were taken, until only the trailing two spots were fully seen on the array, in steps of 76.5\(\mu m\) using the Electrim image acquisition board. This way a distance range of 8 - 15.65 mm for proximity measurements was explored for Vision Skin. The images taken by the Electrim board were later processed in Matlab using the codes given in Appendix II (image parsing), III (image displaying), and VII (proximity calculations). The results are given in the following section.

7.5 Results for uncalibrated three point measurement

Using the set-up given in the last section, proximity measurement experiments were performed. Three laser spots were used, and three corresponding rows (5, 15 and 25) on the shadow mask were chosen for proximity measurements. Hence three independent set of data was obtained, and compared for the accuracy. The leading laser spot (see Figure 7-13 and 7-14) of the triangle follow row 15, allowing proximity measurements on this row to start earlier (at somewhat smaller Z of \(-8\)mm) than that on rows 5 and 15, which are followed by two trailing spots.

Note that these plots used the three point interpolation method discussed in section 7.3.2, which used the interpolation of intensities of the brightest spot and the two neighboring spots. The images were later processed in Matlab and the measured distances were compared to the actual distance from the start in increments of 76.5\(\mu m\). The graph in Figure 7-20 presents the error (measured distance - actual distance) versus the actual distance for row 15 for the three point method. The starting distance is 8306\(\mu m\) (though zero is shown on the x-axis) and the maximum error range is about \(\pm 400\mu m\).
Figure 7-20: Graph of error for row 15 for distances between 8306\(\mu m\) and 12284\(\mu m\) using three point interpolation method

As seen, errors of slightly over \(\pm 400\mu m\) are observed for heights (distances) between 8306\(\mu m\) and 12284\(\mu m\). Note that the sensor at this is not calibrated for differing hole sizes, sensitivity, etc., and as will be seen these errors can be improved. Figure 7-21 and 7-22 give error versus actual distance graphs for rows 5 and 15. The starting distance for both these graphs is 10371.5\(\mu m\) and the end distance is 14426\(\mu m\), which is different (higher) from that for row 15 as explained earlier.
Figure 7-21: Graph of error for row 5 for distances between 10371.5 μm and 14426 μm using three point interpolation method.

Figure 7-22: Graph of error for row 25 for distances between 10371.5 μm and 14426 μm using three point interpolation method.
A maximum deviation of about $\pm 450\mu m$ and $\pm 500\mu m$ for rows 5 and 25 respectively are seen in the graphs. These errors are worse than those for row 15. Note that some rows are better than the others as far as hole size consistency, noise and other factors are concerned. Also the range covered by row 15 starts $8.3\text{mm}$ compared to $10.4\text{mm}$, which can be another reason why its errors are smaller than those for rows 5 and 25.

As mentioned earlier, one of the advantages of using three-spot proximity mode should be the improved accuracy. The errors of no better than $\pm 400\mu m$ would be obtained by using one of these (5, 15 and 25) rows. If the data from these three independent sources is averaged, the accuracy of the sensor should be improved. The graph in Figure 7-23 presents error versus actual distance plot for all three rows averaged. The starting distance on this graph is $10371.5\mu m$ and the end distance is $13355\mu m$. This is the only range when all the three spots are completely on the detector array.

![Graph of error for averaged data of rows 5, 15 and 25 for distances between 10371.5\(\mu m\) and 13355\(\mu m\) using three point interpolation method](image)

Figure 7-23: Graph of error for averaged data of rows 5, 15 and 25 for distances between $10371.5\mu m$ and $13355\mu m$ using three point interpolation method

Averaging of data improves the errors to less than $\pm 300\mu m$. This error has been improved but is still below the acceptable standards. These intensity values near the peak of
the plots are affected by the noise as seen in Figure 7-24, and hence the position of the brightest spot seen on these plots is not always reliable. The following section discusses these sources of noise to explain these large errors. The subsequent sections suggest some schemes for its compensation and calibration.

![Figure 7-24: Intensity data corrupted by noise: Cause of errors](image)

### 7.6 Sources of noise

There can be many sources of noise and while some of these sources are independent, some other might be interrelated and dependent on each other. Some of them are very obvious and are easy to find and understand, viz differing hole size, sensitivity, etc. A larger hole would have a larger acceptance angle (and smaller aspect ratio for the same mask thickness), and hence would collect more diffused light from the object than expected. Similarly, a hole which is more sensitive would record more light intensity than the hole of the same size but lesser sensitivity. The same size holes have different sensitivities because of the many reasons including different slopes of the hole side walls and different sensitivities of
CCD pixels sitting under the holes.

At the same time, there are some sources of noise which are very difficult to track and compensate. One such noise source is speckle noise. Speckle noise refers to the noise because of which the gaussian intensity distribution of the laser beam is not smooth and has jagged peaks all over the distribution especially near the peak. Since the laser based proximity sensors rely on the peak of this distribution for the measurement, it affects the accuracy of the system adversely. The accuracy in distance measurement of laser triangulation sensors is limited by speckle noise [37,39]. Because of the various sources of measurement errors due to specular noises, laser triangulation can be regarded and modelled as a stochastic process [40]. Other sources of noise are temporal and spatial fluctuations of the coherence of laser light as well as photonic and thermal of CCDs and signal processing electronics [40].

Furthermore, “the shape of an object inspected and the orientation of its surface with respect to the probing laser beam” [41], “surface inclination and surface reflection” [42], and “scattering characteristics of the targets” [43] cause systematic errors in triangulation measurements. Some optical effects limit the ability of a triangulation sensor to make measurements when sudden change in surface height occur, on surfaces with significant reflectance variation and roughness [44].

So, by compensating some of the above mentioned sources of error, the errors would be improved. With more and more sources being compensated, the accuracy would improve proportionally. A completed compensation of virtually all kind of noise sources might not be possible though.

7.6.1 System calibration for error compensation

The first and most obvious source of error, i.e. hole size and sensitivity variation, was attempted to compensate by flat illumination calibration discussed in section 6.4. A flat or blank image was taken under a diffused source of light, and the signal registered by the
detectors (holes) was a measure of their hole sizes and sensitivities. The values were inverted and stored in a matrix, which was multiplied to all the previously grabbed images during Matlab processing. The resultant curves were significantly reduced in noise, as seen in Figure 7-25.

![Figure 7-25: Calibration of corrupted data](image)

In another scheme, the brightest light intensity values seen by the detectors of a given row being used for proximity, as the spot moves across the array, were inverted and stored in a matrix. This also gave a measure of various hole sizes and sensitivities. Again, an improvement was seen but not satisfactorily. With these methods, the errors of results shown by graphs in section 7.5 were improved to $\pm (200 - 250) \mu m$ range. The reason was further explored by taking multiple images for the same settings, i.e. same light levels, same integration time of boards, same object height, etc. While the plots were found to be similar (same general jagged shapes), they were not true copies of each other. In other words, the ratio of light intensities seen by any two given holes differ from one image to the other. This explained why using only a flat or blank image with a parallel light, or using brightest detector values did not remove the errors completely. The error compensation by these methods

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was being limited by sources like noise in the CCD.

Since the noise experienced by a CCD sensor is also associated with the temperature of its body, an experiment was performed in which the CCD was cooled by surrounding it with dry ice. Various images at different temperatures, starting with a room temperature of 23°C, were taken. The lowest temperature at which an image could be taken, before the CCD was completely covered by the snowish powder because of cooling, was just a couple of degrees above 0°C. All the images showed a significant level of noise, thereby ruling out the possibility of error compensation by cooling down the sensor.

Using these compensation methods, the errors were significantly improved. A further improvement, however, was sought. The following section presents a new scheme for this purpose.

7.7 Centroid extraction at farther working distances

The three point method for proximity measurement was developed for close operation where only a few detectors are illuminated. At further distances, a better method was needed.

7.7.1 Centre of Full Width Half Maximum (CFWHM) criterion

The Full Width Half Maximum (FWHM) is the width of the gaussian plot at the half way between the maximum and minimum intensity values, and gives a close measure of the apparent spot size. Centre of Full Width Half Maximum (CFWHM) is the centre of FWHM. As seen in the intensity plots of the detectors in Figure 7-15, 7-16, 7-17 and 7-24 earlier, the data is not smooth and corrupted by the noise. But a closer look at the plot reveals that although the areas near the peak are seriously affected, those near the half way point (aver-
age of maximum and minimum values) are not and they form almost noise free walls on the plot. This means that the FWHM is a good criterion for the centroid detection in this case. The FWHM expands with the increase in height as seen from simulation plot of Figure 7-1 but its shape remains symmetrical. Hence the centre (Centre of Full Width Half Maximum, CFWHM) changes proportionally in response of height change of the object. By tracking this shift in CFWHM, a change in object’s height can be measured with errors much lower than those calculated by following the brightest detector location or three-point interpolation around the brightest detector. Figures 7-26 and 7-27 elaborate this idea, where the object is moving further away which corresponds to the image moving from right to left on the detector array.
The Z position and thus the laser spot was moved exactly five hole spacings (765\textmu m) from the position in Figure 7-26 to the one in Figure 7-27. The CFWHM shows a
shift of almost 765\mu m (five hole spacings, as seen in the figure), thereby producing errors of only a few micron. If the brightest spot or the peak of the plot is followed, even after the interpolation a change of about 1000\mu m is calculated, which is off from the actual increment by 235\mu m.

A Matlab code was written to find the height increments on the basis of CFWHM, and is given in Appendix VIII. Based on this code, the proximity data shown in Figure 7-20, 7-21 and 7-22 was again analyses, and the corresponding error versus actual distance plots for rows 15, 5 and 25 are presented in Figure 7-28, 7-29 and 7-30 respectively.

![Graph of error for row 15 for distances between 8306\mu m and 12284\mu m using Centre of Full Width Half Maximum (CFWHM) criterion](image)

Figure 7-28: Graph of error for row 15 for distances between 8306\mu m and 12284\mu m using Centre of Full Width Half Maximum (CFWHM) criterion
Figure 7-29: Graph of error for row 5 for distances between 10371.5\(\mu m\) and 14426\(\mu m\) using Centre of Full Width Half Maximum (CFWHM) criterion.

Figure 7-30: Graph of error for row 25 for distances between 10371.5\(\mu m\) and 14426\(\mu m\) using Centre of Full Width Half Maximum (CFWHM) criterion.
In comparison to before, the worst case errors for rows 15, 5 and 25 are dropped from $\pm 400\mu m$, $\pm 450\mu m$ and $\pm 500\mu m$ to $\pm 100\mu m$, $\pm 175\mu m$ and $\pm 140\mu m$ approximately respectively. This improvement is attributed to the choice of using the CFWHM instead of the brightest detector for proximity measurements under the noise of such a nature. Note that the calculations are based on the raw data, and there is no compensation/calibration done on this data such as hole size and sensitivity compensation, etc.

7.7.2 Calibration

As discussed in section 7.6.1 that the calibrations such as hole size and sensitivity compensation improve the three-point results, though not drastically. The same kind of calibration using a flat or blank image under a parallel light was combined with the Centre of Full Width Half Maximum (CFWHM) criterion (as noted before this significantly improve the curves). This calibration not only reduces the jaggedness near the peak of the plot but also compensates for noise near the centre, i.e. for FWHM. This results in better accuracy and smaller errors. Applying this calibration to the data and using the CFWHM presented in the last section, the results for row 15 were observed. Figure 7-31 presents the measured versus actual height plot and Figure 7-32 the error versus actual height plot for row 15.
Figure 7-31: Graph of ‘Measured Versus Actual Distance’ for row 15 for distances of 8306\(\mu m\) and 12284\(\mu m\) using Centre of Full Width Half Maximum (CFWHM) and calibration.

Figure 7-32: Graph of error for row 15 for distances between 8306\(\mu m\) and 12284\(\mu m\) using Centre of Full Width Half Maximum (CFWHM) criterion and calibration.

Figure 7-31 shows that the measured proximities more closely follow the actual ones. Figure 7-32 gives the error for all the proximity heights. As seen, the worst case errors
are now reduced to only $\pm 75\mu m$. This is a tremendous improvement over the original errors of about $\pm 400\mu m$. The corresponding plots for row 5 are shown in Figure 7-33 and 7-34.

![Figure 7-33: Graph of ‘Measured Versus Actual Distance’ for row 5 for distances of 10371.5\(\mu m\) and 14426\(\mu m\) using Centre of Full Width Half Maximum (CFWHM) and calibration](image)

![Figure 7-34: Graph of error for row 5 for distances between 10371.5\(\mu m\) and 14426\(\mu m\) using Centre of Full Width Half Maximum (CFWHM) criterion and calibration](image)
Similarly for row 15, the worst case errors are reduced to only ±100μm (approximately) from the original errors of ±450μm. Plots for row 25 show the same trend as seen in Figure 7-35 and 7-36.

Figure 7-35: Graph of ‘Measured Versus Actual Distance’ for row 25 for distances of 10371.5μm and 14426μm using Centre of Full Width Half Maximum (CFWHM) and calibration

Figure 7-36: Graph of error for row 25 for distances between 10371.5μm and 14426μm using Centre of Full Width Half Maximum (CFWHM) criterion and calibration
The worst case errors for row 25 are now only $\pm 125\mu m$ as compared to the original errors of about $\pm 500\mu m$. The results for all these rows also improved significantly over the data when the CFWHM was used but not the calibration for the three spots. Another way of presenting the performance of Vision Skin proximity capability is to show percentage error (error/actual height) versus the actual height, which is given in Figure 7-37, 7-38 and 7-39 for rows 15, 5 and 25 respectively.

Figure 7-37: Graph of percentage error for row 15 for distances between 8306$\mu m$ and 12284$\mu m$ using Centre of Full Width Half Maximum (CFWHM) criterion and calibration
A seen in the figures, the errors are below 1%.
7.8 Summary

In this chapter, the proximity measurement capability of Vision Skin was demonstrated. Simulation of a gaussian beam at different heights was given for comparison with the experimental data. Two proximity modes of Vision Skin operation - one-spot and three-spot - were presented. Various centroid detection schemes were discussed and the formulae were characterized. Experimental results for heights between 8 and 15 mm were presented and the sources of errors were discussed. The worst case errors before compensation were ±400μm ±450μm and ±500μm for the three proximity spots. Various error compensation methods were used with partial success. The worst case errors were improved to the range of ±(200 – 250) μm. Finally, the best scheme of compensation which used the Centre of Full Width Half Maximum, CFWHM (centroid of intensity plot at the average of maximum and minimum intensity values) for proximity measurements instead of the peak value interpolation was successfully employed in association with the calibration method. This method reduced the worst case errors to only ±75μm, ±100μm and ±125μm, i.e. below 1% for any given height.
Chapter 8

Conclusions and Future work

In this chapter, the conclusions of the work completed on Vision Skin sensor are drawn and design improvements for the future work are suggested. The suggestions include: better calibration methods, batch production of shadow mask, wavelength filtering of unwanted light sources, better signal processing techniques for imaging, angled holes for stereo vision, design considerations for range improvement, and on-chip optical processing.

8.1 Conclusions

An integrated proximity and imaging sensor called ‘Vision Skin’ has been successfully fabricated in this thesis. Vision Skin has the ability to image simple real life objects up to the distance of 10mm for the aspect ratios used. For longer distances, larger aspect ratio holes or image processing techniques can be implemented to improve the quality of the image, thereby increasing the imaging range of the sensor. The sensor also has the ability to perform proximity measurements on the objects up to the distance of 20mm with an error of $\pm 75\mu m$ in the case of most accurate sample. The error at any position in the sensor’s range
(0-20mm) is less than 1%. All this is made possible with the help of a shadow-mask, which is an array of small (30μm), closely spaced (150μm), high aspect ratio (16.7) holes with acceptance angles of only 3.4°. With the integration of shadow mask in the sensor, conventional use of lenses for such kind of sensors is not required. As a result, the problems of depth of focus, refocusing, etc. encountered by lens systems in the short range are not experienced by Vision Skin, which also remains small and compact without lenses.

Since no item like shadow-mask was available commercially, several different techniques for its production were investigated. The shadow mask discussed above was fabricated by laser micromachining on a 500μm thick sheet of black polypropylene. The technique of drilling angled holes in polypropylene has also been developed and used for proximity mask to get multiple laser beams from a single laser diode, but is not tested for shadow mask. Using angled holes for shadow masks would give stereo vision, wide angle vision and improved proximity results [46], and is recommended for the future work. The other studied shadow mask production techniques are photolithography for multi-layer thin film masks and laser-LIGA with photosensitive polymer. These are suitable for mass production and show promising results although more research is required on them.

Several codes and algorithms (both in Matlab and in C) have been written and used to detect the centroid of the gaussian laser spot on the detector array to calculate the proximity. Simulations have also been performed to compare the experimental imaging and proximity results with the ideal results, and a clear correlation between the two can be seen. Various calibration methods are implemented to compensate the non-uniformity in the sensor holes. While the calibration of differing shadow-mask hole size and sensitivity is done successfully, some other noise sources (e.g. speckle noise) require more research for compensation.
8.2 Future work

In addition to those mentioned above, other areas of improvement include the use of optical filters to improve the illumination ratio between sunlight and the laser beam so that the sensor could work in the normal day-light, use of higher aspect ratio holes and larger detector arrays for range improvement, use of multiple laser beams at various angles for improved range and accuracy, and the use of new technology called ‘On-chip optical processing’, for the fabrication of microoptical components such as microlenses, micromirrors and beam splitters on a single Si substrate by the surface micromachining technique, to obtain multiple laser beams from the same source with the net reduction in the size of the assembly.

The following design improvements and techniques are suggested.

8.2.1 Calibration

As seen in Chapter 7, the gaussian intensity profile of the diode laser seen by Vision Skin sensor is affected by variations especially near the peak of the profile. This noise affects the accuracy of the sensor for proximity measurements. Although several calibration methods have been tested with significant success, none has provided a fool-proof method of calibrating all kind of noise in the sensor. The factor limiting the proximity accuracy of the sensor is not the hole spacing or aspect ratio of the shadow mask, but rather the non-uniformity of sensor’s response. Multiple images taken by the sensor for the same conditions result in images which, although resemble each other, fail to reproduce the identical image. This problem seems to be resulting from noise in the charge-coupled device (CCD). More research is needed to this regard to properly calibrate the sensor for better accuracies. Investigations of other CCDs Selecting a device other than the one used in this thesis (TC245) for proximity measurements would be worthwhile. It has been noted that the TC211 has less noise levels than the TC245 [46].
8.2.2 Shadow mask work

Laser micromachining with polypropylene has resulted in very high aspect ratio (16.7) holes of the size 30μm with an interspacing of 150μm in a 500μm thick sample. The shadow mask has been integrated to the sensor with complete success, but suffers from the lack of possibility of mass production. The mask production using this technique is a time consuming process, and hence a technique which promises batch or mass production with comparable hole dimensions has to be developed. Two other techniques investigated in the thesis - photolithography for multi-layer thin film mask and laser-LIGA with photosensitive polymers - have the potential for mass production and demonstrate promising results but require more research in their areas. Laser-LIGA technique could make a master mask which can be used to make replicas in the batch process. It has also the potential for the manufacturing of angled holes or structures [46]. The multi-layer thin film mask also has the potential batch fabrication process but alignment of different layers might be a problem.

8.2.3 Optical filters

Vision Skin does not operate in the bright day-light, as the laser spot is not distinctively seen by the sensor in the bright ambient light background. The sensor uses a diode laser of wavelength of 670nm, and a group of light emitting diodes (LEDs) also emitting the light near the same wavelength (670nm). If an optical filter is placed on the top of the sensor, properly covering any light leaks, which allows only desired wavelengths (670nm) to pass through dominantly as compared to the rest, the illumination ratio between the sunlight and the laser beam would improve and the sensor might be able to operate in the ambient light. For an example, the Newport's wavelength filter 10LF10-670 which has a peak transmission of 670nm and a FWHM (Full Wave Half Maximum) of 11nm can be used. Figure 8-1 demonstrates the idea.
8.2.4 Better imaging

Vision Skin has the ability to image simple real life objects up to the distances of 10mm, as seen in Chapter 6. The experimental results are shown to resemble the simulated results, which proves that the theory on which the Vision Skin imaging is based is correct. However, the imaging capability can be enhanced by increasing the aspect ratio for the shadow mask holes. Doubling the aspect ratio doubles the range. Also, better signal processing techniques can give the captured images a whole new look. In section 6.4 of the thesis, this is explained with the help of an example - a simple averaging filter drastically improved the image quality. Therefore, better and advanced image processing techniques could improve imaging of Vision Skin more than anything else.

8.2.5 Angled holes

The technique for the fabrication of angled holes has been developed in the thesis (section 3.2.3) for polypropylene samples using laser micromachining. These angled hole masks are used for proximity mask (mask used to split a laser beam into three beams) but a shadow mask containing these holes has not been tested on the CCD. Also, angled holes are possible with laser-LIGA technique in principle. Including angled holes in the shadow masks using one of these technologies would explore many possibilities, including stereo vision, wide angle vision and improved proximity results for Vision Skin sensor [46].
8.2.6 Range improvement

Vision Skin has the ability for proximity measurements up to distances of 20mm from the point of contact. But because of the geometry of the TC245 CCD (the image area is situated with in the CCD body about 6mm from the edge on either side), initial proximities (point of contact to about 7mm) are not accessible for measurement. The angle for the laser beam used in the integrated sensor is 45°. The initial proximities which are not accessible to Vision Skin at this point, can be obtained by using a bare CCD die mounted on a flat surface so that the image area lies right on the edges of the assembly. Also by using shallow angles (e.g. 30°) for the laser beam, more range towards the point of contact can be accessed (multiple beams at various angles (e.g. 30°, 45°, 60°, etc.) would cover many distances currently not covered by the sensor).

For the overall range improvement (on the higher side), larger arrays can be used as the proximity range is limited to the size (length) of the CCD image area. Wide and long CCDs would allow proximity to be measured over much longer distances. As far as accuracy for longer distances (than 20mm) is concerned, the aspect ratio of current shadow mask holes (i.e. 16.7) is still good enough. Although higher aspect ratios would significantly improve the sensor’s behavior over longer distances, e.g. doubling the aspect ratio will make the Vision Skin behave at distances of 10mm as if it currently does at 5mm.

8.2.7 On-chip optical processing

The performance of Vision Skin sensor can be considerably improved by using laser multiple beams (more range and accuracy) and by reducing the size of the components (compact sensor). On-chip optical processing [65] provides the solution by introducing microoptical components such as diffractive and refractive microlenses, micromirrors, beam splitters, etc. In the current system, the lens cases to focus the beam are considerably bigger than the laser diode itself (see section 5.1.3) to focus the beam. Instead of this, a silicon
micromachined fresnel microlens of the size of 280μm similar to those manufactured by [65] is available.

This 280μm microlens was designed with an optical axis of 254μm for passive integration of an edge-emitting semiconductor laser in [65]. A set of microfabricated lens-mounts is used to precisely define the angles of the three-dimensional microlens system for proper alignment to the semiconductor laser. It also greatly improves the mechanical strength and stability of the microlens system.

Furthermore, such a microlens along with several other three-dimensional micro-optical components can be fabricated integrally on a single-Si chip. The Si substrate serves as a micro-optical bench on which microlenses, mirrors, gratings and other optical components are prealigned in the mask layout stage using computer-aided design and then constructed by microfabrication [65]. Additional fine adjustment can be achieved by the on-chip micro-actuators and micropositioners such as rotational and translational stages. With hybrid integration of active optical devices, a complete optical system can be constructed [65]. This three-dimensional microoptical system is constructed on a Si substrate by the surface micromachining technique.

8.3 Summary

This chapter presented the conclusions drawn on the work completed on Vision Skin sensor. Some design improvement for the future work were suggested, including better calibration methods for noise compensation, batch production of shadow mask, wavelength filtering of unwanted light sources, better signal processing techniques for imaging, angled holes for stereo vision, design considerations for range improvement, and on-chip optical processing.
Appendix I

Properties of Polypropylene

This appendix presents the manufacturer’s data on the Marlex polypropylene.

Nominal Physical Properties of Marlex HLN-200 Polypropylene

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity, (W/m-k)</td>
<td>0.12</td>
</tr>
<tr>
<td>Electrical resistivity, (Ω-m)</td>
<td>&gt; $10^{15}$</td>
</tr>
<tr>
<td>Density, ASTM D1505, (g/cc)</td>
<td>0.913</td>
</tr>
<tr>
<td>Melt Flow, ASTM D1238, Condition 230/2.16</td>
<td>20</td>
</tr>
<tr>
<td>(g/10min)</td>
<td></td>
</tr>
<tr>
<td>Tensile Yield Strength</td>
<td></td>
</tr>
<tr>
<td>ASTM D638</td>
<td></td>
</tr>
<tr>
<td>Type I specimen, 2 in/min, psi (MPa)</td>
<td>5300 (37)</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td></td>
</tr>
<tr>
<td>ASTM D790, psi (MPa)</td>
<td>290,000 (2000)</td>
</tr>
<tr>
<td>Izod Impact Strength</td>
<td></td>
</tr>
<tr>
<td>ASTM D256, ftlb/in (J/m)</td>
<td></td>
</tr>
<tr>
<td>Notched, (73 F) 23 C</td>
<td>0.4 (21)</td>
</tr>
</tbody>
</table>
Unnotched (73 F) 23 C

Deflection Temperature
ASTM D648, F, (C)
66 psi (0.46 MPa) 260 (127)
264 psi (1.8 Mpa) 170 (77)

Hardness, Shore D
ASTM D2240
75

Avg. weighted Molecular Weight
300,000

Recommended Processing Temperature
Stock Temperature, F (C) 375-450 (190-232)

Resin Identification System:
Polymer Type (first letter)
H = Homopolymer
Additive System (second and third letters)
L = Antistatic
N = Nucleated
Melt Flow (first three numbers)
Melt flow carried to one decimal place (ie, 200 = 20 MFI)
Appendix II

Code for parsing and displaying image file

The following code is (modified from Appendix A of [45]) used when Cookbook image acquisition boards are used for image capturing. This Matlab code is used to parse and display an image for the TC245 CCD. The first part of the code is that of parsing and the last that of displaying an image from a diskette or hard drive on Sun workstations. The parsing code applies to any given TC245-shadow mask combination, provided all the function parameters are specified in the code below. These parameters are different for different CCD-shadow mask combinations, which has to be found out before applying this code. Also, in the display code, a function to subtract the dark current from the image has been given at the end. The dark current file should be loaded before the image file for that code to work.

Parsing function:

function [p_matrix]=parse245(I,NV,NH,V_start,H_start,V_space,H_space,SV,SH,slope)
%parse245.m(I,NV,NH,V_start,H_start,V_space,H_space,SV,SH,slope)
Display function:

% Reads a PIX file from the TC245
% The Image is stored in 'I'
% I1 & I2 are used for intermediate stored of 2 files
% This program reads the 252x242 full-frame image
% Note that min is taken for rows 1:238 and columns 3:252
% Those areas are close to being blank and do strange contrast
% The histogram looks proper too, when this is done

name = input('Filename: ', 's');
clear I1;
clear I2;
clear I;
% Assuming same header

pid = fopen([name '.pa']);
```matlab
p1 = fread(pid, 7, 'uint8');
p2 = fread(pid, 252*125*2, 'uint8');
fclose(pid);

pid = fopen([name '.pb']);
p2 = fread(pid, 7, 'uint8');
I2 = fread(pid, 252*121*2, 'uint8');
fclose(pid);

% I=[I1 I2];

for x=1:125
  for y=1:252
    i=(x-1)*252*2+(y-1)*2+1;
    I(x,y)=I1(i)+I1(i+1)*256;
  end
  end

for x=126:242
  for y=1:252
    i=(x-126)*252*2+(y-1)*2+1;
    I(x,y)=I2(i)+I2(i+1)*256;
  end
  end

m=max(max(I))
mi=min(min(I(1:238,3:252)))
image((I-mi)/(m-mi)*64)

**Dark current substraction:**

% d = dark current file

getpix2
q=I-d;
l=[i j]=size(I);
for x=1:i
  for y=1:j
    if q(x,y)<0
      q(x,y)=0;
    end
  end
end
save temp q -ascii
```
Appendix III

Code for displaying image file

The following code is used when Electrim boards are used for image capturing. The ‘.tif’ file format (taken by using Electrim image acquisition boards) is first converted into ‘.pnm’ format (not shown in the code). This Matlab code reads a ‘.pnm’ format, and then displays it on Sun workstations. The parsing code given in Appendix I is also used here after the image is converted into ‘.pnm’ format and before it is displayed. The original author of this code is Martin Jagerstand, and Louis Brassard later modified it.

Reading ‘.pnm’ format:

% readppm Reads image files in the ppm format
% % [R,G,B] = readppm(fname);
% or
% % [G] = readppm(fname);
% % fname is a string with the filename; the image is assumed to
% % be a ppm image which is compress with “compress” from unix and
% % is name has to be terminated with “.Z”.
% % Do not supply the “.Z” at the end of the file name.
% %
% % C is an image of same format as those generated by ppmpack
% % Warning: May not accept all header formats. All comments must be within the
function [R,G,B] = readpnm(fname);

fid = fopen([fname,'.pnm'], 'r');

% Read in header

TheLine = fgetl(fid);
while TheLine(1) == '#' % Skip initial comments
    TheLine = fgetl(fid);
end

format = TheLine; % P2 for pbm ....

TheLine = fgetl(fid);
while TheLine(1) == '#' % Skip initial comments
    TheLine = fgetl(fid);
end

size = TheLine; % column (or width), row (or height)

TheLine = fgetl(fid);
while TheLine(1) == '#' % Skip initial comments
    TheLine = fgetl(fid);
end

maxint = TheLine; % maximum integer value for a pixel

% variables initialisation

s = sscanf(size, '%d');
columns = s(1);
rows = s(2);
npixels = rows*columns;
if nargout == 3 [ R,G,B ] = readppm(filename)

R = zeros(columns,rows);
G = zeros(columns,rows);
B = zeros(columns,rows);

% Reading image pixels
if format=='P6' % PPM True color image, byte format
if maxint > 255 error('format P6 and maximum value greater than 255');
end
sizeC = 3*npixels;
C = zeros(sizeC,1);
C(1:sizeC) = fread(fid,3*npixels,'uint8');
reds = 1:3:sizeC;
R(:) = C(reds);
G(:) = C(reds+1);
B(:) = C(reds+2);
elseif format=='P5' % PGM Grey image, byte format
C = zeros(npixels,1);
C(1:npixels) = fread(fid,npixels,'uint8');
keyboard;
R(:) = C(:);
G(:) = C(:);
B(:) = C(:);
elseif format=='P4' % PBM Binary Image, 8 pixels per byte format
C = zeros(npixels,1);
C(1:npixels) = fread(fid,npixels,'uint1');
R(:) = C(:);
G(:) = C(:);
B(:) = C(:);
elseif format=='P3' % PPM True color image, ASCII format
sizeC = 3*npixels;
C = zeros(sizeC,1);
C(1:sizeC) = fscanf(fid,'%3,0f %3.0f %3.0f');
reds = 1:3:sizeC;
R(:) = C(reds);
G(:) = C(reds+1);
B(:) = C(reds+2);
elseif format=='P2' % PBM Grey image, ASCII format
C = zeros(npixels,1);
C(1:npixels) = fscanf(fid,'%3d');
R(:) = C(:);
G(:) = C(:);
B(:) = C(:);
else
error('readpnm: Unknown format');
end
R = R';
G = G';
B = B';

else % [ R ] = readppm(filename)

R = zeros(columns,rows);
fprintf(1,'rows=%d, columns=%d, npixels=%d \n',rows,columns,npixels);

% Reading image pixels

if format=='P6' % PPM True color image, byte format
if maxint > 255 error('format P6 and maximum value greater than 255'); end
sizeC = 3*npixels;
C = zeros(sizeC,1);
C(1:sizeC) = fread(fid,sizeC,'uint8');
reds = 1:3:sizeC;
R(:) = 0.299*C(reds) + 0.587*C(reds+1) + 0.114*C(reds+2);
elseif format=='P5' % PGM Grey image, byte format
C = zeros(npixels,1);
C(1:npixels) = fread(fid,npixels,'uint8');
R(:) = C(:);
elseif format=='P4' % PBM Binary Image, 8 pixels per byte format
C = zeros(npixels,1);
[C(1:npixels),count] = fread(fid,npixels,'uint1');
fprintf(1,'%d pixels read. \n',count);
R(:) = C(:);
elseif format=='P3' % PPM True color image, ASCII format

sizeC = 3*npixels;
C = zeros(sizeC,1);
C(1:sizeC) = fscanf(fid,'%3,0f %3.0f %3.0f');
reds = 1:3:sizeC;
R(:) = 0.299*C(reds) + 0.587*C(reds+1) + 0.114*C(reds+2);
elseif format=='P2' % PBM Grey image, ASCII format
C = zeros(npixels,1);
C(1:npixels) = fscanf(fid,'%3d');
R(:) = C(:);
else
error('readppm: Unknown format');
end
R = R';
Displaying ‘.pnm’ format:

function display(I, ImageName)
  
  %
  % display(I, ImageName)
  %
  % I: image matrix to be display
  % ImageName: optional title
  %
  [rows, columns] = size(I);
  h = figure;
  if columns < 755
    width = 0.77 * columns;
    high = 1.8 * rows;
  else
    width = columns;
    high = rows;
  end;
  set(h, 'Position', [400 400 width high]);
  axis('image');
  height = min(10, 8 * rows / columns);
  set(h, 'PaperPosition', [0.25 1 8 height]);
  colormap(gray(250));
  image(I);

  if nargin > 1
    title(ImageName);
  end;

end
fclose(fid);
Appendix IV

Calculations for a point light source

This appendix shows the calculations for a point light source, and the formulas that are used in the simulation. See reference [45] for the detailed derivation of it.

The diagram in Figure IV-1 is a three dimensional view of a light point and a hole. Also shown is the arbitrary axis labeling.

Figure IV-1: Three dimensional view of a hole
When the point source is directly over a hole, the whole detector is illuminated because of the diffused light. As the spot source moves away in the horizontal direction, the mask begins to shadow the detector. The shadowing will cover a percentage of the area of the circular detector. Another way of viewing the shadowing effect is the intersection of two circles. Figure IV-2 demonstrates the idea. One circle is the circular detector under the mask hole, and the other is the projected circle of light from the circular opening on the top of the mask as seen at the detector surface.

The projected light from the point source on the detector surface is a circle, and the proof is given in [45]. Essentially, the cone of light created from the point source enters the top hole of the mask as a circle, and since the bottom of the detector surface is at the same angle (parallel to) as the opening at the top, a circle is projected. The area of intersection of the light circle and the detector surface is the amount of light falling upon the sensor. The area outside the detector circle would not produce a signal, and would be blocked by the walls of the hole. The radius of the detector is known, since it is the one half the hole diameter of the mask. The radius of the projected light circle is presented in formula (IV-1).

\[ R_1 = \left( \frac{t}{Z} + 1 \right) \frac{D}{2} \]  
(IV-1)
The value of $R_1$ is the radius of the projected light circle, $D$ is the diameter of the hole, $t$ is the thickness of the mask, and $Z$ is the distance from the spot to the top of the mask. As the vertical distance ($Z$) approaches infinity, the light circle approaches the radius of the hole opening ($0.5D$), which makes sense because the diffused light rays become parallel. The centre of the light circle is $C_1$ given in formula (IV-2), where the origin is the centre of the detector circle.

$$C_1 = \left( \frac{D}{2} + R_{xy} \right) \frac{t}{Z} \quad \text{(IV-2)}$$

Only one value is needed for the centre because the formula has no radial dependence. Essentially it is the direction along the central axis of the detector. The value of $R_{xy}$ is the distance from the edge of the detector to the point source on the X-Y plane where the path would go through the centre of the detector.

The point along the central axis where the two circles intersect is given in equation (IV-3).

$$X_i = \frac{\left( \frac{D^2}{4} - R_1^2 + C_1^2 \right)}{2C_1} \quad \text{(IV-3)}$$

The percentage area of the circular detector exposed to light is given in equation (IV-4).

$$A = \frac{f(R_1, C_1 - X_i) + f(0.5D, X_i)}{\pi \left( \frac{D}{2} \right)^2} \quad \text{(IV-4)}$$
The function \( f(u,v) \) is presented in equation (IV-5) below.

\[
f(u,v) = u^2 \cos \left( \frac{u}{v} \right) - v \left( u^2 - v^2 \right)^{\frac{1}{2}}
\]  

(IV-5)

As can be seen from Figure IV-2, it is possible that the projected light circle and the detector do not intersect. At this point, the equations (IV-4) and (IV-5) would produce imaginary values. Thus formula (IV-4) is valid only for a certain range - from the point where the shadowing starts to the point where the detector is in total shadowing. If the light source is between the edges of the holes, the total light area exposed is 100%, and would result in an infinite number of points that intersect the circles instead of just two. The range of \( R_{xy} \) for equation (IV-4) is shown in (IV-6).

\[
0 < R_{xy} < \frac{ZD}{t}
\]  

(IV-6)

The complete calculations for the percentage area of light exposed on the detector is shown in greater detail in [45]. The light intensity \( I \) of the point source at the surface falls as one over the square of the distance from the centre of the detector to the light source point, which changes little over the circle. To calculate the total intensity, the intensity \( I \) is multiplied by the percentage area \( A \) covered by light. The formula is shown in equation (IV-7).

\[
I_{total} = I \times A
\]  

(IV-7)

The formula assumes that the light intensity is close to being the same for the whole surface of the detector. Even though a change in intensity exists from one end of a detector to the other because of a change in total distance, the values are quite small. By doing a calculation where the light source is over the centre of the detector \( R \) and the addition of the radius of the hole \( \Delta X \) which is perpendicular to the direction over the detector, equation
(IV-8) shows the change in the square of the distance. As can be seen from (IV-8), the effect of $\Delta X$ is small compared to large distances ($R$).

\[
\frac{(R^2 + \Delta X^2)}{R^2} = 1 + \left(\frac{\Delta X}{R}\right)^2 \tag{IV-8}
\]

Because the simulations usually work with distances around 1000 $\mu m$, and the holes created are only 30 $\mu m$, the changes in the square of distance from the centre to the edge of the edge of the hole ($\pm 15\mu m$) creates an increase of only 0.025% in intensity, which results in the edge of the detector being only 99.9% of the value in the centre of the detector.
Appendix V

Code for simulating the detector

This appendix presents C codes (Translation of Turbo C code of Appendix D of [45]) for two functions to simulate a point source for one detector. These functions can be used to simulate an array, where the distance is offset from the spot source. The hole size, mask thickness, distance and light intensity are the parameters used. The values in the function ‘sensor’ are eventually normalized to the hole diameter and thickness of the mask to make the calculations simpler. The formulas are valid for certain ranges, thus the use of formula depends upon the range.

float pi = 3.14159265358;

/* formula(r,c,point) */
/* r - radius of circle */
/* d - distance from cord to center */
/* point - the point(value) to be calculated in the function */
/*
/* Used for calculating the integration of (r-(x-c))^2 */
float formula(r,d)
float r;
float d;
float r2;
r2 = pow(r,2.0);
return(r2*acos(d/r) - d*sqrt(r2 - pow(d,2.0)));

/* X,Y,Z - Cartesian co-ordinates for light point source */
/* Z is defined as distance above mask surface */
/* i - intensity of point of light */
/* d - diameter of round sensor */
/* h - height of mask */

float sensor(X,Y,Z,i,d,h)
float X;
float Y;
float Z;
float i;
float d;
float h;
{
float Rxy;
float In;
float light;
float center;
float a;
float Xi;
float on;

Rxy = pow(X,2.0) + pow(Y,2.0);
In = i/(Rxy + pow(Z+h,2.0));

/* normalizing the values so the sensor is a circle with */
/* diameter 1 */

Z = Z/h;
Rxy = sqrt(Rxy)/d - 0.5;

/* Special case where light point is over sensor */
/* no mask effect */
if (Rxy <= 0)
{
   light = In;
}
/* special case where the mask is totally covering the sensor */
/* all values have been normalized */
else if ((Z/Rxy) <= 1)
{
   light = 0;
}
else
{
    center = (0.5 + Rxy)/Z;
    a = 0.5/Z + 0.5;

    /* X intersection, the Y need not be calculated because of integration */
    Xi = (0.25 - pow(a,2.0) + pow(center,2.0))/(2*center);

    /* calculate what is on or lite, using integration */
    on = formula(a,center-Xi) + formula(0.5,Xi);

    on = on/(pi/4);
    light = on*In;
}

return(light);
Appendix VI

Code for simulating checkerboard pattern

The following C code (modification of Appendix E of [45]) is used to simulate a checkerboard pattern as seen by the TC245 sensor, with hole spacings of 153µm (x-direction) and 157.6µm (y-direction), at various heights. The simulation uses only six squares that are approximately 1mm on each side and uses other functions already given in Appendix V.

```c
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <math.h>

/* Supposed to be a checker pattern, but is really */
/* a 1 mm light square. Determines the edging of */
/* the image. */
/* Assuming a mask thickness of 500 um and hole */
/* diameter of 30 um. */

float checker(float Z, float off, float off2)
{

    float answer = 0;
```
int a,b=0;

for (a=1317;a<=2313;a+=3)
for (b=942;b<=1938;b+=3)
{
    answer = answer + sensor((float)(a)-off,(float)(b)-off2,Z,1000000.0,30.0,500.0);
}

for (a=-683;a<=313;a+=3)
for (b=942;b<=1938;b+=3)
{
    answer = answer + sensor((float)(a)-off,(float)(b)-off2,Z,1000000.0,30.0,500.0);
}

for (a=1317;a<=2313;a+=3)
for (b=-1058;b<=-62;b+=3)
{
    answer = answer + sensor((float)(a)-off,(float)(b)-off2,Z,1000000.0,30.0,500.0);
}

for (a=-683;a<=313;a+=3)
for (b=-1058;b<=-62;b+=3)
{
    answer = answer + sensor((float)(a)-off,(float)(b)-off2,Z,1000000.0,30.0,500.0);
}

for (a=317;a<=1313;a+=3)
for (b=-58;b<=938;b+=3)
{
    answer = answer + sensor((float)(a)-off,(float)(b)-off2,Z,1000000.0,30.0,500.0);
}

for (a=317;a<=1313;a+=3)
for (b=1942;b<=2938;b+=3)
{
    answer = answer + sensor((float)(a)-off,(float)(b)-off2,Z,1000000.0,30.0,500.0);
}

return(answer);
}

void main()
{ FILE *filepointer;
  char name[30];
  int o,x,y;
  float I;
  float Z;
  float off,off2;
  printf("file name : ");
  scanf("%s",name);
filepointer = fopen(name,"w");
printf("height : ");
scanf("%f",&Z);

/* will span at 157.6 intervals of displacement like a sensor */
/* and for 153 */
for (y=0;y<17;y++)
{
   for (x=0;x<16;x++)
   {
      off = ((float)(x))*153.0;
      off2 = ((float)(y))*157.6;
      I=checker(Z,off,off2);
      printf("%f\t",I);
      fprintf(filepointer,"%f\t",I);
   }
   fprintf(filepointer,"\n");
   printf("\n");
}

fclose(filepointer);
Appendix VII

Code for calculating proximity

The following Matlab code is used to calculate the centroid of the laser spot using three point interpolation method for proximity measurements. The functions of Appendix II (for Cookbook image acquisition boards) and III (for Electrim image acquisition boards) have to be used in conjunction. The parsing function given in Appendix II has to be applied in either case before using this code. This is modified from Appendix G of [45] for the TC245 CCD image array.

```matlab
contour(I2,10)
pause(0.1)
mx=max(max(I2))
[Y1 j1]=max(I2(5,:));
[Y2 j2]=max(I2(15,:));
[Y3 j3]=max(I2(25,:));

i1=5;
i2=15;
i3=25;

if I2(i1,j1-1) > I2(i1,j1+1)
    mid = j1-1;
```

\[ mn = j_1 + 1; \]
\[ s = 1; \]
else
\[ mid = j_1 + 1; \]
\[ mn = j_1 - 1; \]
\[ s = -1; \]
end

\[ a_1 = I_2(i_1, mid) - I_2(i_1, mn); \]
\[ b_1 = I_2(i_1, j_1) - I_2(i_1, mn); \]
\[ y_1 = (a_1 / b_1 / 2 \cdot s + j_1) \cdot 153 \]

if \( I_2(i_2, j_2 - 1) > I_2(i_2, j_2 + 1) \)
\[ mid = j_2 - 1; \]
\[ mn = j_2 + 1; \]
\[ s = 1; \]
else
\[ mid = j_2 + 1; \]
\[ mn = j_2 - 1; \]
\[ s = -1; \]
end

\[ a_2 = I_2(i_2, mid) - I_2(i_2, mn); \]
\[ b_2 = I_2(i_2, j_2) - I_2(i_2, mn); \]
\[ y_2 = (a_2 / b_2 / 2 \cdot s + j_2) \cdot 153 \]

if \( I_2(i_3, j_3 - 1) > I_2(i_3, j_3 + 1) \)
\[ mid = j_3 - 1; \]
\[ mn = j_3 + 1; \]
\[ s = 1; \]
else
\[ mid = j_3 + 1; \]
\[ mn = j_3 - 1; \]
\[ s = -1; \]
end

\[ a_3 = I_2(i_3, mid) - I_2(i_3, mn); \]
\[ b_3 = I_2(i_3, j_3) - I_2(i_3, mn); \]
\[ y_3 = (a_3 / b_3 / 2 \cdot s + j_3) \cdot 153 \]

all1 = [all1; y_1];
all2 = [all2; y_2];
all3 = [all3; y_3];
all = [all1 all2 all3]
Appendix VIII

Code for Centre of Full Width Half Maximum (CFWHM)

This appendix gives the Matlab code used for proximity measurements using Centre of Full Width half Maximum (CFWHM) method. The following code considers only rows 5, 15 and 25 of the sensor for the three-spot proximity mode. For the other rows, their intensity values have to be similarly read into a matrix (see the first code line for each row), and rest of the code would be the same.

Row 5 calculations:

% Row # 5 code

I5=I2(5,:);

[b5 b5p]=max(I5);
s5=min(I5);

% finding the average of maximum and minimum values and adding min. to it
m5=s5+(b5-s5)/2;
for a=1:40;
M5=[M5 m5];
end
% taking care of R.H.S. of the maximum
for a=b5p:40;
if (I5(a) - m5) > 0
  if (I5(a+1) - m5) < 0
    rup5=a;
    rdp5=a+1;
  end
end
end

ru5=I5(rup5);
rd5=I5(rdp5);

% taking care of L.H.S. of the maximum
for a=1:b5p;
if (I5(a) - m5) < 0
  if (I5(a+1) - m5) > 0
    lup5=a;
    ldp5=a+1;
  end
end
end

lu5=I5(lup5);
ld5=I5(ldp5);

% interpolating the two neighbouring values on R.H.S. using st. line eqn.
% i.e. y=ax+b
a5r=(ru5-rd5)/(rup5-rdp5);
b5r=ru5-a5r*rup5;
xr5=(m5-b5r)/a5r;

% interpolating the two neighbouring values on L.H.S. using st. line eqn.
% i.e. y=ax+b
a5l=(lu5-ld5)/(lup5-ldp5);
b5l=lu5-a5l*lup5;
xl5=(m5-b51)/a5l;

% finding the centre of two interpolated values
x5=(xl5+xr5)/2;

% plotting intensity distribution, average intensity level, left and right hand values and the final value
a=1:40;
plot(a,I5,a,M5,'--',xl5,m5,'x',xr5,m5,'x',x5,m5,'*')
grid
print
pause(0.1)
all1=[all1;x5*153];
clear M5

**Row 15 calculations:**

% Row # 15 code

I15=l2(15,:);

[b bp]=max(I15);
s=min(I15);

% finding the average of maximum and minimum values and adding min. to it
m=s+(b-s)/2;
for a=1:40;
M=[M m];
end

% taking care of R.H.S. of the maximum
for a=bp:40;
  if (I15(a) - m) > 0
    if (I15(a+1) - m) < 0
      rup=a;
      rdp=a+1;
    end
  end
end
ru=I15(rup);
rd=I15(rdp);

% taking care of L.H.S. of the maximum
for a=1:bp;
  if (I15(a) - m) < 0
    if (I15(a+1) - m) > 0
      lup=a;
      ldp=a+1;
    end
  end
end
lu=I15(lup);
ld=I15(ldp);

% interpolating the two neighbouring values on R.H.S. using st. line eqn.
% i.e. y=ax+b

ar=(ru-rd)/(rup-rdp);
br=ru-ar*rup;
\[ x_r = \frac{(m-b_r)}{a_r}; \]

% interpolating the two neighbouring values on L.H.S. using st. line eqn.  
% i.e. \[ y = ax + b \]

\[ a_l = \frac{(l_u - l_d)}{(l_u - l_d)}; \]
\[ b_l = l_u - a_l \cdot l_u; \]
\[ x_l = \frac{(m-b_l)}{a_l}; \]

% finding the centre of two interpolated values

\[ x = \frac{(x_l + x_r)}{2}; \]

% plotting intensity distribution, average intensity level, left and right hand values and the final value

\[ a = 1:40; \]
\[ \text{plot}(a,I_{15},a,M,\text{','--',}x_l,m,\text{'x',}x_r,m,\text{'x',}x,m,\text{'x'}) \]
\[ \text{grid} \]
\[ \text{print} \]
\[ \text{pause}(0.1) \]

\[ \text{all}2 = [\text{all}2; x*153]; \]
\[ \text{clear} M \]

**Row 25 calculations:**

% Row # 25 code

\[ I_{25} = I_{25}(5,:); \]

\[ [b_{25} b_{25p}] = \text{max}(I_{25}); \]
\[ s_{25} = \text{min}(I_{25}); \]

% finding the average of maximum and minimum values and adding min. to it
\[ m_{25} = s_{25} + (b_{25} - s_{25})/2; \]
\[ \text{for } a = 1:40; \]
\[ M_{25} = [M_{25} m_{25}]; \]
\[ \text{end} \]

% taking care of R.H.S. of the maximum
\[ \text{for } a = b_{25p:40}; \]
\[ \text{if } (I_{25}(a) - m_{25}) > 0 \]
\[ \text{if } (I_{25}(a+1) - m_{25}) < 0 \]
\[ r_{up25} = a; \]
\[ r_{dp25} = a+1; \]
\[ \text{end} \]
\[ \text{end} \]
\[ \text{end} \]
ru25=l25(rup25);
rd25=l25(rdp25);

% taking care of L.H.S. of the maximum
for a=1:b25p;
    if (l25(a) - m25) < 0
        if (l25(a+1) - m25) > 0
            lup25=a;
            ldp25=a+1;
        end
    end
end

lu25=l25(lup25);
ld25=l25(ldp25);

% interpolating the two neighbouring values on R.H.S. using st. line eqn.
% i.e. y=ax+b
a25r=(ru25-rd25)/(rup25-rdp25);
b25r=ru25-a25r*rup25;
xr25=(m25-b25r)/a25r;

% interpolating the two neighbouring values on L.H.S. using st. line eqn.
% i.e. y=ax+b
a25l=(lu25-ld25)/(lup25-ldp25);
b25l=lu25-a25l*lup25;
xl25=(m25-b25l)/a25l;

% finding the centre of two interpolated values
x25=(xl25+xr25)/2;

% plotting intensity distribution, average intensity level, left and right hand values and the final value
a=1:40;
plot(a,l25,a,M25,'--',xl25,m25,'x',xr25,m25,'x',x25,m25,'*')
grid
print
pause(0.1)

all3=[all3;x25*153];
clear M25
all=[all1 all2 all3]
References


