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## ABSTRACT

## IMPROVING THE PROCESS OF LASER RETINAL EYE SURGERY USING ELECTROSTATIC MICRO MIRRORS

## by Narashiman Chakravarthy

This thesis describes an improved system for laser eye surgery. The system incorporates hardware based image matching and MEMS micromirrors for feedback control of laser positioning on the eye. Many benefits are described in this thesis, such as nulling out eye movement, tracking laser firing history, enabling precise control of laser firing locations and preventing firing accidents. The aim of this work is to frame this improved laser surgery concept and prove the principle of various components of the system. A featured accomplishment is the modeling and simulation of a prototype microcontroller using VHDL that may be incorporated as part of the improved system.

# IMPROVING THE PROCESS OF LASER RETINAL EYE SURGERY USING ELECTROSTATIC MICRO MIRRORS

by Narashiman Chakravarthy

A Thesis Submitted to the Faculty of New Jersey Institute of Technology in Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical Engineering

**Department of Electrical and Computer Engineering** 

May 2003

# APPROVAL PAGE

# IMPROVING THE PROCESS OF LASER RETINAL EYE SURGERY USING ELECTROSTATIC MICRO MIRRORS

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# TABLE OF CONTENTS

Chapter P	
1 INTRODUCTION AND MOTIVATION	1
1.1 MEMS and its potential	1
1.2 The eye	3
1.3 Wet AMD and Diabetic Edema	3
1.3.1 Dry and Wet AMD	3
1.3.2 Detection of AMD	5
1.3.3 Fluorescein Angiograph	6
1.4 Current Treatment Procedures	7
1.5 Tracking and Locking	8
1.6 Summary of Improvements Offered and Scope of Thesis	9
2 FABRICATION PROCESS OF THE MICRO MIRROR	11
2.1 Introduction	11
2.2 Wafer cleaning and Oxidation	11
2.3 Photolithography and Bulk Anisotropic etching	12
2.4 Wet Oxidation	13
2.5 Silicon fusion bonding	13
2.6 Deep reactive ion etching	14
2.7 Chromium and gold coating	15
3 CHARACTERIZATION OF THE MICRO MIRROR	17

TABLE OF CONTENTS	
(Continued)	

Chapter	Page
3.1 Need for Characterization	17
3.2 The Dimensions of the Micromirror	18
3.3 The Static and dynamic characteristics under electrical bias	22
4 COMPLETE SYSTEM ARCHITECTURE	24
4.1 Introduction and Basic set-up	24
4.1.1 Tracking eye movement	25
4.1.2 Camera, Picture and the complexity of the Image	26
4.1.3 LASER	27
4.1.4 CPU	27
4.2 Working Algorithm of the Controller	28
4.2.1 Basic assumptions and Definitions	29
4.2.2 Least Mean Square Algorithm	30
4.2.3 Diseased area and LASER components	32
4.3 The Mirror Arrangement	33
4.3.1 Proposed construction of the box	34
5 ARCHITECTURE OF MICRO CONTROLLER AND VHDL MODELING	36
5.1 Introduction	36
5.2 Blocks of the Micro controller	36

# TABLE OF CONTENTS (Continued)

Chapter	Page
5.2.1 LMS Comparator	37
5.2.2 Address and Data management	38
5.2.3 LASER controller	38
5.2.4 RAM	40
5.3 Simulation Results and Discussion	42
6 CONCLUSION AND FUTURE WORK	45
APPENDIX LIST OF VARIOUS LASER CHARACTERISTICS	46
REFERENCES	47

# LIST OF TABLES

Table		
A.1 Various Lasers and their characteristics	46	

Figure Pag		
1.1 Micro mirror	2	
1.2 Normal Vision	4	
1.3 Vision with AMD	4	
1.4 Vision with Diabetic Edema	5	
1.5 Amsler grid with and without distortion	5	
2.1 Silicon substrate	11	
2.2 Silicon substrate with cavity	12	
2.3 Oxidized silicon substrate	13	
2.4 Ultra thin wafer bonded substrate	14	
2.5 Photo resist coating and Photolithography	14	
2.6 Etching	14	
2.7 Photo resist strip	15	
2.8 Gold plating	15	
2.9 The SEM of the mirror and Spring	16	
3.1 Working of a Profilometer	18	
3.2 Profilometric view of the mirror	19	
3.3 The X profile of the mirror	20	
3.4 Profilometric view of the spring	21	
3.5 The X axis spring profile	21	
3.6 The Y axis spring profile	21	
3.7 Set up for the Electrostatic and Dynamic Characteristics	22	

# **LIST OF FIGURES**

# LIST OF FIGURES (Continued)

Fig	ure	Page
4.1	Overall setup Block diagram	24
4.2	SSD matching	31
4.3	State of the art digital image collector	33
4.4	The mirror arrangement box	34
4.5	Alignment of the mirrors	35
5.1	LMS comparator	37
5.2	Initial time (no data)	41
5.3	Forced matrices and Data	41
5.4	Position of data and the 10*10 matrix	42
5.5	Shift in the matrix (Jitter)	42
5.6	Corresponding shift in the 10*10 matrix, trace value	43
5.7	Initial Laser hit clock pulse	43
5.8	Final Laser hit clock pulse and the disabled Laser hit signal	44
5.9	Waveform analysis of the disabling of the Laser hit signal	44

#### CHAPTER 1

## **INTRODUCTION AND MOTIVATION**

The objective of this thesis is to develop an improved system for retinal LASER eye surgery, and perhaps other applications, by incorporating MEMS (Micro Electro Mechanical Systems) and closed loop feedback control by image matching. These improvements will address such issues as tracking the saccadic movement of the eye called Nystagmus enabling micro-positioning and control of a LASER spot either on target features or near sensitive features to be avoided such as the Fovea, compiling a temporal and spatial record of the LASER pulses fired during the surgery, and possible automation of the surgical process. In a companion thesis a Graphical User Interface (GUI) is developed to demonstrate the procedural benefits made possible by the improved MEMS/image matching system [1]. In this thesis the essential features of the GUI are implemented as a micro controller.

#### **1.1 MEMS and its Potential**

Micro electro mechanical devices and systems are becoming increasingly prevalent in market applications across a wide array of disciplines, ranging from the automobile industry to biomedical engineering tools. MEMS chips, many of which are fabricated using the same tools as the silicon microelectronics industry, can be easy to batch fabricate and mass-produce leading to low cost devices. Micro devices may be classified into three levels. Level 1 MEMS have no moving parts and are used mainly in energy acquiring sectors such as heat and fluidics. Level 2 MEMS have some moving parts but

1

no abrasive parts. These are used in wider areas of energy such as optics (for deflection) and sound acquisition. The electrostatic micromirror, which we deal with in detail for the present application, is an example of this type of device. Level-3 MEMS have both moving and abrasive parts, and these have applications in almost all of the energy areas. It is interesting to note that MEMS devices become increasingly difficult to fabricate and operate reliably as one moves up in level. Since, the device that is planned to be employed is level-2, special attention is paid to fabrication and performance attributes that suggest that it will be manufacturable and reliable.

The electrostatic micromirror used in this thesis work, shown in Figure 1, was originally designed and fabricated at NJIT in collaboration with Lucent Technologies [2] for telecommunications applications. As will be discussed in a later chapter, this device is a relatively large area mirror (~1 mm<sup>2</sup>) with exceptional flatness, having a radius of curvature that exceeds 2 m. These features, among others, make it attractive for many laser beam steering applications. For example, in the biomedical industry one is aware of a related application where double-gimbaled micromirrors are used to write images directly on the eye [3]. In this thesis the use of micromirrors for controlled eye surgery is explored. Characterization of the device for this application, and the value of using two one degree-of-freedom devices versus a single, double-gimbaled device are explored. The picture below shows our one degree-of-freedom micro mirror.



Figure 1.1 Micromirror.

#### 1.2 The Eye

The eye is composed of many parts, including the cornea, iris, lens, macula, retina and fovea. In addition to these there is an optic nerve, which connects to the brain cells that interpret images. Technology has been applied to many of these eye parts for vision improvement and the treatment of disease. The introduction of lasers for surgery has been especially beneficial, giving rise to numerous techniques. These include PRK, LASIK and a variety of other surgeries, which vary according to disease, and patient needs.

The eye parts of particular concern for this thesis are the retina, macula and fovea. The macula and the retina are the successive layers of the eye, which act as the screen for the "video" displayed by the lens. In this thesis we emphasize the use of laser surgery for the treatment of two of the most important diseases related to the macula: "AGE RELATED WET MACULAR DEGENERATION" and "DIABETIC EDEMA". While these diseases are emphasized, other applications of the techniques discussed in this thesis can also be envisioned. The following is a brief description of the two emphasized diseases, including an overview of the current surgical approach and the proposed improved approach.

## 1.3 Wet AMD and Diabetic Edema

#### 1.3.1 Dry and Wet AMD

Studies [4] show that the percentage of the dry and wet AMD is 90 and 10 percent respectively, but the vision loss percentage is the other way around as 10 and 90 percent, respectively. It is therefore clear that the wet AMD is more severe than the dry AMD.

Wet AMD involves growth of blood vessels under the retina in the macula. The new blood vessels will often leak blood and other fluid under the macula. This causes rapid damage to the macula that can lead to the loss of central vision over a short period of time. The Figures 1.2 and 1.3 below compare normal vision to vision with wet AMD.



Figure 1.2 Normal Vision.



Figure 1.3 Vision with AMD.

The figure below illustrates vision with diabetic edema. Laser treatment may be used in patients with clinically significant macular edema. An effort has been made to show wherever there is a difference between the two diseases in terms of algorithm execution and simulation results.



Figure 1.4 Vision with Diabetic Edema.

## **1.3.2 Detection of AMD**

Initially the doctor tests the eyes manually to spot DRUSEN (tiny yellow spots which reside on retina). These are the initial symptoms of AMD. In wet AMD, there is leakage under the macula, which can lead to distortion in the central vision. When a patient with wet AMD looks at an Amsler grid, which resembles a checkerboard the patient may notice that the straight lines in the pattern appear wavy. The patient may also notice that some of the lines are missing. These may be signs of Wet AMD.



Figure 1.5 Amsler Grid with and without the distortion.

#### **1.3.3 Fluorescein Angiograph**

Once some symptoms are detected for wet AMD, then the doctor calls for a flouroscein angiogram (FA). This is a procedure that allows the blood vessels in the back of the eye to be photographed by injecting a fluorescein dye in a blood vessel of the arm. FA is performed to

- 1. Enable diagnosis.
- 2. Obtain a permanent record of the anatomy of the eye.
- 3. Serve as a reference when performing the eye surgery.
- 4. Determine the parameters of the laser required for surgery.

Fluorescein sodium is a commonly used dye. It is a highly fluorescent, synthetic, sodium salt of Fluorescein, which absorbs blue light with fluorescence. The procedure of the FA is discussed in the following paragraph.

The pupils are dilated with eye drops, and the dye is injected into a vein in the patient's arm. Following the injection, microscope eye photos are taken quickly over a period of about 60 seconds as the dye enters the vessels at the back of the eye. For the application developed in this thesis, the FA image plays a very important role. This will be the image that serves as a digitized, computer based reference for a tracking and locking algorithm used during surgery. The FA will be image-matched with a real-time video image of the eye to provide feedback to the MEMS micromirror to control the location of the laser beam spot during surgery. The algorithm for this process is given in subsequent chapters.

## **1.4 Current Treatment Procedures**

Lasers are currently used for retinal eye surgery. The specific laser used for the procedure depends on various factors involving the age of the patient, severity of the disease, etc. Laser surgery is performed in the eye care professional's office or eye clinic. Before the surgery, the surgeon will dilate the pupil and apply drops to numb the eye. In some cases, the surgeon also may numb the area behind the eye to prevent any discomfort for the patient.

As the patient sits facing the laser machine, the eye care professional will place a special lens to the patient's eye. When the retinal eye surgery is performed using a laser, a portion of the laser target area Sub Retinal Neo Vascularisation (SRNV), is first selected using a slit-lamp microscope and a low power laser spot aligned with the path of the actual surgical laser beam. To identify the SRNV, the FA image is used as visual reference. The SRNV are identified by their relative distance from identifiable features on the real-time image of the eye, visible through the split beam microscope. It is important to note that the real-time image shows much less detail than the FA, so identification of SRNV and ultimate laser surgery decisions currently rely heavily on the interpretation skills of the surgeon.

Once the target area is selected, the surgical laser is fired at the target area. This is performed repeatedly to fire across the whole of the SRNV. A second note of interest is that cataloging the temporal and spatial history of these laser firings is neither automated nor coupled directly to the FA image. It is an aim of this thesis to provide the means to overcome these shortcomings. The current LASER treatment is recommended only in some cases of macular degeneration. This form of treatment is generally deemed feasible only if the abnormal blood vessels are not in the fovea or anywhere near optic nerve. The motion of the eye and the surgeon's control of the placement of the laser set these proximity limitations. If the optic nerve is damaged, a vision loss is highly probable. It is a further intention of this thesis to present a system that addresses these positioning limitations by providing feedback control.

After the surgery, the patient will need to make frequent follow-up visits. During each exam, the patient may have Fluorescein angiography to make sure that the blood vessels are not still leaking, or that new blood vessels have not developed. If the vessels continue to leak, the patient may need additional laser surgery. It is important to realize that laser surgery is not a cure for AMD; it is only a treatment to help stop further vision loss. Unfortunately the risk of new blood vessels growing back after laser treatment is relatively high. However an improved surgery tool will greatly enhance surgeons' ability to treat the disease.

## **1.5 Tracking and Locking**

During the retinal eye surgery, the eye movement is minimized by sedation, before performing the surgery. However, there are minute, involuntary movements of the eye. These movements are called Nystagmus. Due to these movements, the laser may not fall precisely on the target area even after selecting the area using the split beam microscope.

The size of the macula is about 6 x 5  $\text{mm}^2$  [5]. The SRNVM can be of any size between 1-6mm [5]. This means that the saccadic movements the eye is comparable with the dimensions of the LASER. It is expected that these motion problems will be overcome using the feedback control system developed here.

## 1.6 Summary of Improvements Offered and Scope of the Thesis

The following is a summary of the major components required for the improved laser eye

surgery process:

- 1. Track movements of the eye using a high precision frame grabber or a multi array signal analyzer to provide a real time image.
- 2. Use an algorithm to match this image to a reference FA image.
- 3. Develop an algorithm to convert the image matching information into a control voltage to control mirror deflection to keep a laser beam precisely directed onto a chosen spot on the eye.
- 4. Allow the surgeon to select the area for surgery on the FA image, and then have the algorithms perform the locking and tracking function. In one option, the doctor still has the control as to when to fire the laser, but the possibility exists that the firing function could be automated. Since the whole process of tracking the eye is now automatic the error due to the nystagmus or reflexive movement is minimized.
- 5. Allow the surgeon to disable firing if the laser is directed outside of a selected diseased area. With this feature, even if the surgeon accidentally tries to fire the laser system outside the selected area, it will not fire. This would be especially useful for preventing damage to the delicate areas such as fovea.
- 6. Include in the micro controller a history counter, which is used to record the history of the laser being fired at each pixel of the FA image. There is a counter designed for each pixel of the diseased area and the micro controller records the laser hits of that particular pixel so that the surgeon does not hit the part more than needed. Once the surgeon hits the specific spot the required number of times, say 10 hits, the controller automatically excludes the portion

from being hit by disabling the laser over that pixel. This accessory is particularlyvaluable when using the diode laser, which is both invisible and among the strongest of all the lasers available.

7. The latter part of the thesis deals with packaging issues for the micro mirror and how to incorporate this new system as a straightforward adaptation of systems that are currently available.

Chapter 2 will present fabrication details for the micromirror. While the devices were not made as part of this thesis, the details are presented here for completeness. Chapter 3 will present characterization results, to demonstrate the feasibility of using the micromirror for the eye surgery application. Chapter 4 will discuss the whole system set up and the algorithm for image matching and laser tracking controls. It also talks about the packaging and integration issues. Chapter 5 will discuss VHDL architecture, modeling and simulation results to prepare a firmware version of the control system. Chapter 6 will describe future work envisioned for this activity.

#### CHAPTER 2

#### FABRICATION PROCESS OF THE MICRO MIRROR

## 2.1 Introduction

The large area (700u\*700u) micro mirrors are level-2 MEMS, which have movement but no abrasive parts. The fabrication of this mirror is done using bulk anisotropic etching of a bottom silicon wafer to form a cavity, fusion bonding a thin silicon wafer over this cavity, and deep reactive ion etching (DRIE) the thin wafer over the cavity to cut out the micromirror shape. The fabrication was done in the Microelectronics Research Center (MRC) at NJIT [6]. This chapter is included in the thesis for completeness.

## 2.2 Wafer Cleaning and Oxidation

The typical wafer used for the bottom part of the micro mirror is a 4" substrate wafer. The substrate is first cleaned in m-pyrol to remove organic contaminants. Then the wafer is rinsed in cold deionised water and it is spin-dried. Then the wafer is P-cleaned. This bath is composed of sulphuric acid and hydrogen peroxide in a 5:1 ratio. This step is conducted at 110°C for 10 minutes, followed by a hot DI rinse for 10 minutes and a cold DI rinse for 5 minutes.



Figure 2.1 Silicon substrate.

The wafer is then spin-dried. After cleaning, the wafer is oxidized in dry oxygen at  $1050^{\circ}$ C to form a ~100 nm layer that will serve as a mask during cavity formation.

## 2.3 Photolithography and Bulk Anisotrophic Etching

A photo resist (prime Shipley) is spun onto the substrate. It is soft baked on a hot plate at 110°C for a minute. A mask is aligned and the entire set up is exposed to ultra violet light, and then developed. The oxide is then removed in the cavity areas using a buffered oxide etch, and then the photo-resist is stripped from the wafer.

Bulk anisotropic wet etching is then performed in KOH to open cavities in the substrate silicon. For this micromirror, a 45% potassium hydroxide solution is used for etching at an etch rate of 1.66 m/min. The model below explains how the substrate would look after etching.



Figure 2.2 Silicon substrate with cavity.

#### 2.4 Wet Oxidation

The mask oxide is then stripped from the substrate wafer, and the substrate and thin top wafers are cleaned and oxidized to form 1 m thick layers. The oxide serves to insulate the top layer from the substrate during actuation of the mirror, and it enhances fusion bondability to be discussed below.



Figure 2.3 Oxidized silicon substrate.

#### 2.5 Silicon Fusion Bonding

The wafer pair is mated using fusion wafer bonding. The portion of the thin bonded wafer over the cavity later becomes the moving part of the micro actuator. Both the wafers are cleaned and then aligned in the vacuum chamber of an EVI 501 universal wafer bonding system. Bonding is performed in vacuum to form sealed cavities. The wafer pair is then removed from the bonder and annealing in oxygen at 1100°C for one hour increases the bond strength. The following model shows a view of the device after bonding.



Figure 2.4 Ultra thin wafer bonded Substrate.

# 2.6 Deep Reactive Ion Etching (DRIE)

Deep reactive ion etching is a dry etching process. The chemical etch reactions takes place in plasma of energetic ions. The DRIE process [7] is used to obtain high aspect ratio features such as those required for the springs of the micromirror. For this process, the previously oxidized surface of the top silicon wafer is patterned by photolithography to form the shape of the movable plate of the micromirror. This is illustrated below.



Figure 2.5 Photo resist coating and Photolithography.



Figure 2.6 Etching.



Figure 2.7 Photo resist strip.

# 2.7 Chromium and Gold Coating

To enhance the reflecting properties of the device a layer of metal is deposited on the mirror surface. First, a thin,  $\sim$ 2-10 nm adhesion promoting layer of chromium is evaporated onto the surface. This is followed by evaporation of gold to a thickness of about 1000 A°. The wafer is then diced and the chips are characterized. The model below shows the isometric view of the final device.



Figure 2.8 Gold plating.

An SEM of the micromirror and a close up view of the spring structures are given below. Additional fabrication details can be found in other references [6]. The device dimensions required for this work will be listed in the next chapter.



Figure 2.9 SEM of the Mirror and spring.

#### CHAPTER 3

## **CHARACTERIZATION OF THE MICRO MIRROR**

#### **3.1 Need for Characterization**

In this chapter the characterization of the mirror is explained to demonstrate that it is useful for the laser surgery application. To do this, specifications for the mirror, have to be developed including among others, actuation voltage, mirror displacement and resonant frequency. The displacement versus voltage information is critical, and needs to be obtained for each mirror used in the improved surgical tool. It is envisioned that a look up table based on this characterization information would be used to set the precise voltage required to move the mirror through a known displacement determined by the image-matching algorithm.

The resonant frequency of the device would set the upper limit of the operating speed. It is estimated that a 1 kHz resonant frequency will be more than sufficient for the surgery application, since this is higher than image refresh rates contemplated for the image-matching portion of the algorithm. Additional requirements for this particular application are highly controllable movement and a precise stop in a position without any oscillations when a voltage is applied. The dimensions of the mirror also play an important role in building the whole system and they are measured in this chapter, for later optics design considerations in Chapter 5.

## 3.2 The Dimensions of the Micromirror

As the micromirror is a mechanical device, the dimensions of the microstructure determine its characteristics vis-à-vis spring constant, resonant frequency and snap-down voltage. The following dimensions of the microstructure are measured using the profilometric images.

- 1. Length of the mirror plate (l).
- 2. Width of the mirror plate (w).
- 3. Thickness of the mirror plate (t).
- 4. Depth of the cavity under the micromirror and spring (d).
- 5. Length of the springs (ls).
- 6. Width of the springs (ws).

These are measured to calculate the theoretical snap down voltage and resonant frequency later in this chapter. The micromirror is characterized using a WYKO profilometer. The WYKO uses the phenomenon of optical interferometry to display the profiles of the test image. A schematic of the working of the WYKO is shown below. The platform holds the mirror in place. The various pictures and the dimensions of the mirror are shown below



Figure 3.1 Working of a Profilometer.



## Figure 3.2 Profilometric view of the mirror.

The shades of the profilometric image tell about the height and flatness of mirror features. The dark tint in the far end of the cantilever (top of the image) in figure 3.2 is due to the mirror's tilt towards the surface of the substrate. This particular device is snapped down to the bottom of the cavity at the far end of the cantilever, thus the image can be used not only to obtain the mirror plate dimensions, but also the cavity depth and the maximum attainable angular deflection.

The dimensions of the mirror are found by profile analysis. These are important for the reason that the laser in the surgery system will be directed onto the mirror, and thus the plate area should be able to accommodate this spot. For diabetic edema surgery, the LASER spot size is about 50 m. For macular degeneration, the laser spot size ranges from 150 m to 400 m. In both cases, the spot should easily fit on a 700 x 700 micron mirror. The mirror size sets the geometry for a two-mirror design discussed later in this thesis. In this design, horizontal travel of the laser beam is controlled by one mirror, and vertical travel is controlled by a second mirror rotated 90 degrees relative to the first. The 700 m plate length and width are confirmed in the 2-D plots below. The X-profile shows the heights of the surfaces near the end of the cantilever, where it is snapped down to the bottom of the cavity. The mirror width spans from ~0.25 mm to ~0.95 mm. The outstanding mirror flatness is evident in the figure. The mirror radius of curvature is over 2 m, and thus would not be expected to significantly distort laser beams directed onto its surface. The vertical displacement at the end of the mirror is ~6 micrometers, the depth of the cavity. Thus the maximum angular tilt of this mirror is ~6/700 radians or 0.49 degrees. Actually, due to the electrostatic snap down phenomenon that limits the mirror's controllable travel range to ~44% of this maximum displacement, the effective maximum angular tilt is 0.22 degrees. This corresponds to a maximum laser deflection of twice this angle or 0.44 degrees. From the figure, the mirror plate thickness is -46+11 = 57 microns. This thickness assures the mirror flatness.





The spring dimensions as well as the plate size and gap depth determine the electrostatic and dynamical behavior of the mirror. The dimensions of the springs are measured by focusing on the spring alone. The profilometric image and the X-profile will be as shown in figure 3.4 and 3.5, respectively. The length of the spring is calculated as the product of the length of one segment of the spring and the number of segments. The length of a segment of the spring is measured in figure 3.5, which is 207µm. The spring has 2 segments. The total length of the spring is 414µm. The width of the spring is determined in figure 3.6, which is 8.6µm. The figures are given below.



Figure 3.4 Profilometric view of the spring.



Figure 3.5 The X axis spring profile.



Figure 3.6 The Y axis spring profile.

#### 3.3 The Static and Dynamic Characteristics under Electrical Bias

Earlier it was discussed why the mirror requires to have absolute controllability. The movement of the mirror is going to be at most on the order of a few microns. These are extremely small movements, which this mirror is capable of performing with the highest precision. The set up for testing the mirror for its endurance is given below.

When the voltage is applied to the two plates, one being the substrate and the other being the mirror, the electro static force between the plates tries to bring them together. While this is happening the spring constant and various other mechanical factors try to pull the mirror upwards. At a particular point called pull-in or snap-down, the electrostatic force overcomes the mechanical forces and instability occurs forcing the mirror to snap down immediately. This point is called the snap down voltage, which can be calculated theoretically using the various measurements taken earlier such as the spring width, length, thickness, etc. Those calculations are given in the companion thesis [1].





The mirror is run for various trials from the end-to-end voltages in both positive and negative directions. Every mirror tested has a high degree of repeatability, even if tested in air. For example, the snap-down voltage for a given device is repeatable to within 0.2%. In addition, these mirrors are stable, showing no discernable drift, even over many hours biased at a particular deflection angle. These excellent performance qualities can be attributed to the fact that these devices are "full plate" actuators. In other words, the substrate and movable plate electrodes is each the same length. In an effort to increase mirror travel range beyond the 44% limit for full plate devices, shorter substrate electrodes have been used, but these have been shown to be unstable in air because of charging effects in the region where no electrode is present [8]. Double gimbaled devices are necessarily unstable for the same reason.

Thus it is suggested that using two full-plate devices may be the best, most stable and reproducible approach for the present application. Returning to the angle versus voltage plot, in the improved surgery system, a lookup table is formed based on this type of graph, and the tabulations are stored in a register for reference by the ALU of the designed micro controller. These data are used to determine the voltage to be sent to the DAC controlling the micromirror.

## **CHAPTER 4**

## **COMPLETE SYSTEM ARCHITECTURE**

## 4.1 Introduction and Basic Set-up

This chapter gives an overview of the entire system being proposed. In the view shown in Figure 4.1, the conventional system consists of the lasers, static mirrors and camera/microscope. The proposed system connects the camera output via a CPU to a microcontroller for image matching. The microcontroller outputs mirror control signals to a DAC that are amplified and applied to a micromirror pair for feedback control of the laser placement on the eye. More discussion on the nature and function of the various system components is provided in the following sections.



Figure 4.1 Overall setup Block diagram.

#### 4.1.1 Tracking Eye Movement

Relative to the fixed AF image, the real-time image captured by the camera in figure 4.1 can be rotated, skewed or translated along any of three axes. For the demonstration purposes of this thesis, only the most elementary case, translational displacement in one the x-y plane of the AF image is considered. In addition, the motion of the eye can have the same skewing and displacement, but again only the most straightforward two-dimensional translation is considered. In both cases, 2D translation will be the dominant displacement. The process is designed and the error signal is generated based on this assumption, so as to nullify the movement in the (x, y) direction.

The image of the eye, the size captured by the camera, the diseased area or the diseased areas play an important role in designing the algorithm because the nature of the disease will specify the nature of the LASER used. Since the mirror is of the dimensions proportional to the diseased area, the use of these mirrors is a good match for the system.

The movement of the eye is on the order of 40-70 microns [9], which means that the movement is not going to be more than 4-5 pixels, or to be safer, the consideration can be made that it shall never move out more than 10 pixels in each of up, down, right or left. In other words, if a pixel is picked in the image then the pixel cannot move total of 19\*19 pixels around the selected pixel. This important specification is included in the algorithm of the controller and drastically simplifies the problem of tracking, which is later discussed in the working algorithm of the micro controller system. The z movement or the in-out movement of the eye is beyond the scope of this thesis, and is discussed in Chapter 6 as part of the future scope of this research.

#### 4.1.2 Camera, Picture and the Complexity of the Image

For the proof-of-concept work, the use of a video camera interfaced to a frame grabber, which has the suitable specifications to be put in the system is envisioned. One possibility is the "Imagenation pc610" series IR frame grabber. This device has various precisions of which some can be used effectively in the system [10]. The controller is designed in accordance with the 30 frames per second image output of the grabber. The frame grabber output is connected to a CPU, which does the process of scaling and the cropping the image to 256\*256 pixels. Apart from these the entire frame grabber is programmable and hence adds on to the functionality of the camera part of the system.

One common assumption made to execute the working of the controller is that though the object is 3-D in nature, the image itself is considered as a 2-D image. All the image components can be defined as pixels, which have attributes. Each of the pixels is given an individual address starting from (0, 0) and ranging to (256, 256). Each of the pixels has many attributes such as intensity, brightness, RBG combination etc. These attributes vary temporally and spatially, and are determined by various factors such as ambient brightness, etc.

In general, the FA image and the real-time image will not have the same attributes at regions that correspond to the same location of the eye. The Least Mean Square (also called the SUM OF SQUARED DIFFERENCES) algorithm can work very well to match the two images using brightness and the intensity attributes. However the rotation and the scaling of the image needs attention since their solutions are more mechanical in nature. The size of the image can be kept the same when the camera position and the position of the face are kept the same during both the study of FA and the surgery. The algorithm of rotating the image to all the possible degrees and then finding a match in one of those, and by the way adding the rotation error to the image and then tracking the image is out of scope of this thesis, though in principle it can be accounted for by MATLABor similar operations. In Chapter 5 an ASIC micro-controller is developed that accomplishes the image mapping given the constraints discussed above, and delivers resulting control signals for the micromirror.

## **4.1.3 LASER**

There are different types of lasers used for the eye surgery as a whole. They range from green and blue lasers which are used in the corneal surgeries to the krypton red lasers, which are for the retinal surgeries. A description of a laser system available in the industry is given in the Appendix for reference. In the controller model, the surgeon is given the option of selecting a particular type of laser for a particular surgery, and the additional option of changing lasers during surgery. Though the laser firing is considered manual here, it is anticipated that the controller can be designed to be easily be automated, as discussed in Chapter 6. Once the surgeon selects the LASER, the control signal from the laser system is given to the controller so that the controller acts appropriately according to the design.

## 4.1.4 CPU

The system CPU is expected to coordinate the software and hardware components. The hardware part is the ASIC controller and the software is the program, which does the rotation and the cropping of the image. There are many software tools available for these operations, and a graphical users interface developed in the companion thesis utilizes some of these. Once the CPU performs the required operations, it outputs the processed (cropped, rotation-corrected, etc) image signal to the controller in the 32-bit format at 30 frames/second, the same rate it receives it from the camera. The data format essentially contains 16 bits of addresses, 8 bit of data and another 8 bits for the controller to understand whether the received signal is a data signal or various other control signals from other parts of the system like the DAC, etc. These to some extent form the definitions based on which the controller is designed.

## 4.2 Working Algorithm Of The Controller

The micro controller is designed using the well-known algorithm of the LEAST MEAN SQUARE ESTIMATION (LMS). This algorithm is widely used in the area of the image matching due to its ruggedness and achievability. The algorithm is implemented in the controller for registering the FA image to the real-time image, and subsequently tracking the movement of the eye in the x-y plane.

The real-time and FA images are cropped to 256\*256 matrices of pixels. The values of the each pixel from an image are used for the mapping/registering on to other pixels. The pixel values for the simulation are derived using MATLAB. There are two images for the surgeon to work on during the surgery. The first image, also called the reference image, is the FA image of the eye, which will be taken two weeks before the surgery. This image is monochrome, made of gray levels ranging from 0-255 (8-bits).

The next image the surgeon will visualize is the real time, formatted image of the retina, which is in 3-D color scale of 0-255. The camera at the rate of 30 frames per second refreshes the real time image. If the matching has to be done between these two images then there must be some areas in the image that have features that are irregular,

not homogeneous. The many blood vessels that run throughout the eye provide excellent matching features. To track the motion of the eye, each frame captured by the frame grabber is matched to the AF image every  $1/30^{\text{th}}$  of a second.

To register the two images initially, a small matrix selected in the FA image (which has features to match), is matched to a frame of the real-time image. The difference in position from the second image to the first will give an error signal that is translated into a voltage control signal sent to the micro mirrors. In principle, this process is repeated for every frame of the real-time image that is received.

## 4.2.1 Basic assumptions and definitions

There are some specific definitions with regarding to the working of the controller. The definitions are given below. There are some assumptions, which are quoted, as and when required.

- 1. Big mat (x,y,z) is the 256\*256 matrix of the ref frame of the image.
- 2. med\_mat (x,y,z) is the 100\*100 matrix of the selected area in the x frame of the real time image.
- 3. Sma\_mat (x,y,z) is the 25\*25 matrix of the small matrix which is to be matched in the med\_mat(x.y.z).
- 4. Err (x,y) is the error value calculated through the algorithm. It is the amount of position the small matrix has moved from the original position of sma\_mat(x,y)/new\_sma\_mat(x,y).
- 5. New\_sma\_mat (x,y,z) is the new position of the small matrix after the applied Err(x,y) value to the old matrix. X frame is replaced as the ref frame.
- 6. New\_med\_mat (x,y) is the mat defined for a new search in the (x+1) frame. With the new\_sma\_mat (x,y) as reference. The new position of the new\_sma\_mat will be searched in this area in the x+1 frame.

- 7. Dis\_mat\_1(x,y), dis\_mat\_2(x,y), dis\_mat\_3(x,y) are the three selectable diseased areas.
- 8. Ref frame is the initial FA image frame.
- 9. X is the frame in which the doctor specifies the med\_mat.
- 10. X+1 is the consecutive image frame after the  $x^{th}$  frame
- 11. Each frame is of 256\*256 pixel size.
- 12. Each frame is cropped and scaled down/up by the CPU and sent to the Micro controller.
- 13. The laser data type is a separate data type in which there are control signals, which are between the Micro controller and the LASER system.
- 14. The Err (x,y) is applied to the DAC when the surgeon selects the diseased area. The starting address and the ending address correction are applied to the diseased area, which is selected by the surgeon.
- 15. Fovea (x,y,z) is the area which is nullified for the LASER initially before the surgery. The CPU passes on the area to the controller when the surgeon selects the fovea.

## 4.2.2 Least Mean Square Algorithm

The following formula is used for the calculation of the coefficient of the sum of squared differences for the particular sma\_mat versus the corresponding sma\_mat in the med mat.

LSMSV=  $[sma_mat (x, y) - new_sma_mat (x, y)]^2$ 

The sum of squared differences algorithm is based on the law that the difference will be the least of the best matching pixels or a group of pixels. The square is used for getting the whole number as the first coefficient and then the whole matrix is summed up. The position of the matrix, which has the least coefficient, corresponds to the matched area. The failure rate of this algorithm for matching is kept very low due to the precautions taken as follows. The small matrix (sma\_mat) is selected such that it has many features. The larger area (med\_mat) is selected in such a way that there is no way that the (sma\_mat) moves out of it. Taking these two precautions minimizes the chance of this algorithm failing.



## Figure 4.2 SSD Matching.

Once the position of the sma\_mat is found in the med\_mat, the difference in the new and the previous position of the sma\_mat will give the current position. The x frame with the new position replaces the reference frame. Now, as already discussed, the X+1 frame again has the possibility of a movement, but fortunately, the eye moves only a small number of pixels in x-y directions. Thus once the FA image is registered to the real-time image, subsequent match searches can be limited to the area of the previously matched pixels.

One of the most important facts collected from the surgeon is that the eye is not going to move more than a specific amount. In the true real time analysis the eye is sedated and the movement is not going to be more than 50-100 microns. This means that the eye is not going to move more than 5-10 pixels. With this valuable data the micro controller is designed to search and track the image in the 10 pixel range around the

position determined during the initial registration. Therefore the new sma\_mat is searched within even less area than the previous area called the New\_med\_mat. Now the same operation continues, and then new addresses are updated every time the process is executed.

## 4.2.3 Diseased Area and LASER Components

The diseased area is marked on the ref image by the surgeon, and the corresponding pixel addresses are stored in the ram of the controller. The selection depends on the disease type, whether the area is collective as in the case of Macular degeneration or small and spotted as in diabetic edema. The controller is designed to allow up to three areas to be selected by the surgeon and term them as diabetic edema. The process of selection is described in the companion thesis.[1] Once the area is selected the addresses of the diseased area (dis\_mat\_i(x,y) for i=1,2,3,...) also receive the error signals and hence they too get updated. The surgeon selects the type of laser, the spot size and the duration of the laser firing pulse.

As discussed in Chapter1 there is an immense need for a history counter for each pixel in the diseased area. When using the diode LASER, which is invisible, the surgeon will not be able to be certain whether he/she has hit the diseased spot. That problem is solved by the controller, which has a separate counter for each of the pixels and increments the counter whenever the particular pixel is hit by the laser. Once the laser hits so many times, which depends on the power of the laser to ablate the area, the pixel is made void for the laser to hit. This prevents the surgeon from doing the error of hitting the area with the LASER more than what is needed. Now with this new inclusion of the technology the manual errors are greatly reduced. There is one more accomplishment of the controller, which prevents the laser from being fired on to a particular part of the eye, namely the FOVEA, which is marked by the surgeon. This prevents the destruction of fovea even by accident. As with every other matrix the fovea is also treated as a matrix and the addresses are stored in the RAM of the Micro controller. The simulation results are given in the next chapter with the modeling of the micro controller.

## 4.3 The Mirror Arrangement

The mirror arrangement and placement of the mirrors form an important role in completing the system. The characterization of the mirror has revealed the ruggedness of the device and the various other factors such as the reach of the mirror, the repeatability of the mirror, etc. The size of the mirror, which is measured to be  $\sim$ 700\*700 microns, can cover an area of  $\sim$ 30\*30 pixels in the eye. The entire eye is some 256\*256 pixels of which the diseased are is around 15\*15 pixels at the most (Note: each pixel is about 20 microns in diameter). The system currently used is shown below to locate approximately where the micromirrors are expected to be placed.





Figure 4.3 State of the art digital image collector.

## 4.3.1 Proposed Construction of the Mirror Box

From the characterization data (chapter3 the distance between the two mirrors for the mirror to cover the 600\*600 micron area is calculated as 6.375 cm. The mirrors are placed 45 degrees to 45 degrees in an enclosed box made of preferably Aluminum painted black from inside. The choice of aluminum comes due to the ease in the manufacturability and the cost of the material. The box is coated black from inside so as to avoid any reflection and luminance from the box in which the mirror is contained.



Figure 4.4 The mirror arrangement box.

The box being partially evacuated is preferred for the best performance of the mirror. This partial vacuum reduces the air damping if any and also provides the mirror a very good environment to work. The Glass cover, which allows the LASER in/out of the box, is made of high quality glass. Use of the clear polythene instead of the glass is recommended due the advantage of the closeness of the refraction coefficient of the polythene to air than that of the glass to air, though antireflection coatings may also be used. The X and Y positioning of the mirrors is as diagrammed below.



Figure 4.5 Alignment of the mirrors.

It is to be noted that the placement of the box does not considerably change the current system configuration. This leads to the saving of the cost of redesigning the entire system from square one.

#### CHAPTER 5

## ARCHITECTURE OF THE MICRO CONTROLLER AND VHDL MODELING

## **5.1 Introduction**

The microcontroller is designed to quickly conduct the arithmetic and image processing required for this application. The hardware is an ASIC built using the hardware description language VHDL. As discussed in the previous chapter, the controller gets the image signal from the CPU. The images are received in the form of frames from the frame grabber attached to the video camera. These data signals are pre processed using software such as MATLAB and then sent to the controller. The CPU receives the images at the rate of 30 frames a second and sends them to the controller at the same rate. The output of the micro controller controls both the laser system and the micromirror positioning through a DAC.

## 5.2 Blocks of the Micro Controller

A block diagram is shown below for the overall model of the microcontroller. The output and I/O units for communication between the controller and the three external components, the DAC, the laser and the CPU, are clearly illustrated. In addition, the controller contains memory for signal and other data storage and components for data manipulation and management.



Figure 5.1 Basic block diagram of the Micro Controller.

## **5.2.1 LMS Comparator**

The LMS comparator is designed according to the formula given below. The comparator determines the least error when correlating the data of two matrices for image matching. The formula for the LMS algorithm is as follows.

LSMSV=  $[difference of (sma_mat (x, y), med_sma_mat (x, y))]^2$ 

The input to the LMS comparator is the following

- 1. The address of the small matrix
- 2. The address of the medium matrix
- 3. The Z values of both the matrices

The LMS comparator then outputs the address at which the small matrix was found matched in the medium matrix. Basically the comparator has been written down in a procedure and then various functions such as the signal conversion functions have been included to aid the comparator in doing the calculation. The simulation results show that the comparator matches a 10\*10 matrix in a 100\*100 matrix. This is significantly faster than the software approach for image matching. Also from the simulation results, it is clear that the larger the area of the small matrix, the better the probability of finding a match. However the same will take more time for matching due to the number of calculations involved.

#### 5.2.2 Address and Data Management

An address manager is included in the microcontroller to facilitate calculations. Both the Comparator and the LASER system controller for receiving and outputting matrix and error signal address information use the address manager extensively.

There are five matrices as per the definition in Chapter 4; each assigned a separate disease area, but related address. The address relationships are given by mathematical formulations, which are dynamically created by the micro controller itself. The various other addresses include that of the diseased area and new addresses initiated by the controller dynamically.

## 5.2.3 Laser Controller

The surgeon needs control over the placement and firing of the laser on the eye, which has led to the development of this block. This block features various control signals to and from the laser system and also control signals to the CPU to alert the surgeon if there is some error in the controller. This block also includes a fail-safe control, which is used when something goes wrong and shuts down the entire laser system and restarts the process when signaled by the surgeon.

The algorithm of the working of the LASER control is explained in these paragraphs. The selection of the LASER is bypassed through the working model of the controller, but provision has been made for its implementation. The controller outputs to the LASER system a selection signal for the LASER type, quality and the specific spot size. All of the quantities are put in the form of the data type of bits and then dispatched to the LASER system. Whenever, the LASER is fired on to the specific spot a counter in the Controller counts, and once it reaches the preset saturation value the controller sends a stop signal to the LASER. This stop signal does not allow the LASER system to fire additional pulses onto the spot. The saturation depends on the depth of the cut needed and the power of the LASER used. The counter is dynamically assigned so that the surgeon will have the selection freedom of the LASER.

This counter is named the HISTORY COUNTER since it contains the surgery history of the particular pixel. An additional image is the fovea matrix, selected from the FA image by the surgeon as the region to exclude from surgery, thus protecting the fovea. This important component is installed to eliminate the manual error of the surgeon of firing the LASER on to the Fovea by mistake, which costs the patient his vision. By using this component, even if the surgeon prompts the LASER to fire on to an excluded point, the controller will send a prompt signal back to the CPU and to the monitor console that the area is excluded from being hit.

There is a need for a prompt for the surgeon to use the correct LASER at the correct place. For example If a laser has a spot size of 5 to 7 pixels and the exact defect area is about 8 or 9 pixels in diameter, then the last two pixels cannot be hit with such a big laserspot, which might harm neighboring pixels. This component is installed so that if the surgeon attempts to use the same laser, the controller generates a warning signal for the surgeon suggesting the LASER might not be used.

The RAMs are internally designed to store the various matrices (image areas are represented as matrices for the controller and they are used interchangeably in the thesis), which are selected by the surgeon. There are altogether five RAMs to store the addresses and the values of the five matrices discussed earlier. The color values of the diseased areas are not put into a RAM since this is trivial information. The important parts of the data are the addresses and the history of the LASER hits, which are stored in separate addresses.

#### 5.3 Simulation Results and Discussion

This section presents simulation results to prove that the modeled micro controller is capable of executing the intended algorithms. Initially a signal process\_start is switched from low to high to start the process. Then the frame of the FA image is put into RAM for further calculations. The various signals such as Laser data, address of the reference matrix, the number of diseased areas, their sizes and their respective addresses are also input to the RAM. This is illustrated in Figures 5.2 and 5.3. Figure 5.2 shows that the bmatrix's (100\*100 matrix) row, column position and the smatrix1 (10\*10 matrix) gray scale values are zero each. The variables row, col is the address of the 10\*10 matrix in the 256\*256 matrix. The variables row1, col1 represent the starting address of the 100\*100 frame in which the 10\*10 matrix is found.



Figure 5.2 Initial time (no data).

Figure 5.3 shows that the forced 10\*10 matrix, 256\*256, laser square x,y which is the address of the diseased areas and their sizes in the third row.

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Figure 5.3 Forced matrices and Data.

Then the second matrix, which is the real time image, is forced into the Ram along with the clock pulse. This clock pulse has a frequency of 30 pulses per second. Along with this

the address of 100/\*100 matrix is forced. Then the reference matrix is matched with its corresponding area in 100\*100 matrix, which is shown in figures 5.3 and 5.4. Figure 5.4 shows the changes in the initial snapshot when the various values are forced.

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**Figure 5.4** Position of data and the 10\*10 matrix.

Figure 5.5 shows the shift, which is given to the matrix (Jitter), which is two rows shift up. The results are reflected in the fifth figure with the changes in the row and col variables.

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Figure 5.5 Shift in the matrix (Jitter).



Figure 5.6 Corresponding shift in the 10\*10 matrix, trace value.

The snapshots, which follow, show the history counter, which is in-built for each pixel. Here we have four diseased squares for example. The counter goes up for each laser hit and the pixel is checked for the maximum hits, which is specified by the surgeon. Once the hits have reached maximum then the counter disables the laser for that particular pixel. The Figure 5.7 shows the counter 0 goes up for the first clock pulse and the laserhit is counted to one.

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Figure 5.7 Initial Laser hit clock pulse.

The following figure shows the fourth pulse, which is the maximum for, hit and then disables the laserhit.

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Figure 5.8 Final Laser hit clock pulse and the disabled laser hit signal.

The following figure shows the waves for the laser hit disabling function. It is very clear that after the clock pulse, which is set as laser hits here in the simulation, the laser \_signal is disabled.



Figure 5.9 Waveform analysis of the disabling of the Laser hit signal.

#### CHAPTER 6

## **CONCLUSION AND FUTURE WORK**

This thesis has presented an overview for an improved system for laser eye surgery. The system incorporates hardware based image matching and MEMS micromirrors for feedback control of laser positioning on the eye. Many benefits have been described in this thesis, such as nulling out eye movement, tracking laser firing history, enabling precise control of laser firing locations and preventing firing accidents. The aim of this work has been to frame this concept and prove the principle of various components of the system. A featured accomplishment has been the development and simulation of a prototype microcontroller that may be incorporated as part of the improved system.

Despite these accomplishments, a number of areas would benefit from further research and improvement. In particular, the image-matching component would benefit from considering additional image transformation effects such as scaling, skewing, warping, rotation, brightness and intensity. The rotation and scaling may be addressed by more careful control of differences during the FA and real-time image acquisition, for example head angle and camera proximity to the eye. In addition to considering these issues, ultimately a fully integrated prototype should be developed.

# APPENDIX

# LIST OF VARIOUS LASER CHARACTERISTICS

This appendix gives various available laser types and their respective spot sizes.

Table A.1 V	arious I	Lasers a	and [	Their (	Characteristics
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Clinical Indication	Laser delivery system	Spot size (micrometers)	Exposure time (seconds)	Power (milliwatts)
Diabetic retinopathy	Slit lamp, LIO, Acculite	100-500	0.05-0.5	100-1200
Branch retinal vein occlusion	Slit lamp, LIO	100-500	0.05-0.5	100-500
Choroidal Neovascularization	Slit lamp	50-200	0.1-0.5	100-500
Retinal tears	Slit lamp, LIO, Acculite	200-500	0.1-0.5	100-500

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