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## Development of a Micromirror Based Laser Vector Scanning Automotive HUD

By

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Bachelor of Engineering, University of Science and Technology Beijing, 2009

A thesis presented to Ryerson University

in partial fulfillment of the requirements for the degree of Master of Applied Science in the Program of Mechanical Engineering

Toronto, Ontario, Canada, 2011

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Fan Chao

### Abstract

Title of the thesis: Development of a Micromirror Based Laser Vector Scanning Automotive HUD

Name: Fan Chao

Master of Applied Science, Mechanical Engineering, Ryerson University, 2011

Head-Up-Display (HUD) for automobiles is a system that displays the driving information such as the speed, fuel level, turning signal, GPS, etc on the windshield or on the road through a virtual image. With HUD, the driver does not need to lower his head to check the front panel for driving information and thus the driver can have a longer eyes-on-road time to improve the driving safety and comfort. LCD (Liquid Crystal Display) and VFD (Vacuum Fluorescent Display) based HUDs dominate today's automotive HUD market. In this thesis, a novel micromirror laser vector scanning HUD is developed for automobiles, which has the advantages over existing technologies including: 1) Higher brightness and contrast; 2) Wider angle of view; 3) Smaller size; and 4) Lower cost.

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## **Chapter 1 Introduction**

#### 1.1 What is head up display

Head Up Display (HUD) is a system that allows the pilot or the driver to obtain useful information without bending down their head to look at the front panel or the dash board. As a result, the operator can keep their eyes focusing on the view in front which significantly improves the driving safety and comfort. HUD evolved from the reflector sight which is used in the military helicopters and the fighters. The reflector sight is an optical device that can project a cross hair on the gun sight or on a piece of glass in front of the pilot. This kind of reflector sight appeared during the First World War and was widely used in the Second World War. The HUD was developed then for the military purpose which can project the computed gunnery solutions, radar information, and artificial horizontal on the windshield or a piece of reflective glass in front of the pilot. In 1975, the HUD was first used for civil purpose by Sextant Avionique, a main equipment supplier of civil and military avionic systems for the Dassault Mercure aircraft in 1975. In later 1970s, HUD was used in the MD80 series aircraft of Douglas Aircraft Company. By the end of the 20<sup>th</sup> century, the HUD system has been widely used in the aircraft.



Figure 1.1 The HUD on Airbus A350 [1]



Figure 1.2 HUD on Boeing 737-800 [2]



Figure 1.3 The HUD on F16 fighter [3]

#### **1.2 Automotive HUD**

The 1988's Oldsmobile Cutlass Supreme by GM was the first car that equipped with HUD. Since increasing car number, the workload for the driver becomes heavier. With the development of car industry driving safety related information such as GPS, tire Pressure, car reverse radar, outside temperature, driving comfort information such as radio channel, music name, air conditioning temperature are provided to the driver. The large quantities of information which are displayed on the front panel increase the frequency and time the driver look down the dashboard which will add more burdens to the driver. Automotive HUD as a resolution which was used mainly on the aircraft before begin to attract many companies attention. Major car companies in the world all bring out cars installed with HUD, such as BMW 5-series, 7-series, M-series [4]; Lexus RX-series [5]; GM chevrolet covette-series [6]; Peugeot 3008-series and 5008-series [7].



Figure 1.4 The HUD on BMW 5-series [6]



Figure 1.5 The HUD on Peugeot 5008 [7]

#### 1.3 Advantages of the HUD compared to HDD

The traditional dashboard display system is the head down display (HDD) which is always compared with the HUD. It has been proved that HUD improves the driving safety and comfort. The advantages of the HUD compared with HDD are shown below.

HUD has a shorter accommodation time when the drivers obtain necessary driving information. In another word, HUD can achieve a longer eyes-on-road time which increase the driving safety. The process of getting information is composed of 3 stages. First the drivers need to move their eyes from the road to the display. Then focus on the display for a while to obtain information. At last, the eyes transit from the display back to the road again. The time cost of HUD and HDD on this process is compared under the low workload situation and a HUD time benefit window was concluded by R.J. Kiefer. In Kiefer's study [8,9], the process of getting information is defined as speedometer scanning cycle (SSC). In his experiment, the mean time of SSC for HUD is 777ms which is 144ms faster than HDD. The mean display fixation time for HUD is 619ms which is 711ms for the HDD.





Another more reliable study of HUD and HDD is performed by Markus [10]. JANUS eye tracking system is used to measure the total eye gaze time, gaze frequency, and gaze duration time.



Figure 1.7 JANUS eye tracking system [10]

It has been proved that by using HUD 15%-20% reduction of the gaze retention on the display can be achieved compared to HDD in uncritical situation. In a heavy traffic situation, the reduction can be up to 25%. Also, their results show that HUD is more helpful to the older drivers whose ages are between 51 and 60. The information collection using HUD can be 200ms faster.



Figure 1.8 Gaze retention periods according to age [10]

Another simulation experiments performed by Yung-Ching Liu and Ming-Hui Wen [11] enhance the result that HUD enable drivers to have a faster emergence response time and maintain the vehicle speed to a more consistent level.

Load	Performance measures	HUD	HDD	F(1, 10)	<i>p</i> -Value
High	Speed variation (ft/s) RT for speed limit sign changes (s)	10.153	20.396	6.899	0.025
	From 40 to 70 mph From 70 to 40 mph	1.2233 0.99	1.4617 1.2089	5.000 5.826	0.049
_	RT for emergency response (s)	1.3235	2.3274	9.482	0.012
Low	RT for emergency response (s)	1.0073	1.8684	22.269	0.01

Table 1.1 Performance measures for HUD vs. HDD in driving load conditions [11]

Also HUD can display more information than the HDD. Functions such as GPS information for navigation [12,13], road sign recognition [14], and object recognition on the road can be displayed by the HUD while some of them are impossible to integrate on the dashboard. That information will provide driver with a full driving information system that will improve the driving safety and the comfort.



Figure 1.9 The GM augmented reality full windshield display prototype [14]

#### 1.4 Classification of the HUD technology and their working principle

A HUD system is composed of 2 parts, the display module and an optical system. The desired images are generated by the display module first. Then the images source is processed by a series of optical system to form the image on the windshield.

According to the image-forming principles, the HUD can be classified into 2 types. One is to form a real image on the windshield [15]; the other one is to form a virtual image behind the windshield [16]. The real image HUD forms a real image on the windshield, shown in Fig. 1.10.



Figure 1.10 Real image HUD

The virtual image HUD forms a virtual image in front of the windshield, above the engine hood, see Fig. 1.11.



Figure 1.11 Virtual image HUD

According to the display module, the HUD can be classified as follows.

- Emissive displays, such as cathode ray tube (CRT), organic light-emitting diode (OLED), vacuum fluorescent display (VFD)
- (2) Backlit display, such as liquid crystal display (LCD)
- (3) Laser display, such as Liquid crystal on silicon (LCoS) and micromirror based laser scanned displays.

CRT is first used for the head up display. However, because of the bulky volume of the device, high power consumption and harmful radiation, it had been replaced by LCDs [17]-[19]. Nowadays, LCD based head up display share most part of the aircraft HUD market. VFD and LCD HUD share most part of the automotive HUD market because of their compact size and low cost. However, VFD is limited mainly by the amount of information it can display. LCD HUD is limited by the brightness. New emitting display technology OLED can generate a transparent display on a thin layer and is brighter than LCDs which is suitable for real image HUD [20]-[21]. However, its display is limited because of its low brightness, high cost and relative short life time. Compared with the emitting and backlight display, laser display is superior.

Laser is a monochrome, directional light generated by optical amplification process. Because of its highly directional, the laser beam has high power density which can generate brighter display compared to the traditional display methods. Laser based HUD is superior because it can form a high contrast ratio display, which means a better visibility. Contrast ratio is an important performance characteristic for HUD which is defined below:

$$contrast ratio = \frac{Display luminance - Real world luminance}{Display luminance}$$
(1.1)

Display luminance is the luminance of the displayed light that reaches the driver or pilot's eyes. Real world luminance is the ambient luminance of the real world. The preferable HUD contrast ratio is 1.3. Any ratio below 1.2 will cause a dim display. An excessive contrast ratio will cause an opaque display which will be a problem when driving at night or low luminance condition. When driving in the sunny day and towards the sun, the real world luminance can be very high which requires a high display luminance. While most of the other display methods

cannot produce a qualified display, the laser based head up display can still achieve a good performance due to the high power density of laser. Also, laser based HUD has the ability to display a large amount of information.

The laser based techniques can be divided into 2 main categories. One is the hologram display which uses the LCoS as its main component [22]. The Light Blue Optics (LBO) Company is developing projection and HUD products using LCoS [23]. The basic principle of this technique is as follows. Assume we want to generate an image  $F_{xy}$ , we transform the image  $F_{xy}$  into image  $h_{uv}$  which is displayed on the LCoS. Illuminated by a laser beam, the desired image  $F_{xy}$  can be displayed by two-dimensional diffraction.



Figure 1.12 The principle of hologram display [23]



Figure 1.13 Image formed using LBO's holographic laser HUD, captured in daylight [24]

The other laser based HUD technique is using the rotational micromirror which is a Micro-Electro-Mechanical systems (MEMS) product to control the laser beam to scan a certain 2D area. There are two types of display method of laser scanned display, vector display and raster display which corresponding to two types of micromirror, non-resonant micromirror and resonant micromirror. Laser vector display means that the laser spot keeps scanning arbitrary points which form the patterns periodically. If the scan speed is fast enough, stable shapes can be formed. Laser raster display means that the laser spot scans a certain area line by line. In the raster display, each point is one pixel on the image. Laser brightness is modulated in different pixel to generate the desired image. The disadvantage of the vector display is that it only can display the outline of the objects and the amount of the displayed content is limited by the scan speed. Nowadays, most of the commonly used display equipment such as the TV and projector are using the raster display which can provide more image information. However, for the HUD application, vector display had been widely used in the aircraft for the reasons below. First, a brighter display can be achieved because limited information needs to be displayed as simple shapes and the vector display allows a slower scan, consequently a brighter image. Then transparency of the display region is an important safety factor. Raster display in preferred HUD display ratio may cause an opaque region. However, this can be avoided by turning off the laser in the regions which do not contain the useful information. In this point, the vector display and raster display don't have a big difference in HUD. In addition, the laser based raster display requires a higher power laser which consumes more power and has a potential safety problem. In this case the vector based display is more suitable for HUD.

The micromirror used for vector HUD and raster HUD have the common character that they are both rotational and can steer the laser beam to scan through a 2D area.



Figure 1.14 The working principle of micromirror scanned displays

As shown in Fig. 1.14. The micromirror plate is actuated by MEMS actuators such as electrostatic actuator, electromagnet actuator, and piezoelectric actuator and can rotate with respect to two perpendicular axes X and Y. With the rotation of the micromirror, the emergent laser beam is able to scan through a 2D plane. By controlling the micromirror rotation, desired displays can be drawn by the emergent laser beam.

The difference of micromirror for vector HUD and raster HUD is that they work in different principles. The micromirror used for the raster HUD works in the resonant mode which means when the micromirror is working; the micromirror is controlled to vibrate with two axes in different manners and in specific frequencies all the time [28]-[30]. The combination of the two vibrations enables the micromirror to scan through a 2D area line by line, shown in the Fig.1.15.



Figure 1.15 2D area scanned by the laser

In this scan scheme, to achieve the biggest scan area and fastest scan speed, one of the axes of micromirror is vibrating in the resonant frequency. This resonant vibration working mechanism is defined as resonant mode. Opposite to the resonant mode is the non-resonant mode which is usually used for the vector display. When working, the micromirror is controlled to steer the laser beam goes to the desired point on the 2D plane after stabilized goes to another point. If the laser beam is controlled to scan a group of points in order and fast enough, the shapes can be displayed then by the laser path. Some micromirror can just work in one mode and some micromirrors can work in both mode.

One of the examples of raster display HUD is the vehicle HUD from Microvision Company [25,26]. A two-axis electromagnetic actuated micro-scanner is used to reflect and control the laser beam to perform scanning. Another example of raster laser display is developed by

Mirrorcle company which use the electrostatic comb-driven micromirror to display and can perform vector display and raster display.



(a) Electromagnet driven micromirror (b) HUD prototype by MicroVision



Figure 1.16 The micromirror based HUD from MicroVision

(a) Electrostatic driven micromirror (b) Vector display (c) Raster display

#### Figure 1.17 The micromirror based display from ARI [27,28]

The vector display HUD product has not appeared in the market yet. This paper will develop a micromirror based vector display HUD system. The micromirror used here is an electrostatic repulsive force actuated micro-mirror designed by Siyuan He [32]-[35]. The micromirror is driven by 4 repulsive actuators and can steer the laser beam to scan a 2D plane.

Above all, compared to all of the other HUD display techniques, the micromirror based vector HUD has some advantages. First, the laser display can generate higher brightness images

compared to the LCD and OLED display. The brightness is usually 5-10 times of the LCD and OLED. For laser vector display, the laser beam just focus on the desired trajectories which can generate even brighter display than the laser raster display. Second, the micromirror based laser scanned display has a bigger angle of view which is 5-10 time bigger than the traditional HUD such as LCD HUD and OLED HUD. Third, the micromirror based HUD can form both real image and virtual image which makes it flexible. However, the mainly used LCD HUD can only generate virtual image display which cannot be used for some vehicle such as trucks. Different from sedan, the windshield for the truck is almost flat and vertical. From the image forming principle of flat mirror, it is hard to setup the HUD. So micromirror based HUD has more flexibility. Also the micromirror based HUD module has a much smaller volume than the LCD HUD. Because of the curvature of the windshield, a compensational optics is needed to generate an undistorted image on the windshield which increases the volume of the HUD module. For the micromirror based vector HUD, a pre-distorted image can be produced by compensating in the control signal, which does not need the compensational optics. The small size of the electrostatic micromirror whose diameter is 1mm can largely reduce the HUD system volume. At last, the polysilicon multiuser MEMS process (PolyMuMps) fabrication process of the micromirror can make low coat production which results a relative low cost of the HUD system.

#### 1.5 Literature review of the micromirror control

Control is necessary for the micromirrors for several reasons. One reason is that micromirror is a damping system, which means when moving from one desired position to another; the micromirror will have overshoot and oscillation. If this oscillation is not restricted, the display will have distortion. Another reason is that, for the electrostatic attractive force driven micromirror there is a "pull in" phenomenon [36,37]. Close loop is usually performed to eliminate the pull in phenomenon. "Pull in" phenomenon means that the micromirror will be snapped down and stick to the electrode when the micromirror is close to the electrode. The touching of the micromirror and the electrode will cause a short circuit to the driving equipment and may damage both of the driving equipment and the micromirror. Driven by the open loop scheme, the tilt angle of the micromirror is limited beyond the pull in point which leads to a poor

optical performance. It this case close loop control is necessary for this kind of micromirror. For the electrostatic repulsive force micromirror talked in this paper, "pull in" phenomenon does not exist. To overcome the oscillation and the overshoot is the main purpose for control. Because many of the control literatures are about how to eliminate the pull in phenomenon and the control process of which are also valuable to our control research, those papers are also studied below.

Open loop and close loop control are the two control schemes usually used for the microdevice like micromirror control [39]. Each scheme has its own advantages and disadvantages. Open loop control uses the pre-designed signal to drive the micromirror directly which does not require a high computational controller and the feedback mechanism. So the open loop controlled system can be implemented by simple microprocessor without the feedback mechanism. Close loop control requires a feedback back sensor which is usually expensive and increases the complexity and the volume of the system. However, using close loop control, a large operation range, more accurate positioning, fast response, small overshoot and disturbance restricted system can be achieved. In some high performance required applications close loop control is essential. In this case which control method to use is decided by the specific application and system requirement.

Widely used open loop control method for the micro-device is the input shaping control (or pre-shaped control). This control method is first used to improve the dynamic behavior of the linear macro-scale devices. The theory of the input shaping for linear system has been well developed such as zero vibration shaper (ZV) [40], Zero vibration derivative shaper (ZVD) [41], and extra insensitive shaper (EI). Then Borovic B. [38] uses the input shaping method to the micro-devices (MEMS product). However, because of the nonlinearity of most of the MEMS devices, the previous developed linear throes of input shaping cannot be used. Mohammed F. Daqaq [42] developed an iterative algorithm for a nonlinear tensional electrostatic micromirror. Simulation result showed a good performance of their algorithm. However, experiment had not been performed to validate their algorithm and the control performance is highly dependent on the accuracy of the plant model which is not possible but time consuming and costly to obtain.

Closed loop of the micromirror attracts more attention to the researchers because the excellent performance they can achieve. Because of the nonlinearity of the electrostatic force with the driving voltages, most of the electrostatic micromirrors are nonlinear systems which

linear control scheme such as proportional-integral-derivative (PID) controller are not suitable to control the micromirror in a large operating range. However, linear controllers which are easy to be implemented work well in a small linear operation range.

Nonlinear control is widely studied due to its good performance. Adaptive control which is an online parameter self updating method is applied to a 1D electrolstatically driven torsional micromirror by K.P. Tee [43] and Ke-Min Liao [44]. For Ke-Min Liao's [44] work, the Simulation result shows that the adaptive controller has better performance in step response and in trajectory following compared to the open loop control and PID controllers. Experiment is performed and verifies the controller can be practically achieved. However, no detailed real-time performance of the controller is given. Only simulation result is given by K.P. Tee [43].variable universe adaptive fuzzy logic controller (ADFL) which use the fuzzy logic is introduced, which extend the micromirror control area. Further study is needed about this control method. Sliding mode controller is used to control electrostatic micromirrors [44]-[47].

#### **1.6 Thesis objectives**

The objective of the thesis is to design a micromirror based laser scan HUD system. The work is composed of two parts. The first part is to design a control system for the display module. The second part is to build a hardware setup for the HUD system. Real image HUD and virtual images HUD are both built as well. Between the two objectives mentioned above, control of the micromirror has the first priority. Because of the complexity of the micromirror dynamic and the costly process to create the model, the dynamic model of the micromirror will be not fully studied in this thesis. However, an estimation of the system model will be done. Time response and frequency response of the micromirror system will be studied to have an estimation of the system model. A model free open loop control algorithm is developed. The requirement for the open loop is to design a simple open loop algorithm that is easy to implement. FPGA is used to implement the control algorithm. The algorithm should also lead to a minimum distorted image which means the control algorithm should reduce the overshoot as much as possible.

The second task of the thesis is to study and build the optical setup of the HUD system. The optical system is designed to obtain a high contrast ratio and clear display. The whole HUD system then will be tested on the windshield to evaluate the performance.

#### **Chapter 2 The introduction of the micromirror**

#### 2.1 The working principle of the micromirror

The micromirror is fabricated using the mature surface micromachining process, polysilicon multiuser MEMS process (PolyMuMps). It is composed of 4 electrostatic repulsive force actuators and a mirror plate. The actuator is composed of unaligned fixed finger electrode, aligned fixed finger electrode and the moving finger electrode. The aligned fixed finger electrode and the moving finger electrode and are always applied the same voltage, while the voltage on the unaligned fixed finger electrode is different.

The mirror plate is operated by 4 actuators. A rectangular coordinate system can be built on the mirror plate. The origin of the coordinate O lies on the center of the mirror plate and XOY plane is parallel to the substrate, see Fig. 2.1. The actuators are named as North, East, South and West and they can be divided into 2 groups, North-South and East-West. North side and South side actuators control the mirror plate to rotate with respect to Y axis; East side and West side actuators control the mirror plate to rotate with respect to X axis. Combing the 2 rotations around X and Y axis, the mirror plate can rotate to an arbitrary angle inside the tilt range. This working principle allows the micromirror to steer the laser beam to scan through a 2D area, see Fig 2.1.



Figure 2.1 The electrostatic repulsive force actuated micromirror

#### 2.2 Design the driving method of micromirror

The operating voltages for the actuators are 0V-200V. 0V corresponds to the zero displacement of the actuator and 200V corresponding to the maximum displacement. The driving voltages for the actuators are denoted as  $V_N$ ,  $V_E$ ,  $V_S$ ,  $V_W$  and can be divided into 2 groups same as the actuators,  $V_N \sim V_S$  and  $V_E \sim V_W$ .  $V_N \sim V_S$  drive the mirror plate to rotate with respect to Y axis and  $V_E \sim V_W$  drive the mirror to rotate with respect to X axis.

Assume there is a laser beam shooting on the micromirror in a fixed angle. The rotation of the micromirror can enable the laser beam to scan through a 2D plane in front of the micromirror. A rectangular coordinate system is built on the 2D plane which defines the scanning area of the laser beam. The origin of the coordinate is decided by the laser spot reflected by the micromirror on the 2D plane when the micromirror is in its initial position. The initial position of the micromirror is the position from which the micromirror begins to rotate. Because the symmetry structure of the micromirror, the South-North actuators is used to explain the different driving method, see Fig. 2.2, assuming East-West actuators are not actuated.



Figure 2.2 The micromirror working principle

There are 2 driving strategy for the micromirror to perform the display function. The first one is when the micromirror is working, one of the driving voltages belong to one group is fixed while the other one changes, called fixed voltage method. The other one is that the driving voltages belong to one group change at the same time, called changing voltage method. The displacement difference of the actuators in the same group, decides the rotation angle of the micromirror. The larger the displacement is, the greater the rotation angle is.

For the fixed-voltage method, in order to have a maximum rotation angle, the fixed voltage should either be 0V or 200V so that the maximum displacement can be achieved. Take North-South drive for example, when  $V_N$  is chosen to be the fixed voltage which is 0V, increasing  $V_S$  will drive the laser spot to move to the positive direction of X axis from the origin on the 2D plane. In the same fashion, if  $V_S$  is chosen to be the fixed voltage which is 0V, increasing  $V_N$  will drive the laser spot to move to the negative direction of X axis from the origin. Another fixed voltage driving method is to set the initial value of the 4 driving voltages to 200V, which will lift the micromirror to the biggest displacement to the substrate. From this initial position the micromirror begin to rotate. Still take North-South actuators for example, when  $V_N$  is fixed to 200V, decreasing  $V_S$  will drive the laser spot move to the negative direction of X axis. When  $V_S$  is fixed to 200V, decreasing  $V_S$  will drive the laser spot move to the positive direction of X axis.



Figure 2.3 Driving methods of the micromirror (a) Fixed voltage driving method, fixed voltage is set to 0V (b) Fixed voltage driving method, fixed voltage is set to 200V (c) Changing-voltage driving method, initial voltage is set to 75V

The other driving method is the changing-voltage driving method. The micromirror is lifted to a certain height which is approximately half of the maximum height. When the micromirror begins to work, the control voltages belong to one group change the same absolute value, but in different direction. Take North-South for example, before driving initial voltage V<sub>0</sub> is applied to all of the actuators to raise the mirror plate to a certain height. Then if V<sub>N</sub> increase bias voltage  $\Delta V$ , V<sub>S</sub> will decrease bias voltage  $\Delta V_1$ , shown in Eq. (2.1)-(2.2). V<sub>E</sub> and V<sub>W</sub> have the same fashion, shown in Eq. (2.2)-(2.4). In this case, the micromirror will rotate with respect to Y axis.

$$V_N = V_0 + V_1 \tag{2.1}$$

$$V_s = V_0 - \Delta V_1 \tag{2.2}$$

$$V_E = V_0 + \Delta V_2 \tag{2.3}$$

$$V_w = V_0 + \Delta V_2 \tag{2.4}$$

The changing-voltage driving method has some advantages compared with the fixed-voltage driving method due to the characteristic of the micromirror. First, the fixed-voltage method will lose control to the micromirror when the mirror plate is controlled to go back to a smaller rotation angle from a big rotation angle. However, the changing-voltage method has the control of the micromirror all the time. Because the actuators use the electrostatic repulsive force to drive the micromirror, it can just provide the lift up force. In the fixed-voltage driving method, when the mirror plate rotates from a big angle to a smaller angle, the electrostatic repulsive force disappears and the free end of mirror plate will be snapped down by the gravity. In this case, the mirror plate is driven by the electrostatic force when it tilts up and driven by gravity when it tilts down. The different characteristics of the driven force may cause the different dynamic characteristic when the mirror plate is rotating. It has been proved that the lifting up electrostatic force is much bigger than the snapping down gravity which means the falling process of the mirror plate is much slower than the rising process. In this case, the falling process is treated as out of control, because no matter what voltage is applied, this process cannot be controlled. The changing-voltage driving method can overcome this defect, because whatever the mirror rotate, there is always a repulsive force applied to one end of the mirror so that we can control the tilting speed through the driving voltages. The second advantage of the changing-voltage driving method is that for the same laser incident angle the changing-voltage method can achieve a bigger scanning range. The proof is shown below.



Figure 2.4 Changing-voltage driving method

Shown in Fig. 2.4, assume the radius of the mirror plate is l and there is a plane which is parallel to the substrate. The distance between this plane with the substrate of the micromirror is d. For the analysis simplicity the incident laser beam is treated as a thin straight line which means the diameter of the laser beam is ignored. The laser beam is assumed to shoot just onto the center of the mirror plate. The incident angle of the laser beam is assumed to be  $\theta_1$ , and the tilt angle of the micromirror is assumed to be  $\theta$ . The relationship between the tilt angles of the micromirror with laser spot displacement on the 2D plane can be found based on the assumption above.

For the changing-voltage driving method, the mirror plate rotate  $\theta$  degree with respect to its center O. OO<sub>1</sub> is the normal of the mirror plate at its initial position and OO<sub>2</sub> is the normal of the mirror plate after rotation. A<sub>1</sub>O is the incident laser beam. OB<sub>1</sub> is the emergent laser beam with respect to OO<sub>1</sub> and OC<sub>1</sub> is the emergent laser beam with respect to OO<sub>2</sub>. It can be proved that  $\angle B_1OC_1$  equals to 2 $\theta$  and  $\angle OB_1C_1$  equals to  $\pi/2+\theta_1$ . From  $\triangle O_1OB_1$  we can have:

$$OB = \frac{d}{\cos \theta_1} \tag{2.5}$$

From  $\Delta O_1 OC_1$  we can have:

$$OC = \frac{d}{\cos(\theta_1 + 2\theta)} \tag{2.6}$$

Using sine theorem in  $\Delta B_1 OC_1$  and substituting  $OB_1$ ,  $OC_1$  into equation, we can have the displacement of laser spot  $B_1C_1$ .

$$B_1 C_1 = \frac{\sin 2\theta \cdot d}{\cos \theta_1 \cdot \cos(2\theta + \theta_1)}$$
(2.7)

For the fixed-voltage driving method (see Fig. 2.5), the mirror plate rotate  $\theta$  degree with respect to one of its end, E<sub>2</sub> for example here. O'O<sub>1</sub>' is the normal of the mirror plate at its initial position and O'O<sub>2</sub>' is the normal of the mirror plate after rotation. A<sub>2</sub>O' is the incident laser beam. O'B<sub>1</sub>' is the emergent laser beam with respect to O'O<sub>1</sub>' and O'C<sub>1</sub>' is the emergent laser beam with respect to O'O<sub>1</sub>' and O'C<sub>1</sub>' is the emergent laser beam with respect to O'O<sub>2</sub>'. It can be proved that  $\angle B_2D_2C_2$  equals to 2 $\theta$  and  $\angle D_2B_2C_2$  equals to  $\pi/2+\theta_1$ . O'B<sub>2</sub> is the same as changing-voltage method. In  $\Delta F_2O'E_2$ ,  $\angle F_2O'E_2$  equals to  $\pi/2+\theta_1$  and  $\angle F_2O'E_2$  equals to  $\theta$ , sine theorem can be used to obtain O'F<sub>2</sub>.

$$O'F_2 = \sin\theta \cdot \frac{l}{\cos(\theta_1 + \theta)}$$
(2.8)

In  $\Delta O'F_2D_2$ ,  $\angle F_2D_2O'$  is  $2\theta$ ,  $\angle O'F_2D_2$  is  $\pi$ -2( $\theta_1$ + $\theta$ ), sine theorem can be used to obtain  $D_2O'$ .

$$D_2 O' = l \cdot \frac{\sin(\theta_1 + \theta)}{\cos \theta}$$
(2.9)

$$D_2 B_2 = O' B_2 - O' D_2 = \frac{d}{\cos \theta_1} - l \cdot \frac{\sin(\theta_1 + \theta)}{\cos \theta}$$
(2.10)

In  $\Delta D_2 B_2 C_2$ ,  $\angle C_2 D_2 B_2$  is  $2\theta$ ,  $\angle D_2 B_2 C_2$  is  $\pi/2 + \theta_1$ , sine theorem can be used to obtain the displacement of laser spot  $B_2 C_2$ .

$$B_2 C_2 = \frac{\sin 2\theta}{\cos(2\theta + \theta_1)} \cdot \left[\frac{d}{\cos \theta} - l \cdot \frac{\sin(\theta_1 + \theta)}{\cos \theta}\right]$$
(2.11)



Figure 2.5 Fixed voltage driving method (fixed voltage is set to 0V)

Comparing Eq. (2.7) and Eq. (2.11), it can be concluded that changing-voltage driving method can lead to a bigger laser spot movement than fixed voltage method.

#### 2.3 Time response of the micromirror

The model of a plant is very important for analyzing the physical system and designing control system. However, the micromirror system (including the magnification lens) is a non-linear system which makes it difficult to build a mathematical model. The nonlinearity of the system comes from 3 parts. The first one is the non-linear relationship between the driving voltage and the rotation angle. The second one is the changing damping ratio when the micromirror is rotating. The damping of the micromirror comes from 2 sources. One is the mechanical damping which is nearly a constant. The other one is the damping caused by the air. The gap between the mirror plate and the substrate is very close and when the air between the mirror plate and the substrate is compressed it will apply a non-linear friction to the micromirror. Also the lens in front of the micromirror increases the non-linearity of the system.

However, as a control system, instead of modeling the micromirror from mathematical deduction, the micromirror performance can be studied from experiments. The experiments here
refer to the time response test and frequency response test. Both of them treat the micromirror system as a black box and different designed test input signals are given to the micromirror and corresponding output of the system is measured and recorded. By studying the relationship between the system input and output and using the time responses and frequency responses analysis method from control theory, a rough model of the micromirror can be assessed.

The time response of the micromirror consists of 2 parts, the transient response and steadystate response. The transient response is the process that the output of the system goes from the initial state to the final state. The steady-state response is the manner of the system output when the time approaches infinity.

#### 2.4 The transient response of the micromirror

# 2.4.1 The setup of the experiment

The hardware setup for the calibration is shown in the Fig. 2.6 below. The driving signals are sent out by the analog output of NI PCIe-7852R board which is installed into a PCI express slot of the PC mother board. The analogy output and input can be controlled by the FPGA on the board. The output of NI PCIe-7852R board is 0V~2.5V linear driving voltages. The driving voltages are then amplified 60 times to 0V~ 150V by the Bias-Differential Quad-Channel (BDQ) amplifier to drive the micromirror. A 532 nm and 5 mW green laser is used to shot onto the mirror plate. A 900nm pin hole is used to limit the diameter of the laser so that the laser spot is small enough to just lie inside the mirror plate. The PSD (Position Sensing Detector) and On-Tark OT-301 position sensing amplifier is used to detect the position of the laser spot. The PSD is an optical sensor, which can detect the position of the laser spot in the active sensing area. The PSD returns the x and y coordinates of the laser spot on the sensor as the form of analog voltages. The output of the PSD is usually proportional to the laser spot position. The On-Tark OT-301 position sensing amplifier is used to process the output signal from the PSD to reduce the noise and make the output voltage range suitable to use. The X and Y information of the laser spot is then send to the analog input port NI PCIe-7852R to be processed and saved.



**Figure 2.6 Setup for calibration** 

# 2.4.2 The experiment design

The test signal for the time response is always chosen to be the form of the input under which the system is frequently operated. Here step signal is chosen to be the test input. The time response is tested based on the driving method discussed in section 2.2. In this case, the micromirror system has 2 input control voltages,  $V_W$ ,  $V_S$  and 2 outputs X and Y coordinate of the laser spot on the sensor. The transient response of a system depends on the initial condition. Driven by changing-voltage method, the initial condition of the system is when all of the actuators are applied 75V voltage and the mirror plate is parallel to the substrate.  $V_S$  controls the micromirror to rotate along Y axis and  $V_W$  controls the micromirror to rotate along Y axis. The driving axis X and Y are tested separately and 2 sets of experiments are designed for the transient response test.

The first set of the experiment is used to test the performance of North and South actuation, driven by which the laser spot moves along Y axis of the sensor. Bias voltage  $\Delta V_1$  is used to generate the step control signal V<sub>S</sub>, as described in Eq. (2.1)-(2.4). When V<sub>S</sub> and V<sub>N</sub> is given a step control signal, V<sub>W</sub> and V<sub>E</sub> is fixed to be 75V. The second set of the experiment is used to test the performance of West and East actuation driven by which the laser spot moves along X axis of the sensor. Bias voltage  $\Delta V_2$  is used to generate the control voltage V<sub>w</sub>, as described in Eq. (2.1)-(2.4). When V<sub>W</sub> and V<sub>E</sub> are given step control signals, V<sub>N</sub> and V<sub>S</sub> is fixed to be 75V. Each  $\Delta V$  ( $\Delta V_1$  or  $\Delta V_2$ ) can generate a step signal of driving voltage (V<sub>S</sub> or V<sub>W</sub>), shown in figure below.



Figure 2.7 Driving voltage generated by bias voltage

In the experiment, the incensement of  $\Delta V_1$  and  $\Delta V_2$  is 6V.  $V_S$  and  $V_W$  change in this fixed incensement from -36V to 36V, which generates 12 sets of step test voltages. Fig. 2.8 shows the active sensing area. A rectangular coordinate has been built on it. The origin of the coordinate lies in the center of the sensor. When the micromirror is at its initial position the laser spot lies at the origin. Driving the laser spot moving along X axis is called X axis driving and driving the laser spot moving along Y axis is called Y axis driving. When  $\Delta V_1$  is bigger than zero,  $V_S$  is bigger than 75V,  $V_N$  is smaller than 75V and the laser spot will move along the positive Y axis. Otherwise when  $\Delta V_1$  is smaller than zero, the laser spot will move along the negative Y axis. In the same fashion, when  $\Delta V_2$  is bigger than zero, the laser spot will move along the negative X axis, otherwise the laser spot moves along the positive X axis.



Figure 2.8 Moving direction of the laser spot

For each test, only the paired 2 actuators are driven and 35Hz square wave is applied to the corresponding actuators, shown in Fig 2.9. The test signal is designed to be the square wave in order to observe repeatable experiment results. In Fig 2.9 the left coordinate represents the sensing area,, and the left coordinate shows the driving square of one period. The solid signal is  $V_S$  and the dashed signal is  $V_N$ . Taking Y axis actuation for example, for one period of the driving voltages shown below, the solid line is  $V_S$  and the dash line is  $V_N$ , they are generated by bias voltage  $\Delta V_1$  and the signals are symmetry to 75V voltage line. The point *I* is the initial condition of the micromirror and all of the actuators are applied 75V at this time, the laser spot is located at the origin of the sensor. For the first half period of driving signal shown in Fig 2.9, the laser spot is driven from origin to some point P on positive Y axis by a step input  $\Delta V$ . After holding the voltage level for enough time and the micromirror has already settled down, the test signal goes into the second half period and a second step input  $-\Delta V$  is given. The laser point will go back from point P to origin.



Figure 2.9 Moving direction of the laser spot

The square transient response test signal and the reading from the PSD sensor for Y axis and X axis test are shown below which is captured and recorded by the oscilloscope. In Fig. 2.10 the showing signals from top to the bottom are X axis reading from sensor, Y axis reading from sensor,  $V_N$  driving voltage and  $V_S$  driving voltage. In Fig. 2.11 the showing signals from top to the end are X axis reading from sensor, Y axis reading from sensor,  $V_W$  driving voltage and  $V_E$  driving voltage. From the experiment results, the laser spot response follows the input square

wave change in the same frequency while has overshoot in each step. For all of the periods of wave captured, the laser spot responses have the same appearance which can prove that the transient response test is respectably and the whole system works in a stable state. The experiments also reveal that, when the micromirror is driving on one axis, even the driving voltages for the other axis are fixed, the micromirror will still have a small movement on the other axis. This is defined as the coupling phenomenon, the driven axis movement is called the main movement, and the movement of the other axis caused by the main movement is called the coupling movement. The coupling movement is usually much smaller than the main movement and can be omitted.



Figure 2.10 △V<sub>1</sub> =18V measurement, signal from top to the bottom is 1)signal 1 is X axis measurement of the sensor 2)signal 2 is Y axis measurement of the sensor 3)signal 3 is South actuator driving voltage before amplified 4)signal 4 is North actuator driving voltage before amplified



Figure 2.11  $\Delta V_2$  =18V measurement, signal from top to the bottom is 1)signal 1 is X axis measurement of the sensor 2)signal 2 is Y axis measurement of the sensor 3)signal 3 is West actuator driving voltage before amplified 4) signal 4 is East actuator driving voltage before amplified

4 dynamic specifications are measured to describe the performance of the micromirror. The first is the rise time, which is the time required for the system output to rise from 0% to 100%. The second is the settling time, which is the time required for the system response to reach and stay within a certain error band (2% or 5%) about the final value. It is an important measurement of the system. 5% is chosen to be the steady state error for the micromirror system. The shorter the settling time, the faster the micromirror can be driven. The third specification is the peak time which is the time required for the response to reach the peak of the system first time. The fourth specification is the percentage of overshoot, which is defined by the equation below:

Percentage of overshoot = 
$$\frac{c(t_p) - c(\infty)}{c(\infty)} \times 100\%$$
 (2.12)

 $C(t_p)$  is the maximum peak value of the system response,  $c(\infty)$  is the system response when the

time approaches to infinity. The amount of the percentage of overshoot is a direct indicator of the system stability. The smaller the overshoot is, the more stable the system is.

The measurement of the step response is captured by the oscilloscope firstly, and one period of the signal is taken out and analyzed, shown in the figure below. The rising edge and the falling edge are analyzed separately. The transient response specifications are listed from table 2.1 to table 2.4. The relationship of settling time, rise time, percentage of overshoot and peak time with the absolute value of bias voltage are shown in the Fig. 2.14 - Fig. 2.17Each axis test consists of positive side test and negative side test. For each axis side, the laser spot is tested in 2 moving directions, moving away from the origin and moving toward the origin. The measurements in the chart are labeled in the format "A\_B\_C". The first letter "A" is the name of the axis on which the test is performed. The second letter "B" is the side of the axis. The Third letter "C" is to which direction the laser spot moves which can be either "up" or "back". "up" indicates the laser spot moves away from the origin and "back" indicates the laser spot move back to the origin. In this case, for each bias voltage, there are 8 corresponding measurements, Y\_positive\_up, Y\_positive\_back, Y\_negative\_up, Y\_negative\_back, X\_positive\_up, X\_positive\_back, X\_negative\_up and X\_negative\_back.



Figure 2.12 Step response of Y\_positive\_up,  $\Delta V_1 = 18V$ 



Figure 2.13 Step response of Y\_positive\_down,  $\Delta V_1 = -18V$ 

$\Delta V_1(V)$	$V_{N}(V)$	$V_{S}(V)$	Settling time(ms)	Overshoot (%)	Rise time(ms)	Peak time (ms)
-6	81	69	0.77	9.17	0.37	0.53
6	69	81	0.73	9.91	0.32	0.5
-12	87	63	0.77	10.63	0.35	0.47
12	63	87	0.75	9.30	0.35	0.47
-18	93	57	0.73	12.39	0.32	0.43
18	57	93	0.74	11.65	0.33	0.44

Table 2.1 Y axis driving from origin to positive Y

-24	99	51	0.72	14.45	0.3	0.42
24	51	99	0.77	13.98	0.34	0.46
-30	105	45	0.75	18.60	0.31	0.43
30	45	105	0.73	16.76	0.31	0.42
-36	111	39	0.71	20.30	0.28	0.39
36	39	111	0.78	20.17	0.36	0.47

Table 2.2 Y axis driving from origin negative Y

$\Delta V_1(V)$	$V_{N}(V)$	$V_{S}(V)$	Settling time(ms)	Overshoot (%)	Rise time(ms)	Peak time (ms)
-6	81	69	0.76	8.65	0.36	0.49
6	69	81	0.74	8.86	0.35	0.47
-12	87	63	0.77	9.86	0.37	0.49
-18	63	87	0.75	10.75	0.34	0.45
18	93	57	0.78	12.50	0.36	0.46
-24	57	93	0.79	13.27	0.36	0.49
24	99	51	0.77	15.85	0.34	0.44
-30	51	99	0.75	14.59	0.33	0.45
30	105	45	0.75	19.53	0.32	0.44
-36	45	105	0.73	19.58	0.31	0.42
36	111	39	0.74	22.53	0.31	0.43

-18	39	111	0.71	22.98	0.28	0.39

$\Delta V_2(V)$	$V_{\rm E}(V)$	V <sub>W</sub> (V)	Settling time(ms)	Overshoot (%)	Rise time(ms)	Peak time(ms)
-6	81	69	0.75	9.94	0.34	0.46
6	69	81	0.7	8.69	0.33	0.48
-12	87	63	0.76	11.1	0.35	0.48
12	63	87	0.77	10.88	0.36	0.5
-18	93	57	0.8	14.04	0.37	0.48
18	57	93	0.78	13.89	0.37	0.48
-24	99	51	0.76	15.16	0.32	0.44
24	51	99	0.77	17.29	0.34	0.44
-30	105	45	0.73	19.03	0.3	0.41
30	45	105	0.72	20.55	0.29	0.4
-36	111	39	0.72	24.02	0.27	0.4
36	39	111	0.95	21.54	0.28	0.42

# Table 2.3 X axis driving from origin to positive X

Table 2.4 X axis	driving fro	om origin to	negative X
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$\Delta V_2(V)$	$V_E(V)$	$V_W(V)$	Settling time(ms)	Overshoot (%)	Rise time(ms)	Peak time(ms)

-6	81	69	0.75	9.94	0.34	0.46
6	69	81	0.7	8.69	0.33	0.48
-12	87	63	0.76	11.1	0.35	0.48
12	63	87	0.77	10.88	0.36	0.5
-18	93	57	0.8	14.04	0.37	0.48
18	57	93	0.78	13.89	0.37	0.48
-24	99	51	0.76	15.16	0.32	0.44
24	51	99	0.77	17.29	0.34	0.44
-30	105	45	0.73	19.03	0.3	0.41
30	45	105	0.72	20.55	0.29	0.4
-36	111	39	0.72	24.02	0.27	0.4
36	39	111	0.95	21.54	0.28	0.42

Fig. 2.14 shows the relationship between the settling time and the absolute value of the bias voltage. With the incensement of the bias voltage, the settling time of the system responses vary in a small range between 0.7ms and 0.8ms. It can be conclude that, the bias voltage only has insignificant effect on the settling time. The settling time of the system with 5% steady state error band is around 0.75ms.



Figure 2.14 Settling time comparison

Fig. 2.15 shows the relationship between the percentage of overshoot and the absolute value of the bias voltage. With the incensement of the bias voltage, the overshoot of the system responses increases from around 10% to 20%. So the bigger rotation angle of the micromirror is the bigger overshoot the system has. Also the changing overshoot indicates the non-linearity of the system. For each bias voltage, the overshoot of 8 measurements shows a symmetry distribution around the average value. So it can be conclude that in the current driving method the micromirror has a nearly symmetry behavior in the entire axis.



**Figure 2.15 Overshoot comparison** 

Fig. 2.16 and Fig. 2.17 show the relationship between the rise time and the peak time with the absolute value of the bias voltage. Rise time and peak time of the system response shows the same trend of change. With the increase of the voltage bias, the rise time and peak time is getting smaller which means the micromirror will response faster when a bigger voltage change is applied. However, the fast response always companied with big overshoot. For the display purpose, overshoot and the settling time are the most important factors that should be taken into consideration to improve the performance of the system. A faster rise time and peak time follow with a bigger overshoot and unchanged settling time. However, this characteristic can be used in close loop to reduce the settling time and the overshoot.



Figure 2.16 Rise time comparison



Figure 2.17 Peak time comparison

#### **2.5 Frequency response of the micromirror**

Similar to the time response test, frequency response test is performed to study the physical system from another aspect. Frequency response is the steady state response of a system to a sinusoidal input. The frequency of the input sinusoidal signal varies from low to high and the corresponding response of the system is recorded and studied. One advantage of the frequency response is that we can use the data obtained from the experiment on the physical system to have an estimation of the system model. Another advantage is that the frequency response test can given us some information of the system on frequency domain which time response test cannot provide us.

The hardware setup to perform the frequency response is the same with the time response test. The function of the given sinusoidal input to the system is shown in Eq. (2.13). The output function of the system is shown in the Eq. (2.14).

$$X = A_1 \sin(\omega_1 t) \tag{2.13}$$

$$Y = A_2 \sin(\omega_2 t) \tag{2.14}$$

X and Y are the system input and output.  $A_1$  and  $A_2$  are the amplitude and  $\omega_1$  and  $\omega_2$  are the sinusoidal frequency. Same as the time response test, the frequency response is performed separately on X and Y axis. When the micromirror is actuated on one axis, the voltages applied on the other axis are fixed to 75V. The frequency of the input changes from 0.1 Hz to 4 kHz in different incensement. The amplitude of the input sinusoidal signal is fixed to 100V. The input signal and the laser spot response measured by the sensor are recorded by the oscilloscope, Fig. 2.18-Fig. 2.21. It can be noticed that the coupling movement exist and have the similar manner to the main movement. However, comparing to the main movement the coupling movement is small enough to be omitted. For each frequency, the amplitude ratio and the phase shift angle of the output and the input is calculated to obtain the Bode plot, Fig. 2.22-2.23.

Fig. 2.22 and Fig. 2.23 are the magnitude response and phase shift angle response of the system. The curves in solid line are the response for Y axis test and the curves in dashed line are for X axis test. The system response for X axis and Y axis almost coincide which proves the symmetry behavior of X and Y axis. In low frequency, the values of the magnitude response are almost constant; this reveals that the system is type zero. The amplitude reaches to a peak value namely resonant peak with the increase of the frequency. This indicates that the system order is at least 2. The resonant frequency is around 800Hz. The magnitude of the system drops very quickly with the frequency increasing in high frequency range. This indicates that working in high frequency the system will not have the chance to have a full response to the system input.



Figure 2.18 Y axis driving f=10Hz, signal from top to the bottom 1)signal 1 is X axis measurement of the sensor 2)signal 2 is Y axis measurement of the sensor 3)signal 3 is North actuator driving voltage before amplified 4) signal 4 is South actuator driving voltage before amplified



Figure 2.19 X axis driving f=10Hz, signal from top to the bottom 1) signal 1 is X axis measurement of the sensor 2)signal 2 is Y axis measurement of the sensor 3) signal 3 is East actuator driving voltage before amplified 4) signal 4 is West actuator driving voltage before amplified



Figure 2.20 Y axis driving f=800Hz, signal from top to the bottom 1)signal 1 is X axis measurement of the sensor 2)signal 2 is Y axis measurement of the sensor 3)signal 3 is South actuator driving voltage before amplified 4)signal 4 is East actuator driving voltage before amplified



Figure 2.21 X axis driving f=800Hz, signal from top to the bottom 1)signal 1 is X axis measurement of the sensor 2)signal 2 is Y axis measurement of the sensor 3)signal 3 is East actuator driving voltage before amplified 4)signal 4 is West actuator driving voltage before amplified



Figure 2.22 Magnitude response of Bode plot



Figure 2.23 Phase angle response of Bode plot

# **Chapter 3 The open loop control algorithm**

The critical component of the HUD is the 2D micromirror, which consists of 4 repulsiveforce electrostatic actuators and a central mirror plate as shown in Fig. 2.1. The micromirror operates in a non-resonant mode. Voltages applied to the four actuators determine the rotation angle of the micromirror. Open-loop control is used to control the micromirror. Open-loop control methods were selected in order to reduce the cost of the HUD because a high speed Position Sensing Detector (PSD) needed for implementing a closed-loop control system would sharply raise the cost of the system.

The open-loop control method starts with establishing a calibration table which relates the driving voltages applied to the four actuators and the position of the laser spot on a 2D plane.

Assume there is a sequence of points which form a trajectory inside the calibration area which is a2D plane in front of the micromirror. The corresponding driving voltages for any point on the trajectory can be obtained from the interpolation method. Ideally, if the driving voltages for each point are applied to the micromirror in a certain sequence, the laser spot will follow this trajectory. If the driving voltages are sent faster enough and repeatedly, namely, the micromirror rotates fast enough; a stable trajectory can be observed by human being because of the visual Residual effect.

Desired patterns such as numbers and letters which are composed of lines are generated using software. A large number of points on the line patterns can be identified. For each identified point, the driving voltages corresponding to the four actuators are found from the calibration table. Applying those voltages to the micromirror in a sequence and at a certain frequency, the micromirror steers the laser beam on the display screen with the laser spot following a trajectory connecting the selected points to generate the vector line patterns.

# 3.1 Building the calibration table

The calibration table determines the relationship between the position of the laser spot on a 2D plane and the driving voltages applied to the micromirror. The calibration table is also the

steady response of the micromirror based display system. Here micromirror and the magnification lens which is use to magnify the rotation angle of the micromirror is treated as a system. The hardware setup is the same as the time response experiment.

The calibration was performed using the driving method previously discussed in chapter 2, V0=75 V and control voltages ( $\Delta V_1$  and  $\Delta V_2$ ) are varied linearly with a certain step 3V. A group of voltage combinations can be generated to drive the micromirror as follow. The maximum driving voltage for each axis which can drive the laser spot shooting on the active sensing area of the sensor is tested first. A driving voltage higher than the maximum driving voltage may lead to the laser spot shooting outside the active sensing area of the PSD. The minimum driving voltage is 0. For each driving actuator, the driving voltage is generated by dividing the voltage range from 0V to the maximum driving voltage linearly with the certain step 3V. A group of voltage combinations is then generated. Assume the driving voltage and the laser spot position on the sensor has a linear relationship (Ideally). The generated voltages will generate a bunch of linearly distributed laser spot on the sensor, shown in Fig. 3.1.



**Figure 3.1 The ideal calibration results** 

However, because of the nonlinearity of the system, the calibration result is distorted and only has an approximate linear relationship in small area. The actual calibration result is shown in Fig. 3.2. The calibration result gives us the relationship between the designed voltages and the discrete distributed points on the sensor. For the control purpose, the control voltages which can drive the laser spot to move to any arbitrary point on the sensor have to be found out.



**Figure 3.2 Calibration results** 

Interpolation can be used here to build a continuous model of the relationship between the driving voltages and the points on the sensor. Assume there is a function of the coordinate of the points on the sensor and the driving voltages, we can have 4 functions.

$$V_N = f_N(x, y) \tag{3.1}$$

$$V_s = f_s(x, y) \tag{3.2}$$

$$V_W = f_W(x, y) \tag{3.3}$$

$$V_E = f_E(x, y) \tag{3.4}$$

The figures of the above functions are 3D surfaces. Matlab surface fitting tool can be used to create the function model. The surface fitting tool has a GUI which can help finish the fitting task, shown in Fig. 3.3. In order to fit the surface, "X input" and "Y input" are x and y coordinates of the spatial surface. In our case, "X input" is the x coordinate of the points on the sensor and "Y input" is the y coordinate of the points on the sensor. "Z output" is the coordinate of z axis of the surface and in our case it is the driving voltages. There are 4 options for the interpolation method: Triangle-based linear interpolation (linear), Triangle-based cubic interpolation (cubic), Nearest neighbor interpolation and MATLAB 4 griddata method (v4).



Figure 3.3 Matlab surface fitting tool GUI

The fitting result gives the mathematical model and is saved as "sift" structure. After the fitting process, 4 "sift" structure are created named as "model\_East", "model\_West", "model\_North", "model\_South" and are saved to an independent data file. Each structure is treated as the mathematical model and given an arbitrary point on the sensor, the corresponding

driving voltages can be found using the sift structure. It should be noticed here that the voltages found by the interpolation model is not the accurate value of the real input. The voltage is calculated by the known values near it obtained from the calibration result and it is just an approximation. However, if we have enough points from calibration, which means the number of the points obtain from the calibration result is very large and the points are very close to each other, the accuracy of the interpolation method can be very high. In the calibration, 1369 points are used, and the linear step which is used to generate the calibration voltages from the FPGA side is 0.05, corresponding to 3V after amplify. The fitting model generated by "v4" is shown below.



Figure 3.4 V<sub>S</sub> model created by surface fitting

#### 3.2 Three factors to measure the display quality

The number of points to extract from the pattern is an important problem. It is related to the quality of the display which is our first concern in the display system. Three factors which are the distortion of the display, the display frequency and the intensity of the laser distribution mainly affect the display quality.

Distortion of the display is caused by the dynamic performance of the micromirror. From the chapter 2, the micromirror system (micromirror and the magnification lens) can be

approximately treated as a second order system. The micromirror is driving by many step inputs when displaying. The transient response of step input for a second order system has oscillation when the response tends to steady state. This undesired oscillation if big enough will be visible in the display. Overshoot may cause large distortions at sharp corners of a displayed pattern. Along lines of non-sharp corners, the effect of overshoot is less significant because the laser spot overshoots to positions which are still on the displayed pattern. The Fig. 3.5 can have a better explanation of this. We display the blue trajectory by moving the laser point to go through 4 points, A, B, C and D. The dashed line is the desired laser spot trajectory; the solid line is the actual trajectory. B is the middle point between A and C, which means the voltage variation from A to B and from B to C are almost the same which will lead to an almost same overshoot. The overshoot from A to B is invisible because the overshoot part coincides with the line. However, the overshoot from B to C will be visible and will affect the image quality and sometimes will cause a big distortion of the whole image.



Figure 3.5 The overshoot effect on the display

From the result of the step response of chapter 2, a bigger step input will lead to a bigger overshoot. Diving bigger step into several small steps is likely to help reduce the overshoot. 2 methods are tested. One is to equally divide a big step into several small steps; the other is to divide the big step into non-uniform distributed points. The closer to the destination point the laser spot is, the smaller step the laser spot will move, see Fig. 3.7.



Figure 3.7 Unequally division of a big step

A set of experiment has been performed to study the performance of the laser spot driven traveling in a straight trajectory from the origin O of the sensor to point P on Y axis of the sensor, see Fig.3.6 and Fig. 3.7. It has been proved from the time response experiment and the frequency response experiment, the micromirror has a symmetry performance and the coupling movement is really small. So it can be predicted that X axis will have the similar performance as Y in this experiment and the single driving on Y axis will result in the laser spot traveling along y axis. The hardware setup is the same as the experiments discussed in chapter 2. Shown in Fig. 3.6, the left coordinate is the sensor coordinate, the right coordinate gives the control signal. When the laser spot is at origin O of the sensor, the control voltage is  $V_0$  which is equal to 75V on both north side actuator and south side actuator. When laser spot is at position P on the sensor the control voltage is  $V_1$  for South side of the actuator, north side control voltage can be calculated.

A sequence of step signal is applied to north side actuator and South side actuator while the driving voltages applied to west side actuator and east side actuators are fixed to 75V. For the first set of experiments, the big step control voltage is equally divided into several small steps, each step input corresponding to a point on the Y axis of the sensor. Because of the approximate linear relationship with the control voltage and the position of the laser spot, the laser spot will move same distance for each small step driven. For the second set of experiment, the big step control voltage from  $V_0$  to  $V_1$  which is the same as the first set of the experiment is unequally divided into several small steps. The input voltage steps decrease when the laser spot approaching point P. For each set of experiment, different divisions and control time T are tested. The control voltage from 75V to 105V are divided into 5, 25, 50, 100 steps. The control time to increase the control voltage from 75V to 100V is set to be 200us, 400us, 600us, 800us, 1000us 1200us and 1400us. Each step division is performed separately under the 7 different control time. The result of the experiment is analyzed and compared in the chart below. The labels in the chat are written in the form A\_B. The first letter A is the division method, "exp" means the exponential unequally division and "equal" means equally divided. The second letter B is the number of the division.

From the Fig. 3.8 and Fig. 3.9, in the vertical comparison, it can be concluded more division can achieve a smaller overshoot, especially when control time is bigger than 600ms. However, once the division number bigger than 25, the overshoot Vs, control time curve almost coincide which means simply increase the division number will not reduce the overshoot. The result of equally division and unequally division are compared in the Fig. 3.10. It can be concluded that if the control time is smaller than 1000us, the unequally division method has a larger overshoot than equally division, however, when the control time is bigger than 1000us, the unequally division method has a much better performance in reducing the overshoot. The settling time comparisons of 2 sets of experiments are shown in Fig. 3.11. It can be concluded that the equally division can achieve a smaller settling time; however the difference is not significant.



Figure 3.8 Overshoots measurement for equally division



Figure 3.9 Overshoots measurement for unequally division



Figure 3.10 Overshoots measurement comparison of equally and unequally division





Another method to reduce the distortion caused by overshoot is to design desired patterns with smooth outline. The reason is that a smooth curve composed pattern has more tolerance of the distortion.

Display frequency is required to be at least 30fps to make the display look static to the human eye. In addition, the frame rate must be constant. A higher frequency will result in a better, flicker-less pattern. The time interval of moving the laser spots,  $\Delta t$ , which is a constant for all of the points once it is chosen, the number of points that make up a display, *n*, and the display frequency *f* have the relation below:

$$f = \frac{1}{n \cdot \Delta t} \tag{3.5}$$

From Eq. (3.5) the number of points that make up a display and the time interval of moving the laser spots contribute to the display frequency together.

Laser intensity distribution on the display is affected by the density of the point's distribution that makes up the display patterns. If the density is a constant, which means the laser spot will stop on each point almost the same time, laser intensity will be evenly distributed. Otherwise, those areas have a larger point's density will look brighter than other places. Evenly distributed laser intensity gives us a more comfortable looking display.

#### **3.3 Design the scanning points**

The scanning path of the laser spot is continuous so that it can be repeated in relative high frequency to form a stable image to human eyes. So the scanning points consist of 2 parts, the points which identify the desired patterns called as pattern points and the points that transit the laser spot from one pattern to another called transitional points. The pattern points define the shape of display.

#### **3.3.1 Design desired patterns for display**

The desired vector image in our case is the speed information of the vehicle. It is composed of 2 parts, the first part consists of 3 digits which is used to display the value of the speed and the

second part consists of 3 letters "kmh" which is used to display the speed unit. Each digit or letter is called a pattern, so the desired vector image is composed of 6 patterns. The patterns are designed using AutoCAD software. From the calibration result, we can know that the calibration area is -8.3~8.3 for x axis and -7.6~7.6 for y axis. So the patterns we designed must lie in this area, so that we can find the corresponding driving voltages for the points on the trajectory. A frame is built in AutoCAD which can guarantee the designed patterns lie inside the calibration area, Fig. 3.12.



Figure 3.12 Frame generated in AuctoCAD

The range for the frame is -5~5 for x axis and -2~ 2 for y axis. A space is left between adjacent patterns. The frame consists of 4 blocks. From the left to right, is the block number from 1 to 4. The content in the first 3 blocks are the digit numbers. The content in the 4<sup>th</sup> block is the letter "kmh". To design the patterns, the text objects of the digits from 0 to 9 and the letter "kmh" are created in the size which can fit the frame. Then the "txtexp" command is used on the text objects to convert them into polylines which can be edited. Then the shape of each pattern is modified for display, see Fig. 3.13. Then the points can be identified on the designed patterns for the display purpose.



**Figure 3.13 The designed patterns** 

#### **3.3.2 Extract patterns points from the patterns**

From the discussion of 3 factors which affect the display quality we can conclude the method to extract points from the designed patterns can be concluded. Because the number of points to display and the time interval between each point both affect the display frequency. From the conclusion of overshoot effect experiments in section 3.2, which is no matter how many middle points the laser spot go though when it is traveling from one point to another in a certain time interval, the settling time will not change. Namely, more middle points will not help the laser spot to settle down faster. A non-uniform distributed trajectory will lead to a bad quality display. The place which has more points has a brighter display. When more complicated patterns are displayed, this phenomenon is more apparent. Because of the 2 reasons talked above, equally division driving method is chosen to display the patterns and the pattern points are equally extracted from the designed patterns with respect to the length of the patterns.

Equally division driving method requires the points identified on the patterns are uniform distributed. In AutoCAD software, "list" command which can provide the length of selected polyline is used to obtain the length of each pattern. The length is shown in the table below:

Digit	Length	num
1	3.1488	35
2	6.1548	68
3	5.8997	65
4	6.3743	70
5	6.696	74
6	7.7162	85
7	4.3235	48
8	9.0773	100
9	7.9691	88
10	6.8372	75

Table 3.1 The length of the designed patterns

The digit "8" has the largest length, if n points are used to display digit "8". The number of points needed to display other patterns *num* can be calculated from Eq. (3.6).

$$num = \frac{L}{length} \times n \tag{3.6}$$

"L" is the length of digit "8" and "length" is the length of other patterns. After deciding the number of points for each pattern, "divide" Command can be used to averagely divide each pattern into corresponding points. In order to map the coordinates of the identified points of a pattern onto the coordinate system of the sensor, the points are copied into the blocks in Fig. 3.12 and then saved into a text file.

# **3.3.3 Transitional points design**



**Figure 3.14 Transitional points design** 

A decreasing exponential function is used to generate the transitional points. Given the start point of the transitional path, A (x0, y0), and the end point of the transitional path, B (x1, y1), the function of the line is represented as:

$$y = \frac{y_1 - y_0}{x_1 - x_0} \times (x - x_0) + y_0$$
(3.7)

Assume "n" points will be inserted from A to B. Each inserted point has a sequence number "k", indicating the scanning direction from A to B. "k" is an integer variable which is bigger or equal to 0 and smaller or equal to the total number of points inserted "n". An exponential

function is used to generate the shrinking step y axis coordinates of the inserted points. x and y are the coordinates of the inserted points.

$$y(k) = y_1 - \exp(-6 \cdot \frac{k}{n}) \times (y_1 - y_0), k=0...n-1$$
 (3.8)

The slope changing tendency of this function is studied. Assume y(t) is a continuous function with respect to the continuous variable t, shown is Eq. (3.9).

$$y(t) = y_1 - \exp(-6 \cdot t) \times (y_1 - y_0) (0 \le t \le 1)$$
(3.9)

The discreet function and the continuous function should have the same variation tendency. The first order derivative of y(t) implies the change of increment of the y coordinate.

$$\frac{dy(t)}{dt} = 6 \cdot (y_1 - y_0) \cdot \exp(-6 \cdot t)$$
(3.10)

From Eq. (3.10), if y1>y0, y(t) is decreasing which means when y is getting to y1, the increment is getting smaller. If y1<y0, y(t) is increasing which means when y is getting to y1, the increment is getting smaller. So we can prove that Eq. (3.6) can generate the points we need. The increment change of y is shown in Eq. (3.11).



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Figure 3.16 Increment change between 2 points from Eq. (3.11)

Once the y coordinates are generated for each of the inserted transitional points, the corresponding x coordinates can be determined using Eq. (3.7).

### 3.3.4 Save the scanning points

After all of the points needed for the display are generated, they are saved as a vector in the Matlab data file. The dimension of the vector is  $N\times 2$ . The "N" rows of the vector corresponding to all of the points designed. Each point has 2 coordinates X and Y which are corresponding to the column of the vector. Each row corresponding the points are saved in the vector as 4 section in the sequence of "1<sup>st</sup> block points", "2<sup>nd</sup> block points", "3<sup>rd</sup> block points", "4<sup>th</sup> block points". Each section is composed of the points which identify 10 digits and the transitional points followed by each digit. The structure of the first section, "1<sup>st</sup> block points" and the second section, "2<sup>nd</sup> block points" are the same, shown in Fig. 3.17. In order to display the number from "000" to "999", each digit in 1<sup>st</sup> block and 2bd block in the frame can be followed by 10 digits from 0 to 9.

So each digit in 1<sup>st</sup> block and 2<sup>nd</sup> block has 10 transitional points. Because the patterns in the 4<sup>th</sup> block is fixed to "kmh", for each digit in 3<sup>rd</sup> block has only one group of transitional points, in Fig 3.18. The 4<sup>th</sup> block of the frame consists of 3 fixed patterns "k", "m" and "h". The transitional points from "k" to "m" and from "m" to "h" are fixed, in Fig. 3.19. In order to keep the scanning circulating, the laser spot has to go back to the first pattern. So the transitional points which connect the last point of last letter "h" with the first point of first pattern are saved after the patterns pints "h", shown in Fig. 3.19.



Figure 3.17 Structure of 1st block


Figure 3.18 Structure of 3rd block



Figure 3.19 Structure of 4th block

## **Chapter 4 The implementation of calibration**

#### 4.1 Introduction of the developing system

#### 4.1.1 Introduction of LabVIEW

LabVIEW is the abbreviation of Laboratory Virtual Instrument Engineering Workbench, it is a core product of National Instrument Co. Ld. LabVIEW is a graphical programming environment which is different from the traditional programming language such as Visual basic, C, C++ or Java. LabVIEW use the graphical language as its programming language, which is also called as G language. Compared to the traditional programming language, graphical language has its advantages. Although the traditional programming language uses the text language which presents the program logic using the simplified human language, it is still abstract to new learners to some extent. However, the graphical language use the visual graphical blocks to present the program logic. Because graphics are more easily to be perceived by sense, G language is easy to learn. Also LabVIEW has very rich toolbox recourses about measurement, control and simulation, which can provide most of the functions the user need. The graphical blocks in the toolboxes are usually highly integrated, which will take hundreds lines of text language to achieve the same function. A third advantage of LabVIEW is that, it has very good operating system compatibility. LabVIEW development environment can be installed on Windows, Mac, and Linux operating system. The program can run on Microsoft Pocket PC, Microsoft Windows CE, Palm Os and many other embedded platforms like FPGA, DSP, ARM microprocessor. These four advantages of enable LabVIEW a shorter project developing process which is the main reason, LabVIEW is chosen to develop the micromirror control system.

#### 4.1.2 Introduction of FPGA



Figure 4.1 The structure of FPGA

An FPGA (Field Programmable Gate Arrays) is reprogrammable silicon chip which has a matrix of reconfigurable gate array logic circuitry on it. Xilinx and Altera are 2 major vendors for FPGA nowadays and their FPGA may have different structures. However, they share the same basic structure. Usually the FPGA is composed of 3 parts, Configurable Logic Blocks (CLBs, Xilinx) or Array Logic Blocks (ALBs, Altera), I/O blocks and programmable interconnect switches, shown in Fig. 4.1. In this paper, Xilinx is used. With these reconfigurable recourses, a FPGA can be programed to achieve many user defined hardware function. CLBs are the core of FPGA and are composed of flip-flops and look-up tables (LUTs). This is the main specification for a FPGA. Flip-flop is a binary shift register that is used to store state information such as 0 and 1. It is used to synchronize logic and save logical states between clock cycles and is a fundamental building block of digital electronics systems. LUTs are memories which are used to define the truth table of all combinatorial logic such as ANDs, ORs, NANDs, XORs and so on.

In this project, FPGA is chosen to perform control task instead of usually used microprocessor. There are several reasons that FPGA is superior to the microprocessor. The first

reason is that FPGA is faster than microprocessor. The FPGA logic is implemented by the hardware which can work in a really fast speed. The working frequency of FPGA is 40MHz, which means the time resolution is 25ns. However, the time resolution we can control for the microprocessor is in microsecond. One example of fast execution of FPGA logic is that the widely used proportional integral derivative (PID) control algorithm which is included in the LabVIEW FPGA module can execute in 300 nanoseconds. The second reason is that FPGA can perform real parallel execution of the control or program. The microprocessor program executes task in sequence, because the recourse of CPU can only be occupied by one task at one time. In this case, for the control proposes, a FPGA can perform multi-control task at the same time which may take several microprocessors to achieve. A third reason is that the control logic of FPGA is run by the hardware which is more reliable than microprocessor. For microprocessor, there has to be an operation system to run the control logic which may bring many unstable factors. Because of all the reasons above, NI PCIe 7852R board is chosen to perform the control task.

The NI PCIe-7852R multifunction RIO board features a user-programmable FPGA chip for onboard processing and flexible I/O operation. It has 8 analog inputs, each of which has independent sampling rate up to 750 kHz and 16-bit resolution. It has 8 analog outputs, each of which has independent sampling rates up to 1MHz and 16-bit resolution. The voltage range for the input and the output are both -10V~10V. A Virtex-5 FPGA chip is the core of the board. The maximum working frequency is 40MHz. It is programmable with the LabVIEW FPGA Module. 3 DMA channels enable the 7852R board to perform high-speed data transition. The 192kB on board memory allows the FPGA to process large amount of data.



Figure 4.2 NI PCIe-87852R

#### 4.1.3 The structure of the LabVIEW FPGA system

NI PCIe-7852R is installed in the PCI Express slot of the mother board of the PC. The PC-CPU woks as a real-time microprocessor, which runs the Host program. The Host program has the graphical user interface (GUI) and it is used to configure, communicate with and debug the FPGA program. The hardware logic runs on the FPGA is also called FPGA program. The parameters used in the FPGA can be updated by the host program. The output of the NI PCIe-7852R is connected to SCB-68 which is an shield I/O connector by a cable. SCB-68 is a rugged, very low-noise signal termination and is convenient for the I/O connection with controlled plant.



Figure 4.3 The structure of hardware developing system

Both of the Host program and FPGA program are developed under the LabVIEW development environment. A LabVIEW program which is usually called Vi, is composed of 2 parts, the front panel and the block diagram. The front panel is the user interface which imitates the front panel of physical instruments. The front panel includes knob, button and many other input and output controls. The block diagram is the real executable program which is composed of terminals, wires, constant and program control structures. The execution sequence of

LabVIEW program follows the data flow. For example, a data start from some node and follows the wires to the input terminal of the next node. The data is processed in this node and then send out from the output terminal of this node. The data follows the wires again to the next node until it goes into some end node. The sequence of the data flow is the sequence of the program. So LabVIEW program is also called the data flow driven program. The Host program after it is finished can directly run on the PC. Different from the Host program, the FPGA program is needed to compile into bit stream file and download to FPGA. Once the bit stream file is downloaded into FPGA the program becomes the hardware logic. Even a small modification on the FPGA logic needs to recompile the new FPGA file and download again. After download is ready, a start signal from the Host program will start the host program and the FPGA logic at the same time and the system begin to work.

#### 4.2 The calibration program

The calibration program is used to find the relationship between the position of the laser spot on the sensor and the driving voltages of the micromirror. A set of linear voltage is generated to control the micromirror to scan a square area line by line. For a certain driving voltages, the corresponding position of the laser spot position is obtained and saved. If the driving voltages and the position of the laser spot have linear relationship, the distribution of the laser spots on the sensor should also be linear. Calibration program and the open loop control program shows a lot of common code, so only calibration programs is explained in detail.

#### 4.2.1 Calibration LabVIEW host program

The Host program can be separated into 2 parts from their functions. The first part is to prepare the data and set up for FPGA program. The second part is to control the FPGA to perform calibration. The first part of the program is shown in the Fig. 4.4.



Figure 4.4 Preparing data and setup for the FPGA program

This part is composed of 3 parts. The first one is shown below. Firstly, a reference to the FPGA target that will be used to run the specified FPGA program is set, see Fig. 4.5. This reference relates the Host Program with the FPGA hardware and FPGA Program. The reset part is used to resets the FPGA VI on the FPGA target to the default state of the VI. This method sets the FPGA VI controls and indicators to their default states, sets uninitialized shift registers to their default values, clears FIFOs, and sets global variables to their default values. However, this method does not reset memory.



**Figure 4.5 Set the reference** 

Then the data flow goes to the next block to transfer data to FPGA. FIFO and DMA is used to transfer data from host program to FPGA program. FIFO (First In First Out) is a kind of data buffer. The first data saved in the buffer will be firstly read out. Shown in Fig. 4.6, data 1, 2, 3 and 4 are written into the FIFO in sequence. When reading the FIFO, the first written data, 1, is first read out. Once 1 is read out, the pointer point to the data 2. The difference of the FIFO with the normal memory is that FIFO does not have the write and read address. The data stored in the FIFO are addressed by the inside data pointer. After one data is read out, the pointer goes to the next one automatically. When transfer a queue of data, FIFO structure is easier to operate compare to the normal memory. In FPGA, block memory, the LUT, or the flip-flops can be used as FIFO to store data. A register is used to point to the latest data.



Figure 4.6 FIFO working principle

DMA (Direct Memory Access) allows external hardware to access the system memory (read or write) without the interruption of the CPU. Without the DMA, CPU needs to copy data from the external device to the buffer and then write the data from the buffer to the new space. In this period, CPU is used by the transferring process and cannot process other tasks at the same time. When the DMA technique is used, CPU just needs to initialize the data transition before the transition begins. In the process of transition, DMA controller is used to manage and CPU can deal with other tasks. DMA FIFO is used in the LabVIEW to transfer data between the host PC and the FPGA target. A DMA FIFO allocates memory on both the host computer and the FPGA target; however, the 2 FIFOs act as a single FIFO. Before use the DMA FIFO the size of the FIFO (also called the depth of the FIFO) should be set. The depth of the host side FIFO and the FPGA side FIFO are set separately from the host program and the FPGA program. The default value for the hose side FIFO is 10,000 elements and 1024 elements for the FPGA side FIFO. The size of the host side FIFO and the FPGA side FIFO does not necessary to be equal, however, both of them should be big enough. If the FIFO is too small, new data will not be stored into the FIFO and blocked which will lead to the data loss. If the depth of the FIFO is too large, it will cause a waste of the memory resources.



Figure 4.7 Specifies the depth of the host memory part of the DMA FIFO 68

Category A	General
Data Type Interfaces	Name
	EWNS
	Туре
	Host to Target - DMA
	Requested Number of Elements
	8197
	Implementation
	Block Memory
	Actual Number of Elements
	8197
	Control Logic
	Slice Fabric 💌

Figure 4.8 FPGA side FIFO property dialog

Then the transfer direction of the DMA FIFO has to be set before using them. This is finished in the FPGA program, shown in Fig. 4.8."Host to target-DMA" means transfer data from host program to the target FPGA, vice versa. When the FIFO is set to be "Host to target-DMA", one or more elements can be written into the FIFO from the host program at once and only one element can be read out from the FPGA at once. Also the data type stored in the FIFO has to be set. The data type is 116 which is 16 bits integer and range from -32768 to 32767. FPGA just support signed and unsigned integers, Boolean and fixed point data type. Because of the complexity of fixed point data type, integer is the only data type used in the paper. 3 DMA FIFO in the calibration VI has been used. One is to transfer the driving voltages from host program to target FPGA, the other 2 are used to transfer the output of sensor from target FPGA to host program.

The data which are going to be transferred to the FPGA side is generated from the MATLAB script node, shown in Fig. 4.9. MATLAB software version 6.5 or later version is required to be installed on the computer to run MATLAB software script server to execute scripts written in the MATLAB language syntax. The output "E", "W", "N", "S" are the driving voltages which are 1 dimension array of double type and the output "initial" is the initial voltage which is also double

type. The double type data has to be converted into 16 bit signed integer to be accepted and processed by FPGA.



Figure 4.9 MATLAB script node

A subVI is used to convert the 1 dimension double array into 1 dimension 16 bit integer array. SubVI is a LabVIEW program which is used in another LabVIEW program which is similar to the subprogram in C language. In order to create a subVI, a connector pane and an icon should be built. The connector pane defines the input and output of subVI which is used to communicate with other nodes. The icon is the appearance of the subVI when it is used in other VIs.



Figure 4.10 Icon of subVi

The block diagram of the subVI is shown below. "Array" is the input to the subVI which is the 1 dimension integer array and "Array2" is the output which is the 1 dimension output array.



Figure 4.11 Block diagram of subVI

After the driving voltages are converted into integer, they are transferred to the FPGA. The DMA FIFO to perform the transition is named "EWNS". The driving voltages are stored in the FIFO in the sequence of  $V_E$ ,  $V_W$ ,  $V_N$ ,  $V_S$ , shown in the Fig. 4.12 below.



Figure 4.12 Write the host side FIFO





The second part of the host program is to obtain data from the FPGA, save the calibration result and synchronize with the FPGA target, shown in the Fig. 4.14 below.



**Figure 4.14 Perform the calibration** 

The flow chart of this part is shown below.



**Figure 4.15 Flow chart of calibration** 

This part of the program is in a big loop. In the loop, firstly the "Wait on IRQ" node is used to wait for the interruption request, see Fig. 4.16. It waits for the interruption request send from the FPGA. If it receives a request, the signal will goes to the next node; otherwise, it will wait until an interruption request has been received.



Figure 4.16 The "wait on IRQ" node

Once an interruption request has been received, the Read/Write Control Function will be executed, Fig. 4.17. This node can read the current variables from FPGA or write new values to the variables in FPGA. Here the 4 current driving voltages are read out.



**Figure 4.17 Read/Write Control Function** 

Then x axis readings and y axis readings are transferred to host program through the FPGA target to host DMA FIFO. The data from FPGA are 16 bit signed integer and need to be converted to double. Then a mean function is used to calculate the mean of the readings to reduce the noise interference. After the FIFO read node, a FIFO configure node is used to empty the host side FIFO and the FPGA side FIFO to prepare for the next time transfer.



Figure 4.18 The FIFO read and configure

Then the current driving voltages and the corresponding sensor readings are saved into a N by 6 array. N is the number of voltage combinations. The 6 columns are  $V_E$ ,  $V_W$ ,  $V_N$ ,  $V_S$ , X and Y. The program keeps loping until the voltage combinations has all be send out and the N by 6 array is saved into a Excle file.

#### 4.2.2 Calibration LabVIEW FPGA program

The FPGA program controls the analog output and analog input of the hardware. It can be programmed the same as the host program, however, it has to be compiled into bitstream file and transfer into the hardware structure on FPGA. The structure of the calibration FPGA program is shown in Fig. 4.19.



Figure 4.19 FPGA program structure

At the beginning of the program, the output voltages are initialized to the initial position defined in the previous chapter. Without the initialization, the output is random voltages which can be the value of last execution. The initialization is a precaution to protect the micromirror which is shown in Fig. 2.20. The nodes "North", "East", "South" and "West" are the analog output node which can control the analog output. The "initial voltage" is a variable which can be defined by the user from the host program before the execution of the program.



Figure 4.20 Initialization of the output

Then the driving voltage combinations transferred from host program will be saved into the FPGA block memory. FIFO is just a temporary media memory for the data transfer and it should be as small as possible to save FPGA resources. Sometimes the data amount needed to transfer is really large and needed to transfer several times. In this case, the FIFO will be cleared after each transfer to prepare for the next transfer. So the FPGA memory is used to save the data for later use. The flow chart of saving the driving voltages from FIFO to FPGA memory is shown in Fig. 4.21. 4 memory blocks are used to save the voltages, named as "East", "West", "north" and "South" and each memory block is arranged a sequence number from 1 to 4. The 4 memory blocks have the same storage (size) and address. The flow chat of saving the transferred data into the FPGA memory is shown in Fig. 4.22.



Figure 4.21 Writes the data from FIFO to FPGA memory

There are 3 variables used, n1, n2 and size.n1 is the memory address and n2 is the sequence number of the memory. The Labview program is shown in Fig. 4.23. Read FIFO node is used to read one data from the FIFO once it is called. Memory reference refers to the assigned memory block. Write memory node write the input data to the assigned address of the assigned memory block.



Figure 4.22 Saves data from FIFO into the FPGA memory flow chat 78



Figure 4.23 Saves data from FIFO into the FPGA memory diagram

# Chapter 5 Optical system of display and the prototype of HUD

#### 5.1 The optical system of display

The display optical system is first designed in SolidWorks and then set up on the optics breadboard, Fig. 5.1. Laser, pin hole, lens and the micromirror are the main element of the optical system. Post holders and the stages are used to tuning the light path.



Figure 5.1 The SolidWorks modeling of the optical system

• Laser

DPGL-05S-TTL modulated green laser from World Star Tech is used, Fig 5.2.



Figure 5.2 The laser module

The wavelength of the laser is 532nm. The beam diameter is smaller than 1.2mm and the beam shape is circle. The output power is 5mW which belongs to classIIIa. Laser belongs to this class normally would not produce a hazard if viewed directly for only momentary periods with naked eye. A hazard may be caused if viewed using collecting optics. This class is suitable for our application because the power is strong enough to form an image. After attenuated by several optical elements, the laser power will drop sharply. So lower class laser will lead to a low contract image. A higher class laser can hurt the human eyes if directly looked into which will have a potential safety problem. The operating voltage of the laser is 3.3V which is suitable for integration. The laser can be modulated by TTL input, low (0-0.8V), high (1-3.3V) from 0Hz to 3 kHz. In this case, when the laser spot is going along the traditional path it can be shut down. The laser power response to the modulation input is shown in Fig. 5.3. When TTL input is low, the laser is shut down and when TTL input is high, the laser has full power output.



Figure 5.3 The laser modulation [48]

#### • Pin hole

The diameter of the mirror plate of the micromirror is 1mm which is smaller than the diameter of the laser beam. If the laser beam shooting directly to the micromirror, the reflected spot may have some distortion and noise. 600um, 800um, and 900um diameter pin hole are tested to shrink the diameter of the laser beam, Fig 5.4. The smaller the pinhole diameter is, the smaller the laser spot is, and however, a smaller diameter pin hole will block more laser power. It has been proved that 900um pin hole has the same ability as the smaller size pin holes to reduce the reflected noise.



**Figure 5.4 Pinhole** 

• Lens

The double-concave anti-reflection lens with  $MgF_2$  coating is chosen to magnify the rotation angle. The anti-reflection coating performance is shown below Fig. 5.5. When shining with 532nm laser, approximately 1.3% reflection will be generated. The anti-reflection helps to reduce the laser light reflected back to the micromirror which will affect the display quality.



Figure 5.5 Coating performance of the lens [49]

The laser beam path is shown in Fig. 5.6. The laser diameter is firstly shrieked by the pin hole. The plane of the pin hole should be perpendicular to the laser beam and the center of the pin hole should be coincide with the center of the laser beam as much as possible to obtain a

larger output laser power. Once the laser and the pin hole are adjusted, their positions are fixed. Then the micromirror with the stages is positioned on the path of the laser beam. The angle between the micromirror and the incident laser beam is adjusted so that a smaller incident angel and be obtained. A large incident angle will result in a more distorted display. After the angle is fixed, the stage 1 is fixed on the optical breadboard. Stage 1 which adjusts the vertical position of the micromirror and stage 2 which adjusts the horizontal position of the micromirror are used to position the incident laser spot on the mirror plate. The tuning result can be observed on the screen which is positioned perpendicular to the reflected laser beam. If a clear circle spot is obtained, the position of the laser spot on the screen is marked. Then the concave lens is moved onto the path the emergent laser beam. The plane of the concave lens should be perpendicular to the laser beam and the position of the lens is adjusted so that the going through laser beam can shoot on the mark on the screen. Until now the position of the laser, pin hole, micromirror and the lens are fixed. When performing the calibration, the screen is taken place by the PSD. Stage 3 and stage 4 are used to adjust the laser spot lies on the center of the micromirror when it is not driven. The optical system on the optical breadboard is shown in Fig. 5.7.



Figure 5.6 Optical system 2D view



Figure 5.7 Optical system on the optical breadboard

#### 5.2 The image forming system of HUD

As discussed in chapter 1, basically there are 2 type of image forming system. One use the virtual image of display and the other use the real image of the display. Both of the image forming system of HUD are built and tested.

#### 5.2.1 Virtual image HUD

The HUD system is composed of 2 parts; the display module and the reflective plastic glass (see Fig 5.9). The display module integrates the optical system discussed in section 5.1into a small case which is more compact. The reflective plastic glass is a coated plastic glass from Defi-Link VSD X head up display module. It is used to form the virtual image. The setup of the virtual image HUD is shown in Fig. 5.9 and Fig 5.10. A real image is formed on a reflector fist. Then the real image on the reflector is mirrored by the coated plastic glass to form a virtual image in front of the screen. A projector is used to project a high way image on the screen as the background of the HUD. It is proved that the HUD can display a stable image in 40Hz. The

display result is shown in Fig. 5.11.



Figure 5.8 Display module and plastic glass [50]

The test system is shown below.



Figure 5.9 The setup of virtual image HUD



Figure 5.10 The side views of virtual image HUD setup



Figure 5.11 The display result of virtual image HUD

### 5.2.2 Real image HUD

A beam splitter coated glass is used for the real image display. The coating has 40% reflection of the visible light. A transparent Clearview film from ProDisplay is used to enhance the diffusion of the coated glass. The setup and the experiment result are shown below. The displayed real image is formed on the surface of the transparent glass.



Figure 5.12 The setup for the real image HUD



Figure 5.13 The display result of real image HUD

# **Chapter 6 Summary**

#### **6.1 Contributions**

(1) An electrostatic micromirror based laser vector HUD has been developed. The optical system is designed and tested for the display. The display module is composed of micromirror, laser module, pinhole and concave lens.

(2) The time response and frequency response of the electrostatic repulsive force driven micromirror have been tested. The settling time for each driven axis of the micromirror is about 800ms with 5% steady state error. When driven by step signal, the overshoot of the micromirror increase with the incensement of the step input. The frequency response shows that the micromirror has a resonant frequency about 800Hz. The measurements for time response and frequency response on different driving axes have similar results which prove the symmetry structure of the micromirror.

(3) An open loop control algorithm has been developed to perform the micromirror based laser vector display. 3 factors which affect the display quality have been come up with. Based on the 3 factors, the open loop control algorithm has been developed. 2 driving methods which are equally step driving and unequally step driving are tested and compared. Because of their characteristics, the equally step driving method is used to drive the laser spot move along the designed patterns points which are visible and the unequally driving method is used to drive the laser spot move along the transitional points which are invisible.

(4) The control system has been built. FPGA, because of its high speed is chosen to implement the control algorithm. A steady display of 40Hz can be obtained.

(5) The setup of 2 imaging methods for the head up display which are real image HUD and virtual image HUD are built and tested. The developed HUD has the feature of higher brightness and contrast, wider angle of view, smaller size and lower cost.

## 6.2 Future work

(1) The time response and frequency response test can only provide a rough model of the physical system which cannot be used for advanced control. A more accurate mathematical model can be built from the system identification experiments.

(2) Close loop control algorithm can be developed which can perform a much more accurate laser spot position control.

(3) The optical system virtual image HUD and real image HUD are needed to be improved to obtain a more clear display. A compact and easily adjustable display module is needed to be designed.

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