

**A PRECISION LASER SCANNING SYSTEM FOR EXPERIMENTAL MODAL
ANALYSIS: ITS TEST AND CALIBRATION**

by

Xinzuo William Li

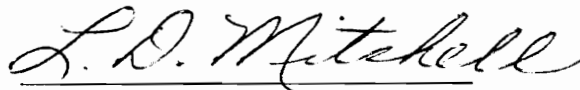
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MASTER OF SCIENCE

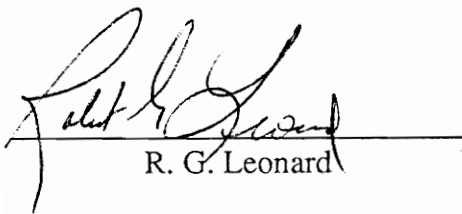
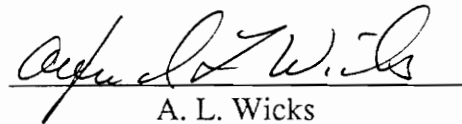
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(ABSTRACT)

The Laser Doppler Velocimetry technique has been widely used for dynamic measurements and experimental modal analysis. A laser scanning system that provides position accuracy, speed, and flexibility plays a key role in this technique. This thesis gives an overview of various laser scanning techniques and the requirements of a laser scanning system for the LDV and modal testing. The G3B/DE2488, a most-advanced galvanometer-based laser scanning system manufactured by the General Scanning Inc., is one of the most suitable laser scanning systems for the LDV and modal testing. The focus of this work was to test and calibrate such a scanning system to meet the requirements for modal testing. A new method to determine laser scanning angles was introduced. Based on this test method, a laser scanning system test rig was designed and constructed. To determine a laser beam scanning angle, the laser and scanner together were translated in a direction perpendicular to the target plane by using a micrometer-driven translation stage. The translation of the scanned laser spot at the target plane due to the translation of the laser-scanner unit was traced by a photodetector and another set of micrometer-driven translation stages that moved in the target plane. The laser beam scanning angle was calculated from the traveled distances of the laser-scanner unit and of the laser spot at the target plane. The test setup was used to determine the overall

performance of the G3B/DE2488 which included the scanning time and accuracy. The errors that affected the scanning accuracy were analyzed. Due to the relatively low precision and quality of the cost-constrained equipment used in the test setup, the accuracy of determining a scanning angle was not very high (around 50 μrad). However, if some high-accuracy and high-resolution equipment such as a beam profiler and a set of motor-driven stages are used, this test method has the potential to determine a laser beam scanning angle with an accuracy in the order of microradians.

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TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGMENTS	iv
LIST OF FIGURES	viii
LIST OF TABLES	xi
CHAPTER ONE	
INTRODUCTION	1
CHAPTER TWO	
LASER SCANNING SYSTEM FOR EXPERIMENTAL MODAL ANALYSIS	4
2.1. Modern Experimental Modal Analysis with Laser Technology	4
2.2. Laser Scanning Technology Overview	11
2.2.1 Refractive Deflectors	12
2.2.2 Reflective Deflectors	15
2.3. Scanning Parameters for LDV	23
2.3.1 Principal Scanning Parameters	24
2.3.2 Secondary Scanning Parameters	25
2.4. Selection of a Scanning System for Experimental Modal Analysis ...	26
CHAPTER THREE	
G3B/DE2488 GALVANOMETER-BASED SCANNING SYSTEM	28
3.1. System Description	28
3.1.1 The X-Y Scan Head	28
3.1.2 The Digital Electronics Scanner Control	34
3.2. System Control	38

TABLE OF CONTENTS (continued)

3.2.1	DE Software	38
3.2.2	Program IEEE-488 Interface Bus	45
3.3.	System Integration and Host Computer Programming	50
CHAPTER FOUR		
SCANNING SYSTEM TEST AND CALIBRATION		54
4.1.	The Needs for Test	54
4.1.1	Targets for Scanning Time and Accuracy	55
4.1.2	Scanning Time of the G3B/DE2488	59
4.1.3	Scanning Accuracy of the G3B/DE2488	61
4.2.	Methods of Testing Scanning Time and Scanning Accuracy	64
4.2.1	Scanning Time Test	65
4.2.2	Scanning Accuracy Test	66
4.3.	Construction of Test Setup	76
CHAPTER FIVE		
ERROR ANALYSIS FOR SCANNING ACCURACY TEST AND TEST RESULTS		81
5.1.	Errors in Scanning Accuracy Test	81
5.1.1	Errors in Laser Alignment	82
5.1.2	Error Due to Mirror Surface Offset	86
5.1.3	Error in Determining the Position of the Focused Laser Spot	90
5.1.4	Laser Beam Angular Drift Error	93
5.1.5	Non-orthogonality Error of the X and Z Translation Stages	100
5.1.6	Other Errors in the Scanning Angle Test	102

TABLE OF CONTENTS (continued)

5.2. Test Results for the Scanning Accuracy	106
CHAPTER SIX	
IMPROVEMENT OF TEST AND SCANNING ACCURACY	110
6.1. Improvement for the Test Accuracy	111
6.1.1 Reducing Uncertainty Error of Determining the Laser Beam Position	111
6.1.2 Reducing the Laser Beam Drift Error	118
6.2. Improvements for the Scanning Accuracy	120
6.2.1 Reducing the Laser Beam Parallel-Shift Error	120
6.2.2 Reducing the Nonlinearity Error of the Scanner	125
CHAPTER SEVEN	
CONCLUSIONS AND RECOMMENDATIONS	130
REFERENCES	133
APPENDIX A Example of "C" Program for Driving the G3B/DE2488 Scanning System Through the HP 9000 Computer	136
APPENDIX B Example of LabVIEW Program for Driving the G3B/DE2488 Scanning System Through the Macintosh Computer	138
APPENDIX C Test Results of the Scanning Time of the G3B/DE2488	141
APPENDIX D Photographs of the Setup for the Scanning Accuracy Test	150
APPENDIX E Measurement Data for G3B Position Sensor from General Scanning Inc.	153
APPENDIX F Scanning Angle Test Results for the X and Y Scanners	154
VITA	156

LIST OF FIGURES

Figure 2.1	Basic layout of a double-frequency Laser Doppler Velocimeter	9
Figure 2.2	The Bragg cell -- an acousto-optic beam deflector	13
Figure 2.3	Deflecting a ray of light by a mirror	16
Figure 2.4	Configurations of moving-iron and moving-coil galvanometers	20
Figure 2.5	Configuration of a differential capacitive rotary position transducer	22
Figure 3.1	X-Y scan head and target configuration	29
Figure 3.2	Statically and dynamically ideal mirror mounting	32
Figure 3.3	Block diagram of the DE2488	35
Figure 3.4	Simplified EDD closed-loop circuit diagram	37
Figure 3.5	X, Y coordinates of the scan field	41
Figure 3.6	Two examples of the DAC output with the same vector size	44
Figure 4.1	The worst case scenario of the position error arrangement	57
Figure 4.2	Position sensor nonlinearity plot of the X scanner	63
Figure 4.3	Position sensor nonlinearity plot of the Y scanner	63
Figure 4.4	Scanning angle test with multiple photodetectors	69
Figure 4.5	Errors in the distance measurements and scanning angle calculation	71
Figure 4.6	The parallel-shift method for the scanning accuracy test	74
Figure 4.7	Top view of the setup for the X scanner accuracy test	77
Figure 4.8	Top view of the laser-scanner unit	79
Figure 5.1	Setting the laser parallel to the X-Y bracket	83
Figure 5.2	Locating the axis of rotation	84
Figure 5.3	The parallel shift error of the scanned laser beam	87
Figure 5.4	Theoretical laser beam parallel-shift error for the X scanner	89

LIST OF FIGURES (continued)

Figure 5.5	Theoretical laser beam parallel-shift error for the Y scanner	89
Figure 5.6	Change of the laser energy due to the displacement of the pinhole	91
Figure 5.7	Measured thermal drift of the X scanner's servo and position sensor	94
Figure 5.8	Measured thermal drift of the Y scanner's servo and position sensor	94
Figure 5.9	Measured thermal drift of the laser beam without the scanners (Laser-scanner unit at vertical position)	97
Figure 5.10	Measured thermal drift of the laser beam without the scanners (Laser-scanner unit at horizontal position)	97
Figure 5.11	The effect of the laser beam's in the scanning angle test	99
Figure 5.12	The effect of the non-orthogonality error of the X and Z stages	101
Figure 5.13	The home-position of the laser beam is not parallel to the Z-axis	104
Figure 5.14	Nonlinearity plot for the X scanner from a typical set of test results	108
Figure 5.15	Nonlinearity plot for the X scanner from a typical set of test results	108
Figure 6.1	Configuration of a typical Keplerian beam expander with spatial filter	114
Figure 6.2	Determining the parallel-shift error of the scanned laser beam	122
Figure 6.3	Polynomial fitted curves of the measured data for the X scanner's position sensor	127
Figure 6.4	Polynomial fitted curves of the measured data for the Y scanner's position sensor	127
Figure 6.5	Plots of the residual position errors from Figure 6.3	129
Figure 6.6	Plots of the residual position errors from Figure 6.4	129
Figure B.1	Front panel of the LabVIEW program	138
Figure B.2	Block diagram of the LabVIEW program (1)	139
Figure B.3	Block diagram of the LabVIEW program (2)	140

LIST OF FIGURES (continued)

Figure C.1	Test results of the scanning time of the G3B/DE2488 (1)	141
Figure C.2	Test results of the scanning time of the G3B/DE2488 (2)	142
Figure C.3	Test results of the scanning time of the G3B/DE2488 (3)	143
Figure C.4	Test results of the scanning time of the G3B/DE2488 (4)	144
Figure C.5	Test results of the scanning time of the G3B/DE2488 (5)	145
Figure C.6	Test results of the scanning time of the G3B/DE2488 (6)	146
Figure C.7	Test results of the scanning time of the G3B/DE2488 (7)	147
Figure C.8	Test results of the scanning time of the G3B/DE2488 (8)	148
Figure C.9	Test results of the scanning time of the G3B/DE2488 (9)	149
Figure D.1	Photograph of the setup (1)	150
Figure D.2	Photograph of the setup (2)	151
Figure D.3	Photograph of the setup (3)	152

LIST OF TABLES

Table 3.1	The specifications and system performance of the G3B galvanometer scanner	31
Table 3.2	DE commands followed by an argument	39
Table 3.3	DE commands without arguments	39
Table 3.4	General bus management lines of the IEEE-488	47
Table 3.5	Handshake lines of the IEEE-488	47
Table 3.6	List of IEEE-488 commands	49
Table 4.1	The allowed scanning angular error for various sample resolutions	59
Table 5.1	Calculated thermal drift of the servo and position sensor of the scanners	95
Table 5.2	Test results of some errors that affect the scanning accuracy	106
Table 6.1	The coefficients of the polynomial fitting for the X and Y scanners	128
Table E.1	Scanning angle test results for the X scanner	154
Table E.2	Scanning angle test results for the Y scanner	155

CHAPTER ONE

INTRODUCTION

The traditional method of experimental modal analysis is to place an accelerometer on each point of the structure that is of interest, in order to measure the dynamic responses of the structure undergoing shock or vibration. This method makes it possible to obtain only a limited number of data points, thus providing incomplete modal information, and sometimes even a false modal shape. Attaching and removing the accelerometers are extremely time consuming procedures. The contacting nature of this method adds mass and local stiffness to the structure. As the accelerometer moves around the structure, the structure's dynamic characteristic changes. In a number of cases, this modal analysis method is not applicable, for instance on high-temperature structures, rotating subjects, or structures that are just too small or too vulnerable to mass load to have the accelerometers attached as they will change the system dynamics.

As the laser technology advances, laser interferometry techniques for non-contacting modal testing have been rapidly developing. The most popular laser interferometry techniques for dynamic measurement are holographic interferometry, speckle interferometry, and heterodyne interferometry. Among laser interferometry techniques, the Laser Doppler Velocimetry (LDV) using the heterodyne interferometry has the most flexibility in use over other techniques. The LDV technique, using a focused laser beam, measures surface velocities of a vibrating object. This technique not only eliminates almost all shortcomings of the traditional method, but also expands the potential applications of modal testing. Nevertheless, the LDV technique requires a laser scanning system that can provide positioning accuracy, speed, and wider applications.

The laser scanning techniques have made great progress since the invention of the laser. Acousto-optic, rotating polygon mirror, and low inertia galvanometer scanning techniques are some of the well-known techniques. The focus of this work is to select a laser scanning system for modal analysis and to develop a procedure for testing and calibrating the system. The principal scanning parameters for the LDV are maximum deflection angle, scanning resolution, scanning time, positioning accuracy, and cost. The general requirements of the scanning system for the LDV and modal testing are high positioning accuracy, high scanning resolution, random accessibility, wide scanning angular coverage in 2-D, fast response and settling times, compact size, and low cost. Among these requirements, high positioning accuracy is perhaps the most troublesome one. It is affected by a number of error elements, such as nonlinearity, repeatability, thermal drift, and optical aberration. The LDV using collinear laser and detector geometry can only measure the velocity of a vibrating object along the line of sight of the laser beam. The velocity vectors that are related to the object have to be determined from scanning position data. In order to have an accuracy comparable to that of the traditional accelerometer method, the laser scanning system for modal analysis needs to have an absolute positioning accuracy of $158\text{ }\mu\text{rad}$ (this will be justified in Chapter Four of this thesis). Such tight specification pushes even the most advanced laser scanning systems to their limits. In most cases, a scanning system calibration is inevitable if the accuracy requirement is to be met.

Contrary to the laser and laser scanning techniques, systematic testing and calibrating techniques for a scanner system are still almost nonexistent. Some scanner manufacturers use optical encoders to calibrate rotary position sensors, but they are unable to identify the overall scanning system performance. This work presents a new method to test and calibrate a scanner system. This method makes it possible to

determine absolute positioning accuracy in the X and Y directions. The drift, repeatability, or linearity of the scanner system can also be obtained. The other features of this testing method are relatively low cost and the possibility of upgrading to automated scanning system calibration.

Chapter Two gives an overview of modern experimental modal analysis with laser technology. The principles of various laser scanning techniques are introduced, along with their features and limitations. The scan parameters for LDV and modal testing are stated and evaluated. The best scanning system is selected to fulfill the scanning requirements for modal testing. In Chapter Three, a state-of-the-art galvanometric scanning system is introduced. This scanning system is manufactured by General Scanning Inc. and is considered to be one of the best of its kind. The hardware, software, and system control are fully described. Chapter Four discusses the scanning time and accuracy of the laser scanning system that are the most important issues for the LDV and modal testing. The needs for the scanning time and accuracy tests are addressed. A new method to test and calibrate the scanning system is presented. The construction of the test setup and the testing procedure, along with the test results of the scanning time, are covered in this chapter. Chapter Five analyzes the sources of errors in the scanning accuracy test and the influence of those errors upon the testing results. The test results of the scanning accuracy are discussed. Chapter Six proposes possible ways to effectively reduce the testing errors and improve the scanning accuracy. Chapter Seven is the conclusion that gives an objective overview of the scanning system and the test setup. The necessary improvements of the test setup for an ultra-high test accuracy are recommended with the costs.

CHAPTER TWO

LASER SCANNING SYSTEM FOR EXPERIMENTAL MODAL ANALYSIS

The advanced laser interferometry techniques have been widely applied to experimental modal analysis and other areas. Understanding the experimental modal analysis and the principle of the laser interferometry for dynamic measurement is essential for selecting a laser scanning system. This chapter provides a brief introduction to the experimental modal analysis and the laser interferometry techniques, as well as an overview of laser scanning techniques. The scanning parameters for modal testing are stated, along with their importance and trade-offs. After all the techniques have been evaluated, the best selection of a scanning system is made for modal testing.

2.1. Modern Experimental Modal Analysis with Laser Technology

The dynamic responses of a structure undergoing shock or vibration which include the natural frequencies of the structure and the acceleration, velocity, and displacement of each point on the structure are of interest in the experimental modal analysis. One of very important dynamic characteristics is the mode shapes of the structure. The traditional method of modal testing is to attach a transducer to each significant point of the structure [1]*. The transducer most widely used for modal testing is the piezoelectric-type accelerometer. The internal mass of the accelerometer applies an inertial force to the piezoelectric crystal. When the crystal is strained, it generates a charge proportional to the applied force that is also proportional to the acceleration of the point to which the accelerometer is attached. This method, along with impulse or random force input, has

* Numbers in brackets refer to references listed at the end of this thesis.

been the primary means of determining the frequency response function of the structure. Using transducers is very effective for obtaining transient dynamic response of the structure. However, this traditional method has several disadvantages. First, the contacting nature of the transducer adds mass and local stiffness to the structure. This will introduce errors into the structure's modal parameters, especially for relatively small structures or higher modes. Second, it is not practical to have a large number of testing points due to the amount of time needed to mount, remove, and clean off the transducers. A limited number of testing points cannot provide adequate information for complex mode shapes. Third, this method cannot be easily applied to the structure that is rotating, has high temperature, or is just too small. Lastly, it is difficult to obtain consistent test results due to the way in which the transducers are mounted and selected.

The invention of coherent laser radiation in the 1960s [2] led to revolutionary changes in modal testing. For the past two decades, laser interferometry techniques have been rapidly developed and widely applied to the structure displacement and vibration measurement [3 - 6].

Interference between two light waves which have different propagation directions, different phases, or different frequencies is due to the construction and destruction of the light waves. Most laser light sources provide stable and coherent light waves in both spatial and temporal domains that are necessary for the interference pattern to remain stationary in space. Forming, recording, and analyzing of the interference patterns constitutes the basis of the laser interferometry techniques. The most commonly used laser interferometry techniques for dynamic measurements are holographic interferometry, speckle interferometry, and heterodyne interferometry.

The holographic interferometry and the speckle interferometry are related and work in very similar ways. Both techniques use expanded laser light to illuminate a part or the

whole object on the surface of which displacement is to be measured. The light scattered from the original and from the deformed object surface are interfered to form a visible fringe pattern on the object surface. The fringe pattern of the holographic interferometry represents the contour lines of the phase change of the scattered light due to the surface displacement. The fringe pattern of the speckle interferometry represents the contour lines of the constant amplitude of the surface displacement. From analyzing the fringe pattern, both in-plane and out-of-plane displacements of the object can be determined with a resolution of the wavelength of light [7]. With time-averaged holographic interferometry or speckle interferometry, the deflection shape of the vibrating object can be easily obtained with the amplitude but without the phase information of the vibration. With stroboscopic or dual pulsed laser techniques, the holographic interferometry and speckle interferometry can determine both the amplitude and the phase of the vibration in both periodic and non-periodic cases [7]. The advantages of the holographic interferometry and the speckle interferometry techniques are that both are non-contact, possess inherently high resolution, require no laser scanning system, can be used to measure both in-plane and out-of-plane motions, and can perform measurements in real time. They also have severe disadvantages. To obtain a proper fringe pattern is not easy. It requires precise setup of the system and extreme stability in the order of wavelength of light. The object must be excited properly, with limited magnitude of surface displacement, but without rigid body translation. The laser output power must be sufficiently large, which is not only expensive but also not safe. The maximum observable area for each setup is limited by the amount of laser power available. After the fringe pattern has been obtained, the process of interpreting the fringe pattern can

also be very complicated and difficult, especially separating the in-plane and out-of-plane components of the motion, since they are both contained in the fringe pattern. The other problems include the errors due to the aberration of the optical system and nonlinearity of the recording medium.

The heterodyne interferometry results from the superposition of two light waves with slightly different frequencies. The intensity of the superimposed light wave is modulated at a beat frequency that is the difference between the two original frequencies. A photodetector then can be used to convert the modulated intensity of the light wave to a sinusoidal electrical signal. So in the heterodyne interferometry, no fringe pattern can be actually seen by the human eye, since the interference occurs in temporal domain rather than in spatial domain. The best known application of the heterodyne interferometry is perhaps the LDV.

LDV, based on the heterodyne interferometry and the Doppler effect, is fast becoming one of the most popular techniques for dynamic measurement (more precisely velocity measurement). The Doppler effect is the frequency shift (also called Doppler shift) of the scattered light from a moving particle or surface that is illuminated by a laser beam. The amount of the frequency shift is proportional to the velocity of the scattering particle or surface. The frequency-shifted light is scattered from the object surface and is collected by optical lenses. Then it comes back through the same optical path as that of the measuring beam and combines with a reference beam that has the original or a known frequency to produce the heterodyne interferometry. By using a photodetector and advanced signal processing techniques, this Doppler frequency can be accurately determined; then the velocity of the scattering particle or surface can be calculated according to the following equation:

$$V = \Delta f \frac{\lambda}{2}, \quad (2.1)$$

where V is the velocity of the particle or surface along the line of sight of the measuring beam, Δf is the Doppler frequency, and λ is the wave length of the measuring beam.

A number of techniques have been developed along with the LDV for different applications and the improvement of the accuracy [8-10]. The most popular one is the double-frequency technique, which can reduce the low-frequency noise of the measurement. Figure 2.1 shows a simplified layout of a double-frequency LDV. In this technique, two optical frequencies, f_1 and f_2 , of the laser beam are a few MHz apart. They can be produced either by a dual-frequency laser or by a frequency shifting device such as a Bragg cell. The optical frequency laser beams are each polarized in opposite directions so that a polarizing beam splitter can separate them. Two photodetectors are used to pick up the reference signal ($f_2 - f_1$) and the Doppler shifted signal ($f_2 - f_1 \pm \Delta f$). In most cases, additional detectors are used for extracting phase information to determine the direction of the motion. The technique used in the Ometron's scanning LDV for modal testing, which is currently used in our modal laboratory, uses a single-frequency laser. However, the basic principles of a single-frequency LDV and a double-frequency LDV are the same; i. e., Equation (2.1) applies.

For over a decade, the advances in the laser technology, optical detectors, and signal processing has improved LDV relative to over other dynamic measurement and modal testing techniques. Some of these advantages are as follows:

- The non-contact and non-destructive nature of the LDV imposes virtually no limit on the types or sizes of the objects to be measured.
- Since no mass or local stiffness is added to the object, the dynamic characteristic of the object is preserved.

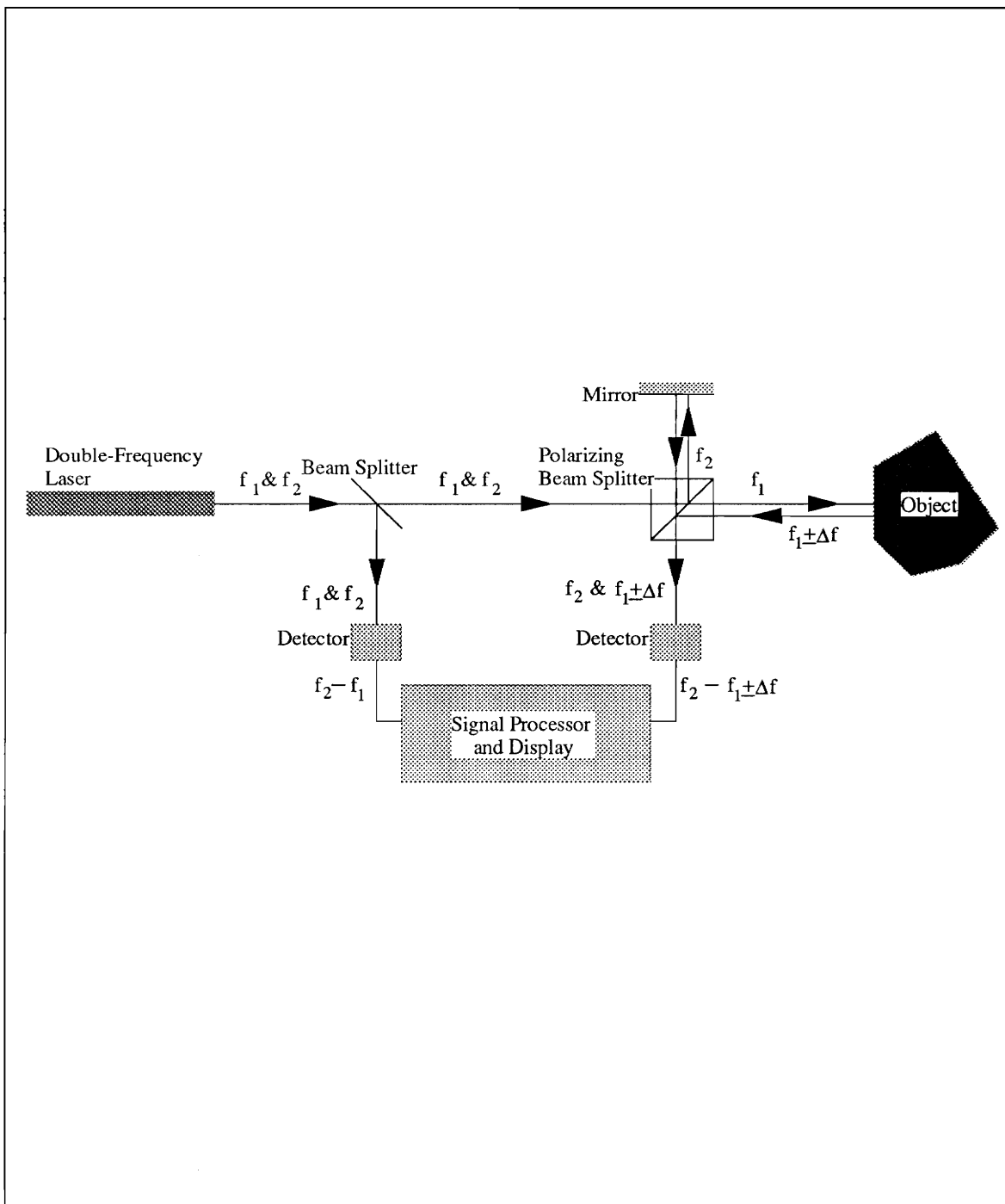


Figure 2.1 Basic layout of a double-frequency Laser Doppler Velocimeter

- The measuring laser beam is focused onto the object instead of being expanded to illuminate the object, so a small power laser can be employed and a long-distance measurement can be attained.
- The LDV has no fringes to be interpreted, so a very high accuracy within 1% and a wide dynamic range (frequency from near DC to a few hundred kHz and displacement amplitude from 10^{-9} to 10^{-1} m) can be obtained.
- The LDV has no special requirement for stability or vibration isolation for the system, so it is easy to set up and it is relatively portable.

As other techniques, LDV has some disadvantages, too:

- The main disadvantage is that it requires a laser scanning system for the full-field measurement or simply positioning the measuring beam to any spot on the object.
- The spatial resolution, the accuracy of the velocity vectors, and the speed of measurement depend on the scanning system.
- Since the Doppler frequency shift that is used to extract dynamic data is caused by the relative motion of the tested object with respect to the scanner, any correlated vibrations of the scanner and the tested object can have effect on the data extraction.
- The high-performance laser scanning system and electronics for data processing are expensive.

Clearly, a laser scanning system is critical for the LDV technique to excel in modal testing. And it has some different requirements from other applications:

- Since the measuring beam and scattered light both go through the scanner and since the frequency and phase of the light are the primary measurement data, the scanner should preserve the frequency and phase information carried by the measuring beam and the scattered light.

- The spatial resolution and the full-field area of the measurement depends on the scanner. So, naturally it is desirable for a scanner to have wide scanning angles and a high angular resolution, yet remain compact in size.
- The scanner system should have good flexibility, and not only be able to perform raster scan in both X and Y directions but also to position the laser beam to any random spot on the object within the scanning field for setup and gain setting purposes.
- In order to allow accurate determination of the velocity vectors in 3D and measurements comparable with those of the accelerometer, the absolute positioning error of the scanner, which includes non-repeatability, drift, and non-linearity, must be kept as low as possible.
- In order to ensure that the detectors and signal processing system have adequate time to obtain valid velocity and phase data, a dwell time is needed at each measured point; thus a low-inertia scanner with short traveling and settling times is desired for fast full-field measurements.
- The first torsional resonance frequency of the scanner should be at less five to ten times higher than the scanning rate for fast scanner settling.

2.2. Laser Scanning Technology Overview

A laser beam consists of photons traveling in waveform at the speed of light. Since the photon conveys no net electric charge, unlike an electron beam, the laser beam cannot be deflected by electric or magnetic fields directly. Rather, the direction of a laser beam can be altered by reflection, refraction, and diffraction. The research in laser scanning techniques has been very active for the past couple of decades as the laser technology has

been advancing. Most scanning techniques can be categorized into two groups: refractive deflectors and reflective deflectors.

2.2.1 Refractive Deflectors

The speed of light in a material medium, such as water, crystal, or air, differs from the speed of light in a vacuum. The ratio of the speed of light in a vacuum over the speed of light in a medium is defined as the refractive index of the medium. When a beam of light penetrates a surface that is a boundary for two different refractive indices with an angle, the direction of the beam will be altered according to the law of refraction. Some crystals exhibit significant change of the refractive index under the influence of an electric field, sound wave, or simply just light. Modulating the refractive index of crystals to alter the direction of a laser beam is the basic concept of acousto-optic, electro-optic, and opto-optic laser scanning techniques [11-15].

Figure 2.2 illustrates an acousto-optic beam deflector, also known as the Bragg cell. In the Bragg cell, the refractive index of a suitable crystal is locally varied by a strong acoustic wave generated at radio frequency by an acoustic transducer to form a thick moving diffraction grating, with the grating pitch equal to the acoustic wavelength. When a laser beam passes through the diffraction grating, it will be diffracted into a number of beams, which are identified by orders. The zero-order beam is the undiffracted beam. The angle of a diffracted beam, θ , is given by

$$\theta \cong \sin(\theta) = m \frac{\lambda}{\lambda_a} \quad (2.2)$$

where m is the diffracted order, λ is the wavelength of the incident laser beam measure in air, and λ_a is the acoustic wavelength in the crystal. The acoustic wavelength can be controlled by varying the frequency of the radio frequency oscillator.

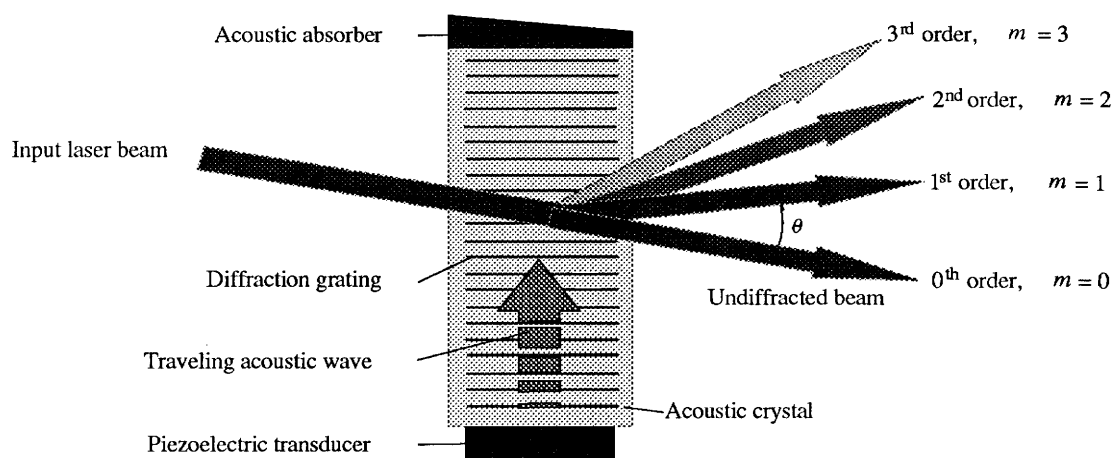


Figure 2.2 The Bragg cell -- an acousto-optic beam deflector

The intensity of the different orders of the diffracted beams is a function of the intensity of the acoustic wave and the physical properties of the crystal. For a well-aligned Bragg cell, higher-order beams can be suppressed so that most of the incident beam intensity (about 85%) is diffracted into the first-order beam. The laser scanning is achieved by controlling the radio frequency generated by the transducer to change the diffraction angle of the first-order beam.

The main advantages of the acousto-optic deflector are that it contains no moving parts, has fast response time, and is compact. The big disadvantage is small obtainable deflection angles for a single deflector, only a degree or two. The non-linearity of the crystal and the change of the refractive index due to the strain or temperature changes can severely reduce the scanning accuracy. However, two main problems prevent the acousto-optic scanner from being the candidate for the LDV. The first problem is the frequency and phase shifting of the deflected laser beam (this certainly is not a weakness if the Bragg cell is to be used as a frequency modulator). The second one is the irreversible optical path for the scattered light coming back through the scanner.

The technique of opto-optical beam deflection is very similar to that of acousto-optic beam deflection. The diffraction grating is generated by two ancillary interfering coherent light beams, instead of an acoustic wave, in a crystal that exhibits the photorefractive effect. The diffraction angle of the useful beam is changed by altering the frequency of the ancillary light beams. Compared to the acousto-optic deflector, the diffraction efficiency and response time for the opto-optic deflector are very low, and the ancillary equipment is too complex for the practical application.

In all materials, the polarization will be changed by an applied electric field, and this results in a linear change of the refractive index in some crystals. This is called electro-optic effect, and it is the base of electro-optic scanning techniques. In an electro-optic

deflector, two or more prisms made of the same material are stuck together. They are arranged so as to have opposite changes in polarization when an electric field is applied. The combined effect of this arrangement is that when an expanded laser beam passes through the deflector, the wavefronts will be linearly tilted due to linear variation in the refractive index. The scan of a laser beam is achieved by changing the voltage of the applied electric field, which is proportional to the deflection angle. In the real world, electro-optic techniques have found more applications in beam modulation, mainly in modulating phase and/or amplitude of the laser beam, than in beam deflection. This is because the electro-optic deflector not only suffers from most of the same shortcomings that the acousto-optic deflector has, but also has the high voltage problem. Since the maximum refractive index change for a crystal is generally limited to 10^{-3} , a high voltage (up to a few kilo-volts) is needed to obtain the electro-optic effect for deflecting a laser beam.

2.2.2 Reflective Deflectors

Most reflective deflectors involve moving mirrors. The concept is old and simple: a ray of light incident upon a mirror will be reflected with the reflection angle equal to the incident angle; and when the mirror surface is rotated perpendicularly to the incident beam by an angle α , the reflected beam is rotated by 2α (Figure 2.3). However, designing and manufacturing the scanners to fulfill the scanning requirements could be quite complicated.

The mirrors are usually made of glass, silicon, or light metals with highly reflective coatings. The type of coating for a mirror mainly depends on the wavelength of the laser beam, the reflectivity requirement, and the cost. Most mirrors for laser scanners are

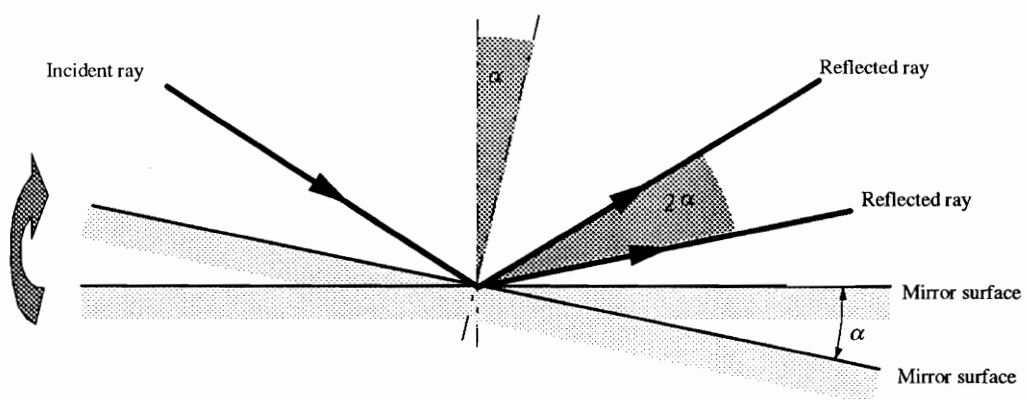


Figure 2.3 Deflecting a ray of light by a mirror

either first surface plane mirrors or multifaceted polygonal (or pyramidal) mirrors. Plane mirrors are mostly used in slow and discrete scanning, while multifaceted mirrors are used in fast and continuous line scanning. Mirror surface flatness and geometric precision of the multifaceted mirror are the primary concerns for a mirror.

For a reflective deflector, the mirror-driven device is the most important component. Most commercial scanners are driven by motors, piezoelectric transducers, or galvanometers.

DC motors are usually used to drive high-inertia multifaceted mirrors for line or raster scanning. Supposing the polygon mirror has n facets, for each motor rotation the laser beam makes n unidirectional line scans. The full-field scanning angle is $4\pi/n$ for a prismatic polygon scanner and $2\pi/n$ for a pyramidal polygon scanner. A motor speed of several thousand rpm is common and easy to be obtained (some motors can run up to 150,000 rpm) [16]. Therefore, high scan speed and wide scan field are the main features of rotary polygon scanners. The other features include high scan resolution, constant scan angular velocity, low light loss, and relatively simple electronic control. However, this type of scanner is not suitable for random access or subraster positioning due to the high inertia. The high speed and high inertia not only shorten the life of the bearings but also cause wobble and jitter problems. In general, the scanning accuracy is relatively low because of the difficulties in precise fabrication, assembly, and balancing [17]. For two-dimensional raster scan, an auxiliary scanner is needed.

A quite popular type of scanner that works the same way as the polygon scanner is the rotating-hologram scanner [18]. Although holographic scanners deflect a laser beam in a different manner from the polygon scanners, the same high-speed multiple-line scan format makes these two types of scanners have similar applications. That is the sole reason for the holographic scanner to be categorized as a reflective scanner and to be

discussed here. Holographic scanner uses hologram gratings instead of mirror facets. As in the case of a multifaceted polygon mirror, several hologram gratings are mounted on the surface of a flat disc or on the facets of a pyramidal polygon wheel. The hologram can be either diffractive or reflective, which depends on the process of the hologram. From the holograph principle, the input beam that acts as the reconstruction light is normal to the hologram surface for the self-conjugates of the original reference light used in the process of the hologram; the deflected output beam then is the reconstruction of the original object light. The hologram can not only deflect a laser beam but also focus it. The main advantages of the hologram spin head over the polygon mirror are lower inertia, easier manufacturing and assembly, and lower cost. The shortcomings are light loss (up to 20%) and aberration because of the difference between the input beam and the original reference beam.

Stepping motors and brushless servo motors are used to drive a polygon mirror or a plane mirror. With a low inertia plane mirror, stepping motors and servo motors can provide very flexible scanning, which includes random access and full-turn scan. A standard stepping motor has a full step size of 1.8° . Some sophisticated electronic microstepping drivers can produce up to 50,000 microsteps per full 1.8° step. Unfortunately, the typical positioning accuracy of the motor is limited to about $\pm 5\%$ of one full step, or 0.09° due to the errors in manufacturing and assembly [19].

Piezoelectric transducers are used to steer a laser beam when only a small deflection angle but high resolution and high accuracy are required. Piezoelectric effect, which is the deformation of the micro structure of a material caused by an applied electric field or vice versa, has been found in some ceramic materials. A typical configuration of the piezoelectric scanner is comprised of two slices of piezoelectric ceramic material and a plane mirror. The two ceramic slices are bonded together, with one end fixed and the

other free. When opposite electric fields are applied to the ceramic slices, the piezoelectric effect causes one to expand and the other to contract, so that the combined effect bends the assembly and deflects the mirror that is mounted on the free end. The deflection of the mirror is proportional to the voltage applied. The features of piezoelectric scanners are high frequency, high resolution and accuracy, compact size, and long life. The main drawbacks are small deflection angle ($1^\circ \sim 2^\circ$) and high voltage required [20].

Galvanometers have been the primary driving devices for low inertia scanners that use a small plane mirror. The scanning format can be vibratory, continual, or discrete [21]. Galvanometers come with two basic designs: moving-iron and moving-coil (Figure 2.4).

In a typical moving-iron galvanometer, the rotor and the stator are made of the ferric alloy with high magnetic permeability. Two magnets at each side of the rotor create a bias magnetic field to line up the rotor. When electric current passes through the driving coil windings, it produces a new magnetic field. The combined actions of the permanent magnets and drive coil windings are additive at one pole and subtractive at the other; thus, a torque proportional to drive current is generated to the rotor. A mechanical torsion bar is usually attached to the end of the rotor. The equilibrium of the magnetic torque and mechanical torque defines the angular position of the rotor. The rotor can rotate up to 60° peak-to-peak, which produces an optical scanning angle of 120° [20]. The resolution of galvanometers is mainly determined by the electronic drivers. Moving-iron galvanometers have a very high torque-to-inertia ratio, which causes high acceleration and short traveling time. However, high electrical inductance generated in the closed-loop stator reduces the rate of current change [22].

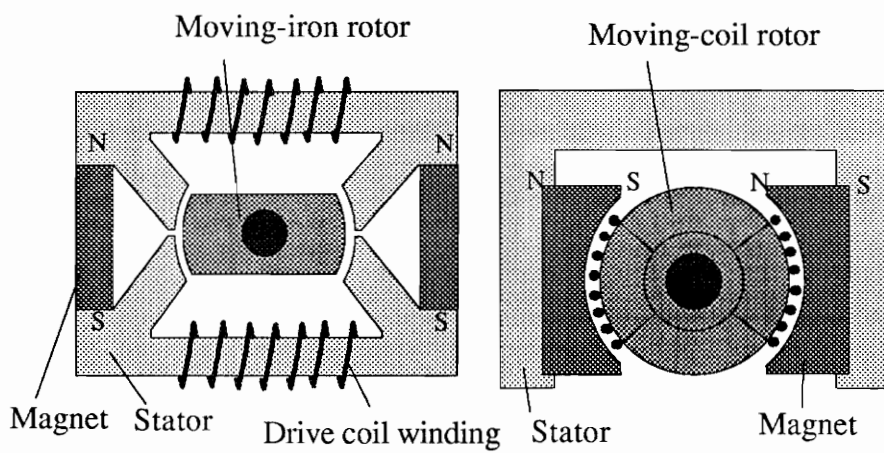


Figure 2.4 Configurations of moving-iron and moving-coil galvanometers
(Adapted from [22])

The very first moving-coil galvanometer was invented one and half centuries ago. Modern technology, especially the introduction of ultrahigh-energy-density permanent magnetic materials, gives the moving-coil technique a very promising future for low-inertia laser scanners. A moving-coil galvanometer is comprised of a stator with two permanent magnets and a rotor with two drive coil windings. When the input current passes through the coil windings, it generates a magnetic field that interacts with permanent magnets. This interaction produces a torque and deflects the rotor. Since the airgap between the rotor and stator is much larger for the moving-coil galvanometer than for the moving-iron galvanometer, a higher magnetic flux density is needed for moving-coil galvanometer to generate sufficient torque. Using the new ultrahigh-energy-density permanent magnetic materials instead of large current may give the moving-coil galvanometer a better performance than that of the moving-iron galvanometer. In general, the former has lower rotor inertia, higher maximum torque, and much shorter electrical time constant than the latter.

Galvanometers alone cannot provide high scanning accuracy. A precise rotary position transducer is the key element. There are two basic types of rotary position transducers: analog and digital. The most common analog position transducers used with galvanometers and servo motors are either inductive or capacitive. They work in very similar ways, but the capacitive position transducer is more favorable because of its immunity to the interference of the drive magnetic circuit. Figure 2.5 represents a typical configuration of a differential capacitive rotary position transducer. This type of capacitive position transducer has very low inertia and compact size. Its resolution can be as high as $1\text{ }\mu\text{rad}$ [22]. However, its accuracy suffers from nonlinearity and thermal drift, although the most advanced capacitive sensor is claimed to have an accuracy as high as $0.5\text{ }\mu\text{rad}$ [23]. Magnetic pickups and optical encoders are the most common digital rotary

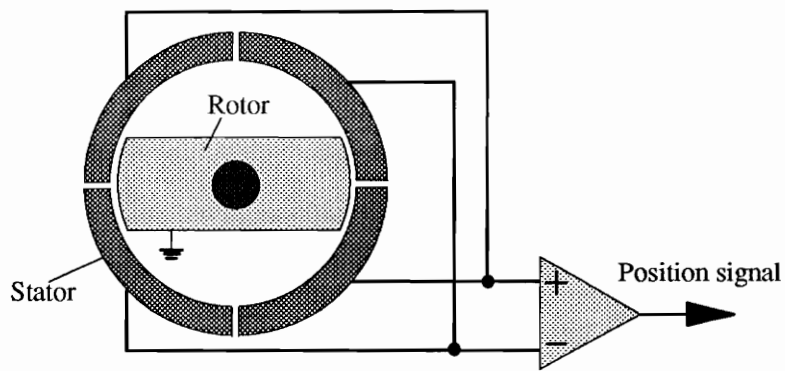


Figure 2.5 Configuration of a differential capacitive rotary position transducer

position sensors. Magnetic pickups have very low resolution and accuracy, so they are usually used for sensing motor rotating speed. The most advanced optical encoders can have resolution up to 2^{22} per revolution, or $1.5 \mu\text{rad}$, although their speed is generally very low for the correct position detection. Since optical encoders detect the rotary position in digital format, the nonlinearity and temperature problems accompanied by capacitive position sensor are not a concerns for them. But they are not suitable for galvanometers due to their high inertia and large size. Most of high resolution optical encoders have a diameter of 6 to 10 inches.

For X-Y scanning, generally two techniques are used. One is to use a scanner scanning in X direction and to let the object or the scanner travel in Y direction. An example of this technique can be found in a laser printer. The other technique is to use a pair of scanners that are set orthogonally to each other and deflect the beam in X and Y directions independently. The most common configuration of a commercial 2D scanner is a polygon scanner with a galvanometer scanner or two galvanometer scanners. The two-scanner configuration is more complicated, but more flexible than the single-scanner configuration. There is a variation of the two-scanner configuration: one motor is used to drive a plane mirror, and another larger motor is used to drive the first motor and the same mirror, where the rotating axes of the motors are orthogonal to each other. This type of configuration makes laser alignment simple but adds tremendous inertia to the second motor, which increases dynamic errors and slows down the scanning rate.

2.3. Scanning Parameters for LDV

Scanning parameters are the bases for the selection of a scanner. The weight of each scanning parameter usually varies with the applications. Sometimes they may be defined

differently for different applications. Scanning parameters for LDV can probably be divided into two groups: principal parameters and secondary parameters.

2.3.1 Principal Scanning Parameters

The principal scanning parameters are the most important factors for scanner selection.

Maximum deflection angle α : the excursion of the deflected laser beam. This parameter is mainly determined by the scanner. For the mirror surface parallel to the rotating axis and the input beam perpendicular to the rotating axis, the maximum rotation of the mirror surface is half of α . A larger α is usually desired because it can cover more surface of the object with single setup or make the distance between the scanner and the object shorter. The trade-offs for a large α are increases in the size of mirrors and in nonlinearity errors and decrease in scanning resolution.

Scanning resolution $\Delta\alpha$: the smallest beam deflection angle. This definition is different from the conventional definition of the scanning resolution, according to which it is the ratio of laser spot displacement to spot diameter. Although the scanner may impose a limit on the scanning resolution, it depends on the scanner drive in most cases. Just as the maximum deflection angle, $\Delta\alpha$ is twice of the minimum resolvable mirror surface rotation, or the step size. A small $\Delta\alpha$ is beneficial to the scanning precision and accuracy, and to the stability of the servo control. But high scanning resolution could make the scanning system much more complicated and very expensive.

Scanning time T : the total time needed for the beam to travel a given angle. Again, this is different from the conventional definition of scanning speed of scanning frequency. The scanning time includes the response time of the drive, the scanner traveling time, and the scanner settling time. This parameter is determined by the

combination of data transmission rate, D/A converter time, electrical time constant of the scanner, scanner torque, rotor and mirror inertia, position sensor response time, and electrical and mechanical damping. Shorter scanning time can help the LDV to obtain consistent data, since the dynamic responses of the object may be affected by the changes of room temperature or the instability of the exciting force. The excessive heat created by the high speed scanning may need additional cooling, or otherwise it may damage the scanner or reduce the accuracy of the position sensor.

Scanning accuracy: the closeness to a given position in space that the beam can be deflected to. This parameter is one of the most important scanning parameters for LDV and is primarily dominated by the position sensor of the scanner. It is affected by a number of error sources, such as nonlinearity, non-repeatability, thermal drift, wobble and jitter, mirror mounting, optical distortion, and non-orthogonality for X-Y scanning. Clearly, scanning accuracy can never exceed scanning resolution. High cost, slow scanning speed, and large size are usually traded for high scanning accuracy.

Cost: this includes the scanning system cost and the maintenance cost. This is always the important element for the selection of a scanner. However, if the scanning accuracy and speed cannot be compromised, there is little one can do to decrease the cost.

2.3.2 Secondary Scanning Parameters

The secondary scanning parameters are not as critical as the principal parameters. However, they also affect scanner selection.

Pupil diameter D : the diameter of the largest collimated beam that can pass through the scanner at all deflection angles. The maximum deflection angle and the mirror size determine the pupil diameter. A large diameter of an expanded beam not only reduces the laser power density to avoid damaging optics, but also reduces optical aberration, laser

beam divergence, and focused spot size. A large D requires a large mirror size; this will increase inertia and scanning time.

Resonance frequency: the first torsional resonance frequency of the system. This parameter may limit the scanning rate. By rule of thumb, the maximum scanning rate should be less than 20% of the first torsional resonance frequency of the system.

Overall size and weight: usually only the scanner part needs to be considered. In most cases, this parameter is not critical. Compact size is good for handling and mobility.

Power requirement: the electrical power consumed by the scanner and scanner drive. Low power dissipation means less heat generated, and it is desired for the scanning system stability.

Life expectation: how long or how many numbers of operations each component can last. This parameter may be related to environment. One question that should be considered is how often system calibrations are needed.

2.4. Selection of a Scanning System for Experimental Modal Analysis

From the first section of this chapter, it is evident that the LDV technique has a number of advantages over other laser techniques used for modal testing. However, in order to obtain accurate velocity vectors from any point of a structure, the LDV needs a critical X-Y scanning system. The requirements of the scanner for the LDV eliminate refractive beam deflectors from consideration due to the frequency shift and small deflection angle. Polygon and hologram scanners, due to high inertia and the inability to allow random access, are not suitable for the LDV, either. Thus, low inertia reflective scanners are the only possible solution.

Among low inertia scanners, the piezoelectric scanner has only $1^\circ \sim 2^\circ$ scanning angle. Although multi-stage configuration may increase the scanning angle, the

complexity of the system and the errors accumulated from each stage make the piezoelectric scanner impractical for the LDV.

A single mirror scanner driven by a stepping or brushless servo motor can provide unlimited scanning angles ($0 - 360^\circ$). But such a large scanning angle costs scanning resolution. The inherent low accuracy of a motor may be improved by a closed-loop drive. A high resolution optical encoder is then necessary for the system. High resolution optical encoders usually have high inertia and slow response time. They are not only very large but also very expensive. If the size, speed, and cost present no objection, a high resolution encoder along with stepping or servo motor may be used for a plane mirror scanner for the modal testing. However, the absolute positioning accuracy of such a scanner may be still limited by the resolution of the motor, rather than that of the encoder, due to the unstable control beyond the motor resolution.

Compared to the motors and piezoelectric transducers, galvanometers can provide adequate scanning angle and scanning resolution. With a capacitive position sensor, galvanometer scanners can have a very short scan time and yet high accuracy. The nonlinearity error of the position sensor is most likely repeatable; thus, through accurate calibration, the nonlinearity error can be reduced. The easy solution for thermal drift is to control the temperature of the position sensor by using a closed-loop thermal blanket. The compact size and moderate cost of galvanometer scanners are the other attractive features. For X-Y scanning, a pair of galvanometers can be easily configured to deflect the X and Y mirrors independently.

Clearly, galvanometer scanners are the best candidates to fulfill all the scanning requirements for the LDV and modal testing. The full description of a galvanometer-based scanning system for modal testing is presented in the following chapter.

CHAPTER THREE

G3B/DE2488 GALVANOMETER-BASED SCANNING SYSTEM

Although most galvanometer scanners possess important features needed for the LDV and modal testing, only the most advanced galvanometer-based scanning systems have the chance to meet the ultra-tight positioning accuracy requirement for modal testing. The G3B/DE2488 galvanometer-based scanning system is perhaps one of the best of its kind. This scanning system is manufactured by the General Scanning Inc. which is recognized as one of the top galvanometer scanner manufacturers in the world. Because of its superior performance, the G3B/DE2488 scanning system has found wide applications in various industries, as well as in experimental modal analysis.

3.1. System Description

The G3B/DE2488 galvanometer-based scanning system consists of an X-Y scan head (two G3B galvanometer scanners) and a digital electronics scanner controller (DE2488). This system can be driven by a host computer through an IEEE-488 interface bus. The maximum deflection angle of the G3B is 60° optical peak-to-peak. The DE2488 has a 16-bit scanning resolution.

3.1.1 The X-Y Scan Head

The X-Y scan head and target configuration is shown in Figure 3.1. The input laser beam is deflected by the X scanner first then the Y scanner. The axes of rotation of the X and Y scanners are orthogonal to each other. The Y scanner's axis of rotation is parallel to the X-axis to produce the Y scan. The X scanner's axis of rotation, however, is not parallel to the Z-axis. In order to shorten the distance between the X and Y mirrors so

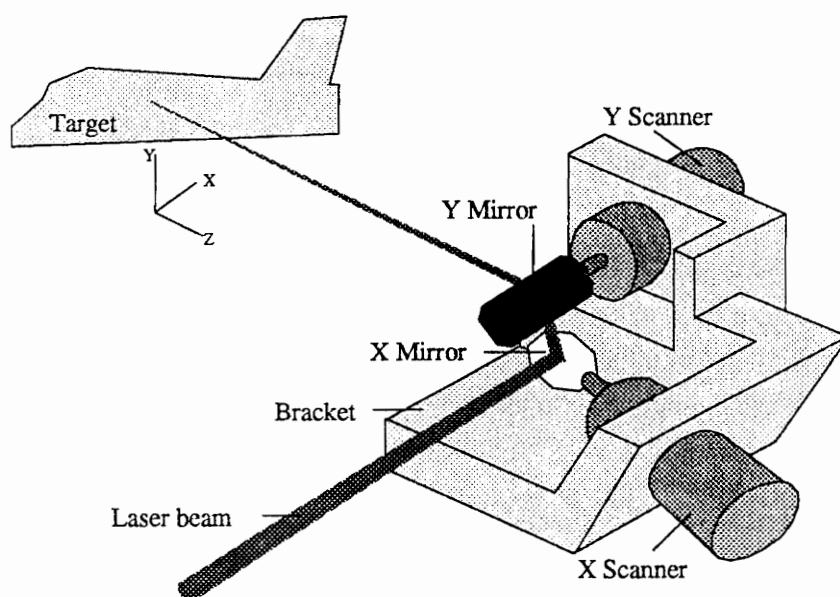


Figure 3.1 X-Y scan head and target configuration

that the Y mirror can have the minimal size, an optimal angle of 17° is set between the Z-axis and the X scanner's axis of rotation. The distance between the centers of the X mirror and the Y mirror is 26 mm. This distance is required to obtain the maximum scanning angle without mirror collision.

Both the X and Y scanners use the G3Bs that are moving-iron galvanometers with advanced capacitive position sensors. As explained in Chapter 2, the angular position of the galvanometer is a function of the drive current that passes through the drive coil windings. The position sensor is attached to the end of galvanometer and is charged by an oscillating voltage. When the G3B turns to a position, the position sensor generates a differential output current proportional to the angular position of the rotor. This output current is then converted to voltage that becomes the raw position signal. To reduce thermal drift, the temperature of the position sensor chamber is maintained at about 40°C by a built-in heating unit that contains a heater and a thermistor. The warming up time of the G3B is approximately 45 minutes. The body of the G3B is about 53 mm in diameter and 112 mm in length. The overall size of the X-Y scan head is 173x150x112 mm. Table 3.1 shows the specifications and the system performance of the G3B published by the General Scanning Inc.

The substrate of the mirror is made of fused quartz for extreme thermal stability. The front side of the mirror is coated with the Durable Silver that has better than 95% reflectivity for a He-Ne laser beam at an incident angle of 45° . The mirror thickness is 3 mm. The mirror flatness is better than $1/8$ wavelength over usable aperture (pupil diameter) which is 20 mm. Since the Y mirror has to cover the full scanning angle produced by the X mirror, the size of the Y mirror is larger than that of the X mirror. The inertia of the mirror and mount is about 7 gm-cm^2 for the X mirror and about 9 gm-cm^2 for the Y mirror.

Table 3.1 The specifications and system performance of the G3B galvanometer scanner
(Adapted from [24])

Parameters	Units	Typical Values	Notes
Rated Excursion, max.	p-to-p degrees	60	Angular specifications in degrees/ μ rad optical.
Rotor Inertia	gm-cm ²	6	
Sensor Angular Sensitivity	μ A/degree	5.5	General Scanning driver.
Coil Resistance	Ohms	2	
Coil Inductance	mH	6	
Torque Constant	Nm/A	0.05	
Maximum Current	A	4	
Linearity	% of rated excursion	0.01	
Gain Drift	ppm/ $^{\circ}$ C	100	10 $^{\circ}$ C to 50 $^{\circ}$ C, average, 6 hour test, galvanometer only in oven.
Offset Drift	μ rad/ $^{\circ}$ C	50	Same as above.
Repeatability	μ rad	2	Short term (30 sec.).
Wobble	μ rad	4	Depends strongly on mirror size and operational speed. May be lower in some applications.
System Jitter	μ rad	22	Same as above.

From the static point of view, the ideal way to mount mirror would be to have the axis of rotation lie on the mirror surface (Figure 3.2), so that the reflecting point could be stationary if the incident laser beam intersects the mirror surface at the axis of rotation. Since the mirror has a thickness and mass, the static ideal way of mirror mounting can be a dynamic disaster. If the mirror surface coincides with the axis of rotation, then the mirror's mass center must be off the axis of rotation. If the mass of the mirror is not balanced about the axis of rotation, the mirror imbalance force would cause transverse

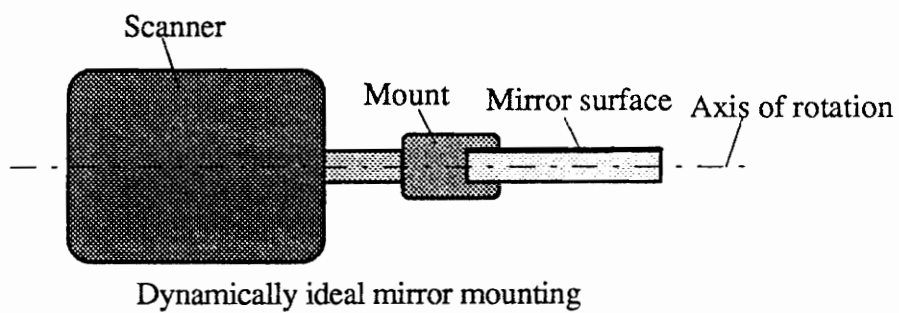
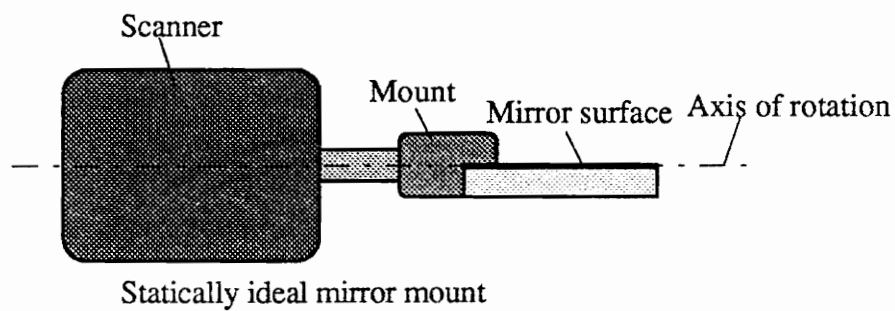


Figure 3.2 Statically and dynamically ideal mirror mounting

and torsional excitations of the mirror and rotor assembly in stepwise scanning. This undesirable excitation can severely affect scanning accuracy or prolong mirror settling time. The wobble of the mirror caused by the mirror imbalance can also put extra loads on the bearings so that the bearing life could be shortened. Moreover, the rotational inertia will rise if the mirror is unbalanced. This will slow the response to a stepwise scan command. If the off-center mirror mass is balanced about the axis of rotation by a counter mass, then it not only complicates designing and mounting but also increases a tremendous mass moment of inertia. For a mass-balanced mirror mounting with the minimal inertia, the center of gravity of the mirror and its mount should be right on the axis of rotation. The mirrors of the X and Y scanners are mounted in this way. For both the X and Y mirrors, the distance of the front mirror surface to the axis of rotation is 1.5 mm.

The mirror travel time can be calculated by the following equation:

$$t = \sqrt{\frac{2I\theta}{T}}, \quad (3.1)$$

where t is the mirror travel time in seconds, I is the total mass moment of inertia of the mirror, mirror mount, and scanner rotor in gm-cm^2 , θ is the step angle in optical radians, and T is the maximum torque of the galvanometer in dyne-cm. Equation (3.1) is derived by assuming that the scanner drives the mirror from stand still to reach the given step angle with the maximum acceleration. For a step angle of 1° , the mirror travel time is about 4.8 ms for the X scanner and about 5.1 ms for the Y scanner. However, the time calculated by Equation (3.1) is not ideal condition for the step response of the scanner, because the mirror still has a large velocity at the end of the step angle. The ideal step

response of the scanner would be that the scanner drives the mirror from stand still with the maximum acceleration for the first half of the step angle, then decelerates the mirror to the stop at the end of the second half of the step angle. With the same notations as in Equation (3.1), the following equation gives the ideal step response of the scanner:

$$t = 2\sqrt{\frac{I\theta}{T}} \quad (3.2)$$

For a step angle of 1° , the ideal step response time found by Equation (3.2) is about 6.8 ms for the X scanner and about 7.2 ms for the Y scanner. The actual step response time should be longer than the ideal value since the actual torque will be less than the maximum torque. The raster scan rate for the G3B is about 150 Hz.

3.1.2 The Digital Electronics Scanner Control

The DE2488 is a two-axis galvanometer controller with an IEEE-488 interface bus. Figure 3.3 shows the block diagram of the DE2488. The heart of the DE2488 is the Euro Digital Generator (EDG) that generates the digitally corrected X and Y digital coordinates. Another function of the EDG is to maintain system timing clock for laser synchronous control. The EDG contains a Central Processor Unit (EDG CPU), a 12V power supply card (EDG 12V), a parallel input/output conversion card (EDG PIO), and an IEEE-488 interface card (EDG 488). All components of the EDG are connected to a standard VME bus backplane. The EDG 488 card receives commands and scanning data from the host computer. It also sends back the log-on message and scanning status to the host computer. The EDG CPU card houses a Motorola 68000 microprocessor,

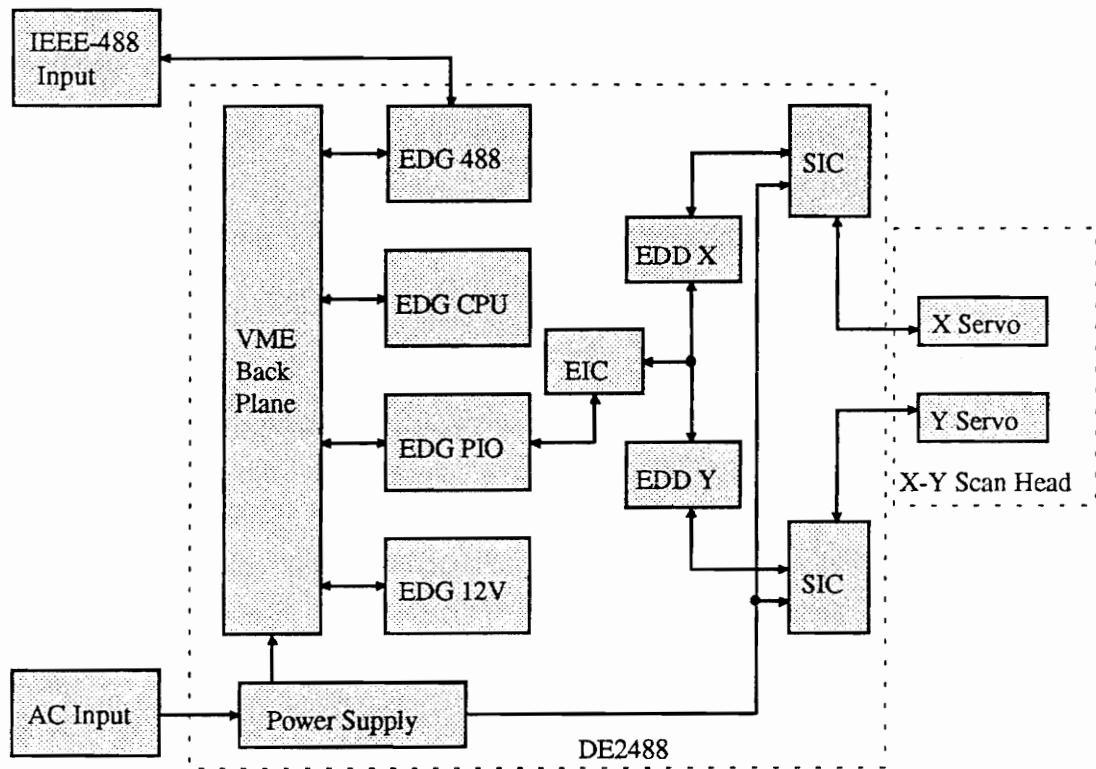


Figure 3.3 Block diagram of the DE2488
(Modified from [25])

programmed ROMs, 512K of RAM, and a RS-232 port (not used). It generates field corrected X and Y digital coordinates of vector endpoints according to the data from the host computer and reads scanner status information from the scanner drivers. The EDG 12V card receives a +5V from the power supply and produces a $\pm 12V$ output for the EDG. The function of the EDG PIO is to transfer scanning information between the EDG and the other parts of the DE2488.

The X and Y digital coordinates generated by the EDG are sent to the Euro Digital Drivers (EDD) cards through the Euro Interface Card (EIC). The function of the EIC is to assist in the communications between the EDG and the EDD. A set of DIP switches on the EIC card allows setting the IEEE-488 bus address of the DE2488. The EIC also produces laser modulation signals according to the laser control signals from the EDG. However, the laser control line is not used for modal testing.

Two EDD cards, EDD X and EDD Y, convert the X and Y digital coordinates separately into analog drive signals by a 16-bit D/A converter. The analog drive signal is compared with the actual position signal from the position sensor. The differences between these two signals are the position error signals. Before the position error signals are sent to correct the drive signal, they are amplified and integrated to remove the static position error. The compensated drive signals are then fed into an amplifier to produce the drive current for the scanner. Figure 3.4 shows a simplified EDD closed-loop circuit diagram. The position signals are also differentiated to generate velocity signals that provide damping to the scanner. The EDD card also houses a closed-loop temperature control circuit to maintain a preset operating temperature of the position sensor.

Between the EDD card and the scanner, there is a Scanner Interface Card (SIC). The SIC provides the power for amplifiers and completes the closed-loop control circuit. It

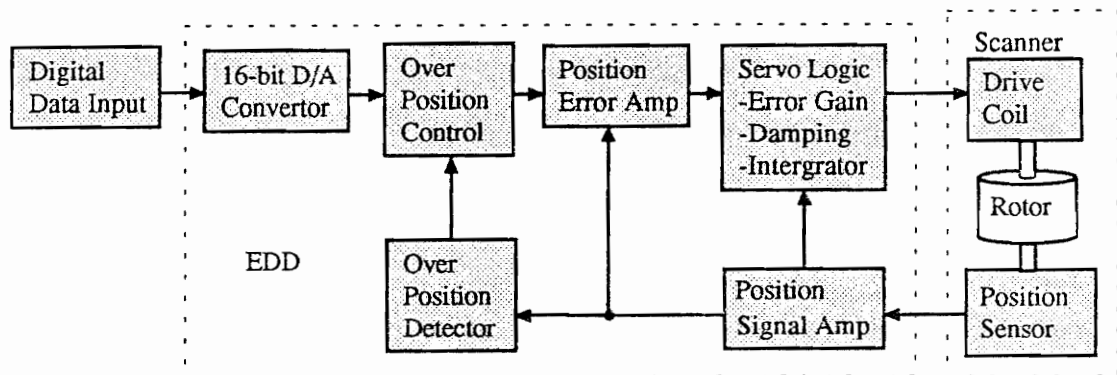


Figure 3.4 Simplified EDD closed-loop circuit diagram
(Modified from [25])

also houses a diagnostic connector that can be used to monitor the drive signals and the position error signals. It is possible to input analog drive signals via the diagnostic connector with the D/A converter being turned off.

3.2. System Control

System control mainly involves two parts: programming the DE2488 with the DE software and communicating with the IEEE-488 interface bus. The DE software is developed by the General Scanning to command the DE series scanner controllers. The commands of the DE software are simple, yet they provide great flexibility to the scanning system. However, to send the DE commands one has to use IEEE-488 bus commands to prepare the talker and listener status between IEEE-488 devices. Understanding both the DE software and the IEEE-488 standards is necessary for proper system control.

3.2.1 DE Software

The DE software contains a set of two-letter commands followed by an argument and/or a terminator. Some of the DE commands require arguments to specify times or digital values. All commands are sent to the DE2488 through the IEEE-488 interface bus. They must be in upper case format with a carriage return [CR] (ASCII 0D Hex) as the terminator. Since the EDG ignores line feeds (ASCII 0A Hex), a null byte (ASCII 00 Hex) must be appended to the end of each line. Valid arguments consist of non-negative integers and must be within the defined ranges. They are also sent as ASCII characters, i.e., 0 = 30H, 1 = 31H..., etc. Table 3.2 lists the DE commands that must be followed by an argument. Table 3.3 is the list of the DE commands that have no argument.

Table 3.2 DE commands followed by an argument (Modified from [25])

Command	Range	Units	Default	Function
NX	0-65535	LSB's	32768	X endpoint of drawn vector.
NY	0-65535	LSB's	32768	Y endpoint of drawn vector.
JX	0-65535	LSB's	32768	X endpoint of non-drawn vector.
JY	0-65535	LSB's	32768	Y endpoint of non-drawn vector.
SP	210-65534	μ s	210	Time between vector steps.
SS	1-32767	LSB's	32	Incremental Next step size.
JS	1-32767	LSB's	512	Incremental Jump step size.
SD	2-65534	μ s	4	Delay prior to Next vectors.
JD	2-65534	μ s	1000	Delay after Jump vectors.
LO	20-65534	μ s	290	Laser on delay.
LF	2-65534	μ s	274	Laser off delay.

Table 3.3 DE commands without arguments (Adapted from [25])

Command	Function
CV	Enter continuous vector mode.
NC	Non continuous vector mode. (Default)
AB	Absolute vector entry mode. (Default)
DL	Delta vector entry mode.
ST	Request for system status.
CL	Clear vector list.
EC	Execute and clear vector list.
EX	Execute stored vector list.
RX	Continuously repeated executes. RESET to stop.
LT	Enter load geometric correction table mode.
QT	Quit (exit) load correction table mode.
CT	Clear correction table, fill grid with zeros.

The DE commands can also be divided into six groups by their functions: 1.) vector coordinate, 2.) scanner control, 3.) laser control, 4.) vector table execution, 5.) utility, and 6.) grid correction.

1.) *Vector coordinate commands* include JX, JY, NX, NY, AB, and DL. They define the endpoints of scan vectors. The 16-bit D/A converter gives an XY coordinate range of 0 to 65535, which describes a square scan field (Figure 3.5). The unit of the XY coordinate is in Least Significant Bits (LSB) of the DAC ($1 \text{ LSB} = 1/65536$ of the maximum deflection angle). When the power of the DE2488 is switched to on or the RESET button is pressed, the scanner is reset to the home position. Since the XY coordinate of the home position is half DAC step between 32767 and 32768, the home position is not attainable by any vector coordinate command.

The Jump (JX, JY) commands position the scanners to the endpoints of the specified vector with the laser off. It takes the shortest traveling time but the longest settling time for the motion of the scanners. The JX and JY can be the suitable vector commands for modal testing if the mirrors are well balanced so that the settling time is short. The Next (NX, NY) commands turn on the laser and drive the scanners with a constant speed. The NX and NY may have the shortest total step response time because of the shorter settling time. They are primarily designed for the applications that requires uniform exposure of the laser beam. The EDG CPU always takes two numbers from the vector table at one time to calculate the X and Y coordinates of one vector. Therefore, the JX and JY commands must be used together as a pair with the JX prior to the JY. The same rule applies to the NX and NY. No any other command is need or should be entered to separate the JX and JY pair or the NX and NY pair. Also, the Jump command cannot be mixed with the Next command, for instance, the JX and NY cannot be used together as a

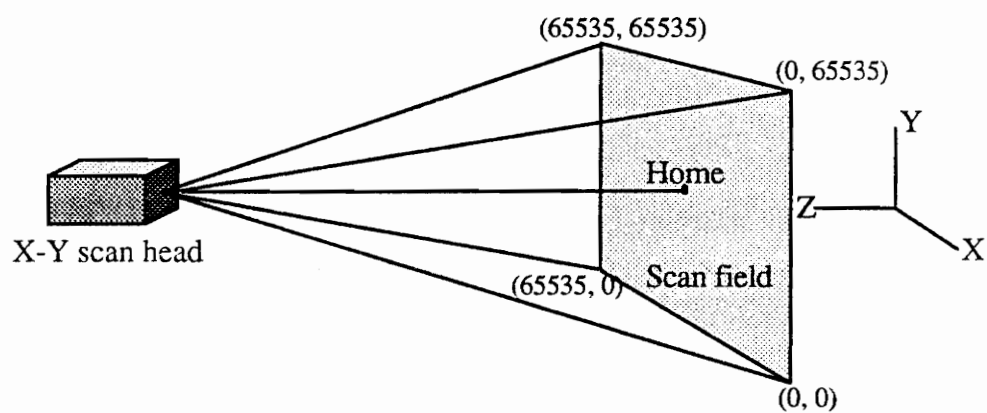


Figure 3.5 X, Y coordinates of the scan field

pair for one vector. Otherwise, the vector table will be contaminated, and the vector calculation will be incorrect.

The AB and DL commands specify the vector calculation modes. In the Absolute (AB) mode, the arguments of the Jump and Next commands are interpreted as the absolute endpoint location. In the Delta (DL) mode, the arguments of the Jump and Next commands are interpreted as the relative motion from current location. An XY coordinate pair may use only one mode, either the AB or the DL, not both. The arguments of the Jump and Next commands in the DL mode specify both the direction and magnitude of motion. A positive moving (increment) is defined by a number from 1 through 32767. A negative motion (decrement) is given by an argument 65535 through 32768 that corresponds to -1 through -32768. The EDG CPU will check each Delta argument value. If any resulting value of the Delta argument added to the current location is out of the scanning range (<0 or >65535), the Delta argument will be ignored, and the Bit 1 (Argument Error) and the Bit 6 (Service Request) of the status register will be set on the IEEE-488 bus (The detail of the IEEE-488 interface bus will be discussed in the next section).

The maximum capacity of the vector table (download limit) is 32,000 XY vector pairs (or 160x200 points). If the 32,000 limit is reached, it is necessary to execute the vector table and to clear the table before the host computer sends any more vector pairs. It is very important for the host computer not to exceed the download limit, otherwise a reset is needed and the data are lost.

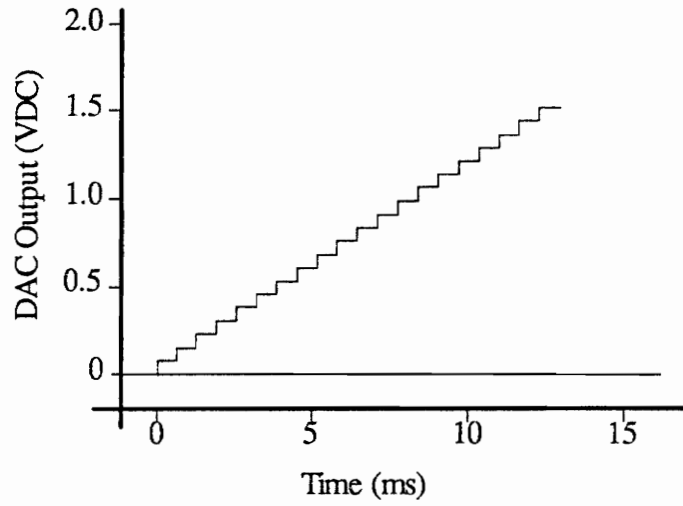
2.) *Scanner control commands* include SS, JS, SP, SD, and JD. These commands determine the scan time that includes response time, traveling time, and settling time. The DAC output of a drive signal is a digital ramp. The SS (Step Size for the Next commands) command and the JS (Jump Size for Jump commands) command determine

the voltage increment of the ramp. A smaller jump (or step) size corresponds to a smaller voltage increment. The SP (Step Period) command determines the time between each voltage increment. The SP and JS (or SS for Next commands) together define the slope of the DAC output ramp that determines the slew rate at which the vector pairs are executed. Therefore, the speed of vector pair execution (mirror traveling time) is the function of the jump size (or step size) and the step period. Figure 3.6 shows two examples of the DAC output ramps with the same vector sizes but different jump sizes and step periods. For a smooth DAC output that gives better dynamic performance of the scanner, the step period should be as short as possible. However, the minimum value of the step period is limited by the speed of the ROMs. In most cases, the scan speed can be adjusted by changing the jump (or step) size as the step period is fixed to the minimum value.

The SD (Scanner Delay) and JD (Jump Delay) commands provide settling time for the mirror. The SD command adds a delay time before the execution of a vector that is with the Next command. The JD command adds a delay time after the execution of each vector that is specified by the Jump command.

3.) *Laser control commands include* LO (Laser on), LF (Laser off), CV (Continuous Vectors), and NV (Non-continuous Vectors). The laser is turned on by the LO command and off by the LF command for each drawn vector that is specified by the Next command. The arguments of the LO and LF commands specify the delay time. If several drawn vectors (with the Next commands) are executed continuously, the CV command keeps the laser on after the first drawn vector until the last drawn vector or until the NV command is entered. The SD, LO, and LF delays between each vector are skipped for the CV command. The NV command sets the laser control to the normal mode. Since the laser output power for modal testing is very small (less than 1 mW), the laser can be kept

a.) Vector size = 10000 LSB
 Jump Size = 200 LSB
 Step period = 210 μ S
 Jump Delay = 3 μ S



b.) Vector size = 10000 LSB
 Jump Size = 2000 LSB
 Step period = 400 μ S
 Jump Delay = 3 μ S

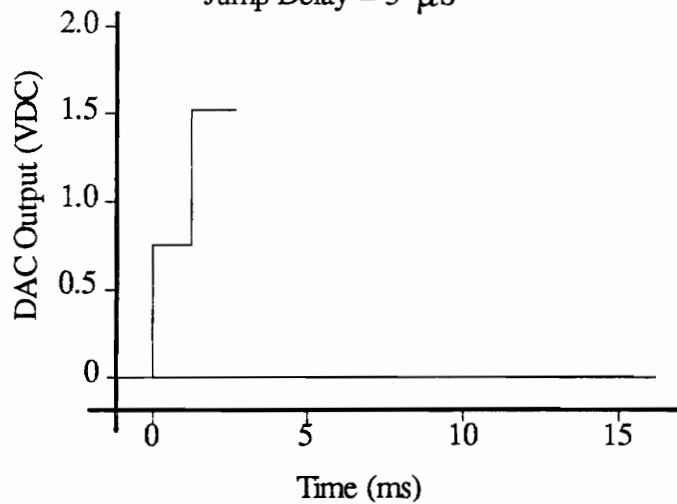


Figure 3.6 Two examples of the DAC output with the same vector sizes

on for entire scanning without damaging the object. Therefore, the laser control is not needed. However, the laser control signal may be used to trigger the LDV data processor.

4.) *Vector table execution commands* include CL (Clear), EX (Execute), EC (Execute and Clear), and RX (Repeat Execute). The CL command clears the vector list without execution. The EX command executes the vector list without clearing. After the execution is completed, the EDG positions the pointer to the beginning of the vector list and enters the input mode. New vector pairs can be added to the current list if the 32,000 vector pairs limit is not exceeded. The EC command is the combination of the EX and CL. The RX command is primarily used for scanner testing. The repeated execution of the vector list by the RX command can be interrupted only by a hardware reset.

5.) *Utility commands* include ST (Status) and TS (Laser Test). The ST command causes the EDG to test the status lines of the EDD and to report the test results to the host computer. The status lines of the EDD board monitor the power, temperature, and position of the scanner. The laser test commands, TS1 and TS0, turn the laser on and off to focus or test the laser.

6.) *Grid correction commands* are used to correct geometric distortion of flat scan field. They include CT (Clear Table), LT (Load Table), and QT (Quit Table). A grid correction table can be loaded by the LT command or cleared by the CT command. The QT command returns the EDG to the normal input mode after the table is downloaded. Since only the absolute position in space is concerned for modal testing, there is no need for geometric corrections.

3.2.2 Program IEEE-488 Interface Bus

The DE2488 scanner controller is connected to the host computer via an IEEE-488 interface bus which is also called HPIB (Hewlett-Packard Interface Bus) or GPIB

(General Purpose Interface Bus). The primary function of the IEEE-488 bus is to manage the transfer of information between the computer and peripheral devices. By setting the standards for the IEEE-488 interface bus, the electrical and mechanical hardware is compatible among devices. The functional compatibility of the IEEE-488 bus also provides great versatility to accommodate a wide variety of electronic instruments. This section provides only a brief introduction to the IEEE-488 interface bus. An in-depth description can be found in the HPIB tutorial book [26].

Up to 15 devices (including the computer and interface) may be connected to one IEEE-488 bus to form a bus network. Each device on the network may be assigned to a unique address (0 through 30) by setting a 5-bit DIP switch. Within the IEEE-488 bus network, only one computer can be configured as the System Controller that is the Active Controller at power-up. The System Controller can pass control to another device that is capable of managing the interface bus. The Active Controller assigns the talker that places the data on the bus and the listeners that accept the data. The capability of a device to be a controller, a talker, or/and a listener can usually be identified with the capability code that is marked near the connector.

Three types of data are transferred on the bus: IEEE-488 commands, addresses of devices, and device-dependent messages. These data can be transferred on the bus by using any commonly understood BCD, alphanumeric, or binary code. Usually this is the 7-bit ASCII character code. Data transfer is asynchronous. The data transfer rate is automatically adjusted to the slowest participating device on the bus. With some cares, the data rate can be achieved up to 1 Mbyte per second. The data transmission is done in a bit parallel-byte serial manner with eight bi-directional data lines (DIO1 - DIO8). Five lines are used to coordinate data transfer (Table 3.4). Three lines are used to implement the handshake between the transmitter and the receiver (Table 3.5). Every byte of data

transferred undergoes the handshake. In order to insure the data transmission speed and accuracy, the total transmission path length over the interconnecting cables is limited to 20 meters or 2 meters per device. However, this limitation can be surpassed by using the Intra-Facility or Inter-Facility HPIB Extension.

Table 3.4 General bus management lines of the IEEE-488

Name	Mnemonic	Description
Attention	ATN	Switches the bus to command mode(ATN TRUE) or data mode(ATN FALSE).
Interface Clear	IFC	Resets the bus to the power-up condition.
Service Request	SRQ	Requests service from current active controller.
Remote Enable	REN	Sets all listeners on the bus in remote operating mode.
End Or Identify	EOI	Indicates the end of data message; also used with ATN to Parallel Poll devices for their status bit

Table 3.5 Handshake lines of the IEEE-488

Name	Mnemonic	Description
Data Valid	DAV	Indicates valid data on the data(DIO) lines.
Not Data Accepted	NDAC	Indicates that not all the listeners have accepted the data on the bus.
Not Ready For Data	NRFD	Indicates that not all the listeners are ready to accept data from the bus.

Most IEEE-488 devices are capable of generating a service request when they need assistance from the Active Controller. Service requests are generally made after the device has completed a task or when an error condition exists. If a device on the bus needs service, it asserts the bus Service Request line (SRQ). Once the SRQ line is asserted (made low), it remains low (true) until the request has been satisfied. Serial

polling the devices by the Active Controller, which is a sequential poll of individual devices on the bus, can provide the information as to which device and what kind of service it requires. Many devices automatically clear their SRQ state and return a status byte message to the Active Controller. The status byte is device-dependent. However, Bit 7 (or D6 of Bit D0 through D7) is always used to indicate which device that is currently asserting SRQ.

At anytime there can be only one talker and may be multiple listeners on the bus. All active devices on the bus must monitor ATN line at all times and respond to it within 200 ns. When ATN is asserted (true or logic LOW), the interface is placed in the Command mode in which the data on the Data lines are interpreted as IEEE-488 commands or addresses. When ATN is false, the interface is in the Data mode in which the active talker sends device-dependent data to all active listeners.

Each IEEE-488 bus command is associated with a decimal value that corresponds to an ASCII character. Table 3.6 lists IEEE-488 commands, along with the decimal value and ASCII character equivalents of each command.

These IEEE-488 bus commands can be categorized into four groups:

1.) *Universal commands* cause every active device on the bus to perform a specific interface operation, even though some devices are not addressed as current listeners. They include UNL, UNT, DCL, LLO, SPE, SPD, and PPU.

2.) *Addressed commands* are similar to universal commands, but only the addressed devices response to the commands. The commands are ignored by all unaddressed devices on the bus. This group of commands includes GET, SDC, GTL, PPC, and TCT.

3.) *Talk and listen addresses commands* assign active talker and listeners on the bus. The valid talk and listen addresses are 0 through 30 which are specified by the first five bits (DIO1 through DIO5) of the address byte. The sixth and seventh bits (DIO6 and

DIO7) of the address byte are used to specify whether the address is for talk or for listen. Address 31 is reserved for the command UNTALK ("-") or UNLISTEN ("?"). Therefore, it is illegal for any device to have the address 31. Also, Address 21 should be avoided for an instrument address, because it is usually reserved for the computer interface talk and listen address.

4.) *Secondary commands* provide additional command codes, but they must always be used in conjunction with a command from one of the above groups. The secondary commands include the PPE and PPD. They can be used for extended secondary talk and listen addresses. Use of these commands must be always preceded by a PPC command.

Table 3.6 List of IEEE-488 commands

Command Name	Mnemonic	Decimal Value	ASCII Character
UNLISTEN	UNL	63	?
UNTALK	UNT	95	-
DEVICE CLEAR	DCL	20	DC4
LOCAL LOCKOUT	LLO	17	DC1
SERIAL POLL ENABLE	SPE	24	CAN
SERIAL POLL DISABLE	SPD	25	EM
PARALLEL POLL UNCONFIGURE	PPU	21	NAK
GROUP EXECUTE TRIGGER	GET	08	BS
SELECTED DEVICE CLEAR	SDC	04	EOT
GO TO LOCAL	GTL	01	SOH
PARALLEL POLL CONFIGURE	PPC	05	ENQ
TAKE CONTROL	TCT	09	HT
PARALLEL POLL ENABLE	PPE	96-111	' thru o
PARALLEL POLL DISABLE	PPD	112	P
My Talk Addresses 0-30	MTA	64-94	@ thru ^
My Listen Addresses 0-30	MLA	32-62	space thru >

The following is a general program sequence to transfer device-dependent data, started with the Active Controller sends the command in the command mode:

Command	Explanation
UNT	Unaddresses the current talker
UNL	Unaddresses all current listeners
MTA	Addresses the new talker
MLA	Addresses the new listener
ATN down	Asserts ATN line to Data mode
<message>	Device-dependent data are transferred
ATN up	Resets ATN line to Command mode
UNT	Unaddresses the current talker
UNL	Unaddresses all current listeners

3.3. System Integration and Host Computer Programming

The IEEE-488 bus capability codes for the DE2488 are SH1, AH1, T6, L4, SR1, RL0, PP0, DC1, DT0, C0, and E2. These codes specify that the DE2488 has the source and acceptor handshake capabilities, the basic talker and listener functions, service request capability, no remote local and parallel poll capabilities, complete device clear capability, no device trigger and controller capabilities, and tristate driver (refer to reference [26] for the detail on the capability codes). Clearly, a host computer with an IEEE-488 interface bus is required to transfer scan data and to command the DE2488 scanner controller. The host computer must be configured as the System Controller or the Controller-In-Charge (CIC) for the IEEE-488 bus since the DE2488 cannot be the

controller. It is responsible for originating all commands and data handled on the bus and responding to the request for service from the DE2488.

Programming the IEEE-488 interface bus with the standard commands can be quite troublesome. Unnecessarily addressing or unaddressing of the devices and improperly handling of the control and handshake lines not only reduce the bus efficiency, but also cause undefined bus behavior, or the interface operation simply becomes chaos. Fortunately, there are some commercial software packages available that can greatly simplify programming the IEEE-488 interface bus. Two of such software packages are HP-UX Device I/O Library (DIL) developed by the Hewlett-Packard Company [27] and LabVIEW developed by the National Instruments Corporation [28].

Two different computers have been used as the host to the DE2488. One is a HP 9000 Series 300 Model 385 computer with built-in IEEE-488 interface. The other is a Macintosh Model IIfx computer with a National Instruments NB-DMA2800 card, an IEEE-488 interface card.

The HP 9000 computer, along with the HP-UX operating system, provides high speed execution and a powerful environment for programming. The HP-UX DIL contains a number of subroutines that can be called to send bus commands very conveniently by automatically handling the ATN line and the handshaking operations. Also, since the HP-UX has the auto-addressing capability, much of the tedium of addressing devices to talk or listen can be eliminated by using auto-addressed special device files.

The computer program to drive the DE2488/G3B scanning system was written in C program language, see Appendix A. In order to run the program, an auto-addressed special device file named "de2488" was created first for the DE2488 and placed in the

"/dev" directory underneath the root directory of the HP-UX. The following line shows how this file was created:

```
mknod /dev/de2488 c 21 0x071700
```

where, "mknod" is the HP-UX command to create a special device file; "/dev/de2488" is the pathname and filename; "c" specifies the created file as a character special file; "21" is the major number for an IEEE-488 bus; "0x" specifies that the characters which follow represent hexadecimal value; "07" specifies the select code of the interface card of the computer, which is determined by switch settings on the IEEE-488 interface card; "17" is the address of the device (decimal address 23), which is set by the 5-bit DIP switch on the EIC card of the DE2488; "00" specifies the secondary addresses that are not used for an interface.

Some DIL subroutines require a raw device file, such as the subroutine for serial polling the IEEE-488 bus. Thus, a raw device file named "de_raw" was also created in the same way as the auto-addressed device file. The only difference was to use device address 1f (decimal address 31) for the raw device file instead of address 17 though the actual DIP switch setting on the DE2488 was always on 17 (decimal address 23). Address 1f (hexadecimal) is reserved by HP-UX for raw device files. Any device address in the range 0 through 30 is auto-addressed.

The example program in Appendix A reads the message from the DE2488, serial polls the DE2488, and writes the DE commands to the DE2488. The "eid" is an entity identifier of the device special file that is supplied to the DIL subroutines as a parameter. The "read" and "write" are two HP-UX system calls, which provide low-level I/O operations. The DE commands and their arguments are sent as character strings. A carriage return (`\r`) and a null character (`\0`) are appended to the end of each DE command to indicate the end of a single command. The DIL subroutine "hpib_poll" is

called to serial poll the IEEE-488 bus that can determine the status of the DE2488 and reset the service request. If the message from the DE2488 has not been read by the host yet, bit 0 of the status register of the DE2488 is set. If the command is not valid or the argument is out of range, bit 1 or bit 2 is set. Bit 3 is set to indicate the completion of command execution. Bit 0 through bit 3 are always set with the service request. Bit 4 of the status register indicates that the command execution is in progress. When bit 4 is set, the host computer must not download any command. Bit 6 indicates that the service request is asserted by the DE2488.

Using LabVIEW to program the DE2488 on the Macintosh computer can be really enjoyable. The program is written by graphs, symbols, and lines. The GPIB and Serial Port VI Library [29] of the LabVIEW contains all the subroutines that are needed to perform various IEEE-488 interface operations. It is certainly simpler and more convenient to use the LabVIEW than to use the HP-UX for programming the scanning system. The only drawback is that the Macintosh computer is not as powerful as the HP 9000 computer. Appendix B is an example program written with the LabVIEW to generate 2D scan vector list, to read message from the DE2488, to serial poll, and to send the DE commands.

CHAPTER FOUR

SCANNING SYSTEM TEST AND CALIBRATION

Without doubt, the G3B/DE2488 galvanometer-based scanning system is one of the best systems for the LDV and modal testing. However, the ultra-tight requirements for modal testing and lack of adequate test data on the scanning accuracy and time by the manufacturer make the scanning system testing and calibration inevitable. Only through systematically testing and calibrating, the performance characteristics of the scanning system can be determined. With adequate calibration data, computer correction is possible to improve the scanning accuracy.

4.1. The Needs for Test

To determine whether a test is needed or what kind test is needed for the G3B/DE2488 scanning system, we must first establish the specifications for the key scan parameters. Once our specifications are set, we can compare them with manufacturer's specifications for the scanning system. The manufacturer's specifications should be given reasonable margins; and the size of margin depends on the reliability and importance of each parameter. If our specification is safely within the manufacturer's specification for a scan parameter, a test for that parameter may not be necessary. Nevertheless, one thing should be kept in mind. There may be some hidden error sources that the manufacturer never documents or is unaware of. This is because the users are not aware of the need for the specification, the manufacturer does not know how to determine that particular parameter, or simply the manufacturer does not care to determine that parameter. If our specification is obviously out of reach of the manufacturer's specification, then test and calibration may help to provide the data to be used to computer correct for this error. In

the worst cases, a test can determine the realistic performance of the scanning system so that our specifications can be revised accordingly with full cognizance of its effort on system performance.

4.1.1 Targets for Scanning Time and Accuracy

The scanning accuracy and time are the most important parameters for the LDV and modal testing. The general requirements are as high as possible for the scanning accuracy and as short as possible for the scanning time. The current technology and cost are the two main factors that set the bottomlines for the scanning accuracy and time. A more realistic approach of setting our specifications is to make the scanning accuracy and time comparable with some existing techniques and/or instrument used in modal testing.

The reference used to set our specifications for the scanning time is the Vibration Pattern Imager (VPI) 9000 (type No. V/9010) manufactured by the Ometron Ltd. of England. The scanners used in the VPI 9000 are General Scanning's model G325DT galvanometers. The sampling delay time of the VPI 9000 is 6 ~ 8 ms for each point. This delay time accounts for the scanner's step response time and settling time. Since the G3B has a larger rotor mass moment of inertia than the G325DT, the target of scanning time for the G3B/DE2488 is set to 8 ms for a step size less than 1° . This scanning time includes scan data transmission time, DAC time, mirror travel time, and mirror settling time. With the data-collection time needed for the LDV in sine dwell mode, the sampling rate for modal testing can be in the neighborhood of 60 points per second. Our specification for scanning accuracy, however, is set in a different way. That is described as follow.

First, let us assume that the scanned position errors in the X and Y directions, ϵ_x and ϵ_y , and that the measured distance error in the Z direction, ϵ_z , are all equal to ϵ

$$\varepsilon_x = \varepsilon_y = \varepsilon_z = \varepsilon \quad (4.1)$$

This assumption may not be valid, but simplifies the derivation. The analytical result will give an order of magnitude of the needed scanning accuracy. These errors cause the actual scan vector to deviate from its theoretical position. This deviation leads to an error in determining the velocity vector. To have the accuracy of the LDV modal testing technique be comparable to that of the accelerometer technique, the angular deviation of the velocity vector obtained by the LDV should be equivalent to the accelerometer's cross-axis sensitivity. Figure 4.1 depicts the worst case scenario that would produce the maximum angular deviation of the velocity vector.

In Figure 4.1, X_i and X_{i+1} are the two ideal scanned laser spots on a flat scan field that is parallel to the X-Y plane. The scanning angle between X_i and X_{i+1} is the minimal sample interval α_n that is the maximum scan angle α over the number of sample point intervals n . For the Ometron's VPI 9000, the maximum scanning angle is $\pm 12.5^\circ$ optical in both the X and Y directions with 12-bit scanning resolutions. The maximum sampling capability of the VPI 9000 is limited to 8-bit (256 x 256) by the software. However, other implementations such as the Zonic Corp's LAZON[®] implementation of the LDV have 12-bit scanning resolution with 12-bit sampling capability (4096 x 4096). The G3B/DE2488 scanning system has the maximum scanning angle of $\pm 20^\circ$ optical with 16-bit scanning resolution, meaning that a full (65536 x 65536) sampling capability is possible if the software permits.

The outward normal of the scan vector $X_i X_{i+1}$ is the vector that is parallel to the Z-axis (not shown in the figure). In the worst case, the position errors ε_x , ε_y , and ε_z are so arranged that the points X'_i and X'_{i+1} become the actual positions of the points X_i and X_{i+1} . The outward normal, Z , of the scan vector $X'_i X'_{i+1}$ will have the maximum angular

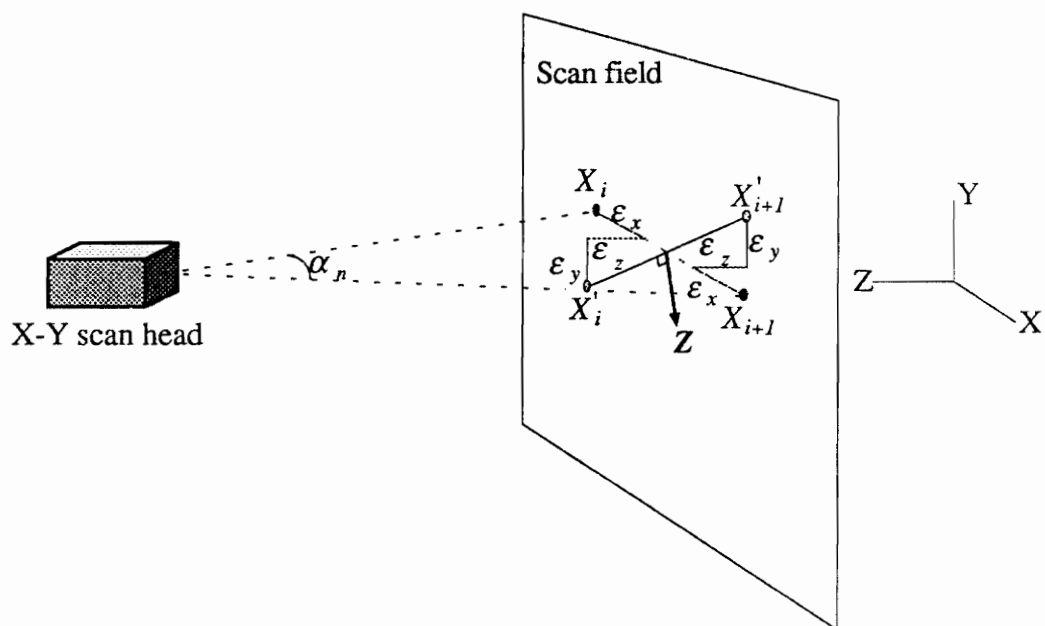


Figure 4.1 The worst case scenario of the position error arrangement

deviation from the theoretical direction that is the Z-axis. The angle between the outward normal, $\mathbf{Z}$, and the Z-axis, β , can be determined approximately from the following equation:

$$\beta \cong \tan^{-1} \left(\frac{\sqrt{\varepsilon_y^2 + \varepsilon_z^2}}{\frac{\alpha_n l}{2} - \varepsilon_x} \right), \quad (4.2)$$

where l is the distance from the scanner to the scan field. From Equation (4.2), the scanning angular position error, ε_α , can be expressed in the terms of β and α_n

$$\varepsilon_\alpha \cong \frac{\varepsilon}{l} = \frac{\alpha_n \tan \beta}{2(\sqrt{2} + \tan \beta)} \quad (4.3)$$

A typical value of cross-axis sensitivity for an accelerometer is about 5%. That means 5% of the in-plane acceleration of the test structure may be added to the out-plane acceleration. If a facilitating, but maybe unrealistic assumption is made that the magnitudes of the in-plane and out-plane accelerations are the same, the outward normal acceleration measured by the accelerometer may be off by as much as 5% due to the cross-axis sensitivity. Therefore, the allowable angular deviation, β , for the outward normal of a scan vector that produces an equivalent error as the accelerometer should be

$$\cos \beta \geq \frac{1}{1.05} \quad \text{or} \quad \beta \leq 17.752^\circ \quad (4.4)$$

Substitute the value of β into Equation (4.3), we have

$$\varepsilon_{\alpha} \leq 0.0923\alpha_n \quad (4.5)$$

Table 4.1 shows the allowed scanning angular error, ε_{α} , for various sample space resolutions. One thing should be kept in mind is that these values are obtained from the worst case that is unlikely to be happened to two adjacent scan points with the minimal scanning step size. Also, the derivation involves the distance measurement error that is uncontrollable by the scanning system.

Table 4.1 The allowed scanning angular error for various sample resolutions
(When the measurement is equivalent to a 5 % accelerometer crosstalk)

Maximum Sample Resolution	8-bit	12-bit	16-bit
Maximum Scanning Angle, α (μrad)	25	25	40
Maximum Number of Samples (X x Y)	256 x 256	4096 x 4096	65536 x 65536
Minimal Sample Interval, α_n (μrad)	1711.1	106.6	10.7
Allowed Scanning Error, ε_{α} (μrad)	157.9	9.8	1.0

4.1.2 Scanning Time of the G3B/DE2488

Refer to Section 3.1.1, the ideal step response time of the G3B/DE2488 for a step size of 1° is about 6.8 ms for the X scanner or 7.2 ms for the Y scanner. The actual step response time is usually longer than the ideal value and depends on the DAC output rate which is the function of the DE software (refer to Figure 3.6). The scanner manufacturer suggests that the step response time of the G3B/DE2488 is about 6 ms for a step size less than 1° or 7.5 ms for a step size between 1° and 10° (unspecified for the X or Y scanner). In most cases, the X scanner does the line scan. That is, to scan 256 x 256 data points, the

scanner needs to move to and to stop at only each scan line for a total of 256 times. Therefore, the scanning time is more critical for the X scanner than for the Y scanner in determining the total scanning time, though the Y scanner has longer scan time than the X scanner due to the larger mirror size of the Y scanner.

To eliminate the scanning position errors due to wobble and jitter, a near complete mirror settle is necessary (settling to better than one part in 10,000). However, the General Scanning Inc. does not give much guidance on mirror settling time of the G3B/DE2488. The only suggestion from the DE Series User Manual is that it can take more than 1 ms to settle the mirror for a large step size. Since the scanner settling time is a function of mirror mounting, step size, and slew rate of the mirror, it is difficult to determine the settling time by analytical means.

The data transmission time depends on both the host computer and the DE controller. The IEEE-488 interface bus has a data transfer rate from 0.5 to 1 megabyte per second. If the entire scan vector list (up to 32,000 data points) is downloaded to the DE2488 by the host computer before execution, it may take a few seconds to transfer the data. Since this transmission time does not add to scanning time of each point during the scanning, the bus transmission time will have little effect on the total scanning time taken for the tested structure. However, the host computer has no control over the DE2488 during the scanning if the entire scan vector list is already stored in the EDG (refer to Section 3.2.1). Any command sent from the host computer during vector execution will cause the IEEE-488 interface bus to hang until vector execution is completed and bit 3 (Done) and bit 6 (Service Request) of the DE2488's status register are set (refer to Section 3.3). Without the control of the host computer, the data-collection time of the LDV has to be set uniformly for each scanned point regardless of the quality of the collected data. The data-collection time of the LDV may vary from point to point, depends on the structure's

localized surface condition, such as reflectivity, incident angle, and magnitude of dynamic response at each point. This data-collection time for each point can be anywhere from 1 ms to 10 ms for sine dwell data acquisition. If a long uniform time is set to collect data at each point, the total time spent scanning a test structure can be very long. A large portion of time is wasted. If the uniform data-collection time is set short, then some of collected dynamic data may be not valid. The ideal solution of this problem is to have the host computer send one scan vector followed by an execution command to the DE2488. After the DE executes the move, the host computer triggers dynamic data collection. When the collected data is found to be satisfactory for that tested point, the host computer sends the next scan vector and execution command to the DE2488. In this algorithm, the data transmission time will add to the scanning time for each point. It may take more than 1 ms for data transmission between the host computer and the DE2488. If this puts too much time on the total scanning time, an alternative may be to send the entire scan vector list before an execution command is sent. The uniform data-collection time for each point can be set short, but should be long enough to accommodate the data-collection time required for most points. If a few points have invalid data after the full scanning, they can individually have repeated scanning to recollect the data.

In comparison with data transmission time, step response and settling time which include DAC time contributes most of the scanning time budget. The 8 ms scanning time target is possible to meet, but will be a close call. Testing data transmission time, step response time, and settling time will certainly help to plan the time budget and to make the scanning time as short as possible without sacrificing scanning accuracy.

4.1.3 Scanning Accuracy of the G3B/DE2488

The absolute position accuracy target is not easy to meet for the G3B/DE2488 scanning system, or perhaps for all other kinds of laser scanning system. A number of sources can introduce errors to degrade the position accuracy of the scanning system. Some of the errors are specified by the manufacturer, but some are not.

From manufacturer's specifications (refer to Section 3.1.1), the linearity of the G3B has a typical value of 0.01% over 60° , or $105\ \mu\text{rad}$. However, the specified maximum linearity error is 15 times the typical value (0.15% over 60°). The position sensor linearity plots of the X and Y scanners provided by the General Scanning Inc. also show about $300\ \mu\text{rad}$ nonlinearity error over 40° scanning angle (Figures 4.2 and 4.3). The 40° is the maximum scanning angle of the X and Y scanners which is set electrically and mechanically for modal testing. The original data can be found in Appendix E.

The other specified error sources are thermal drift, repeatability, wobble, and jitter. For a well-settled mirror, wobble and jitter are not the problems since they only associate with the mirror movement. The non-repeatability error of the VPI 9000 which uses G325DT galvanometer scanners has been observed as high as 0.053° , or $93\ \mu\text{rad}$. The maximum non-repeatability error for the G3B is specified to $5\ \mu\text{rad}$; therefore, this error does not seem critical. Thermal drift errors include gain and zero drifts. The specified maximum values are $100\ \text{ppm}/^\circ\text{C}$ for gain drift and $75\ \mu\text{rad}/^\circ\text{C}$ for zero drift. With a temperature-controlled position sensor, the specified minimal values are $10\ \text{ppm}/^\circ\text{C}$ (or $3.5\ \mu\text{rad}/^\circ\text{C}$ at $\pm 20^\circ$ scanning angles) for gain drift and $10\ \mu\text{rad}/^\circ\text{C}$ for zero drift. Although both the X and Y scanners have temperature-control, it is questionable whether the thermal drifts of the scanners can be kept to the minimal values.

Some unspecified sources of errors include mirror mounting, scanner mounting, thermal drift of electrical circuit, and laser drift. Since there is an offset distance between

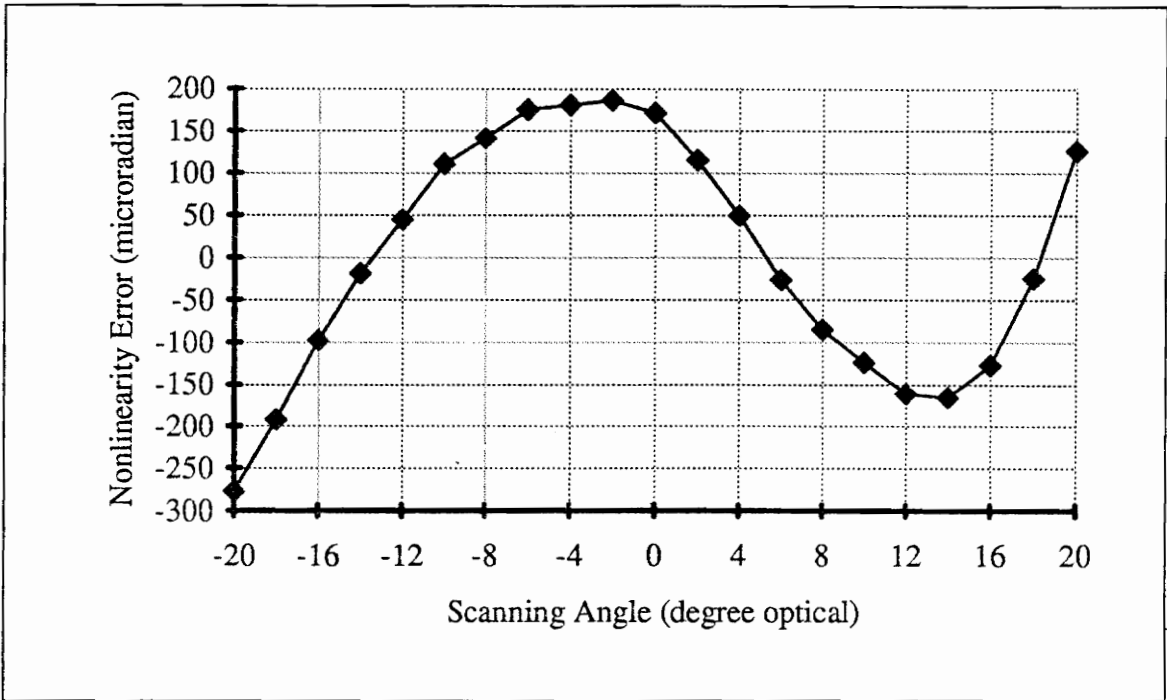


Figure 4.2 Position sensor nonlinearity plot of the X scanner (G3B, S/N 604920)
(From the data provided by the General Scanning Inc.)

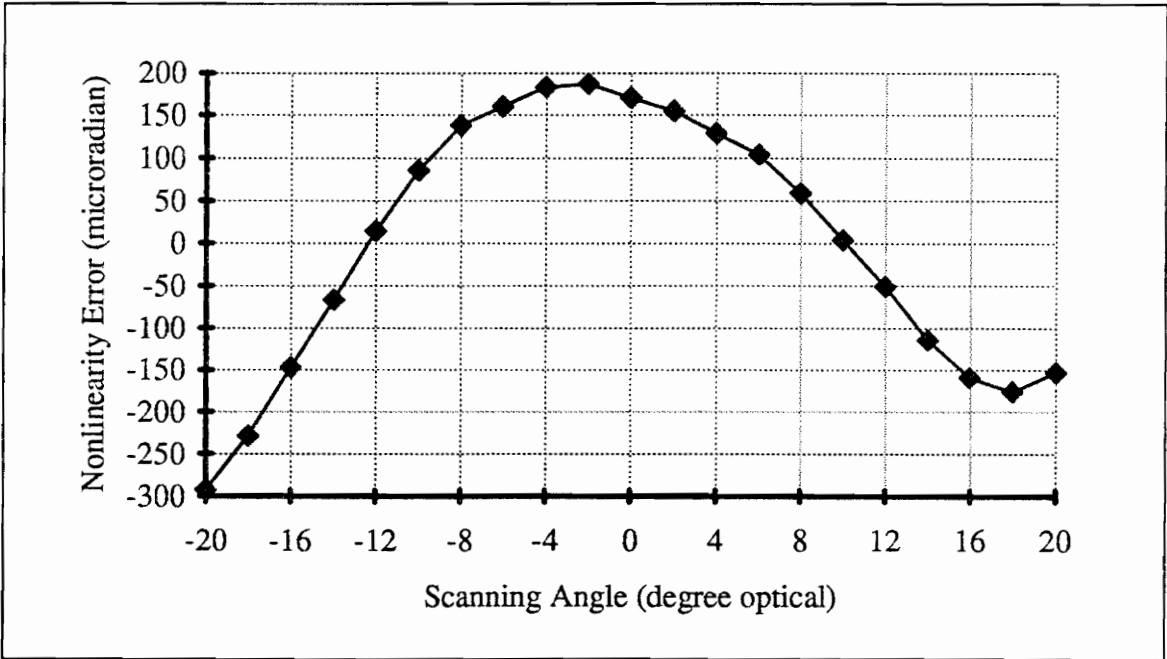


Figure 4.3 Position sensor nonlinearity plot of the Y scanner (G3B, S/N 604919)
(From the data provided by the General Scanning Inc.)

the scanner's axis of rotation and the mirror's front surface (refer to Figure 3.2b), the laser incident point on the mirror surface changes as the mirror rotates. This change of the point of reflection will cause a parallel shift error of the laser beam during scanning. The effect of the parallel shift error of laser beam on the angular position error, however, decreases as the distance between the scanner and the object increases. A full analysis in regard of the parallel shift error of laser beam will be given in the next chapter.

An angular misalignment of the mirror and the axis of rotation is another source of errors due to the mirror mounting. The mounting of scanners on the X-Y block usually causes a non-orthogonality error of the X and Y scan axes. Another source of error may be from the DE2488 scanner controller. Electrical circuits are very sensitive to the change of temperature. The DAC output of the DE2488 controller can be expected to have thermal drift if the room temperature varies. The sources of errors from laser alignment and drift are not scanner related, nevertheless, they do affect the scanning accuracy.

Clearly, the combination effect of all these errors is beyond the possibility for the scanning system to meet the position accuracy target. However, other than the errors due to thermal drift, most errors should be repeatable, such as position sensor nonlinearity error and various mounting errors. Theoretically, the repeatable errors can be calibrated out. Therefore, a position accuracy test can help to reduce the repeatable errors and to determine the characteristic of thermal drift of the scanning system.

4.2. Methods of Testing Scanning Time and Scanning Accuracy

For a high performance scanning system, the manufacturers usually specify the time and accuracy of the system. However, most users may never question if these specifications are reliable or how they are determined. In most cases, users just take manufacturer's words because their applications may not require such high performance,

or they just have no proper equipment and manpower to test the scanning system. Therefore, scanning system test has been ignored, and the techniques of testing often do not match the advances of the scanning system.

4.2.1 Scanning Time Test

Scanning time tests are a relatively easy task in comparison with the scanning accuracy test. With an oscilloscope, the data transmission time between the host computer and the DE2488 controller, the latency of the DE2488, the DAC output time, the travel time of the scanner, and the settling time can be easily monitored. A multi-channel digital oscilloscope with capabilities of storing and outputting data is very helpful to accurately determine times.

To measure the data transmission time, the ATN line of the IEEE-488 bus can be used. The ATN line is down only when the IEEE-488 bus is in the Data mode in which the DE commands and XY vector list are transferred (refer to Section 3.2.2). By measuring the length of the ATN line down period, the data transmission time can be determined.

The DAC time can be monitored on the D/A Out line of the DE2488's diagnostic connector. The D/A Out line, along with the ATN line of the bus, can be recorded simultaneously to determine the latency of the DE2488 which is indicated by the interval between the up of the ATN line and the bounce of the D/A Out line.

The scanner travel and settling time can be determined from the Position Signal line or the Position Error line. The separation of the travel time and the settling time can be somewhat troublesome, because both the signals from the Position Signal and the Position Error lines have been integrated to remove static errors before they are sent to the diagnostic connector. Therefore, it might be difficult to identify the settling pattern from these signals, especially the Position Error signal due to the low signal-to-noise ratio of the

system and the oscilloscope. However, since the main concern is the total scanning time, it is not critical to separate the travel time and the settling time. For a given step size, a shorter travel time usually requires a longer settling time, or vice versa. Care must be taken to assure that it is not the case that the signals from the Position Signal line or the Position Error line appear to be settled but the mirror may be still wobbling. To accurately determine the settling time, a high-resolution laser beam detection device with fast response time may be required. The laser beam can be directed to the null position of the detector first, then moved away from the detector. When the laser beam swings back to the preset position, the clocked output of the photodetector can be used to determine the settling time. A bi-cell, quadrant, or linear array photodetector should be able to do the job. By using this method, one can determine the time for the scanner to settle within one part in 10,000. However, the detector and the processing electronics can be costly.

4.2.2 Scanning Accuracy Test

Scanning accuracy test is much more complicated than scanning time test, especially for a high-accuracy scanning system. The most common test method used by scanner manufacturers and users is either indirectly measuring scanning accuracy by determining the angular position of the scanner's rotor or directly measuring the positions of the scanned laser spot in the space.

In the indirect method, the rotor of the scanner, along with the angular position sensor, is connected to an optical rotary encoder or a master angular position sensor that has a known accuracy and linearity characteristic. For a high-performance scanner, such as the G3B, a closed-loop drive circuit is always used; so the scanning accuracy of the scanner is mainly determined by the performance of the scanner's position transducer. It is the position transducer of the scanner that needs to be tested and calibrated. For a scanner

required ultra-high accuracy, it does not make much sense to use an analog master sensor for testing and calibrating the scanner that has its position transducer with the same or even higher level of accuracy as the master sensor. Unlike the master position sensor that gives an analog signal for the position of the scanner's rotor, an optical rotary encoder outputs digital position signal. Because of its superhigh resolution and superior accuracy, the optical encoder becomes the favorite for high-performance scanner testing. Optical encoders have two basic types: incremental and absolute encoders. The incremental optical encoder can only tell the relative angular positions of the scanner's rotor. They are generally simpler and less expensive than the absolute optical encoder. The resolutions of absolute optical encoders are usually much higher than the incremental type. The state-of-the-art absolute optical encoder can have a resolution up to 22-bit, or $1.5\ \mu\text{rad}$.

However, using the optical encoder to test scanning accuracy has several serious drawbacks. First, only the rotor's angular positions are tested. The effects of mirror mounting, optical aberration, laser alignment, and X-Y configuration on the scanning accuracy are not taken into account. Also, the resolution and error in the determination of the rotor's angular position will be doubled for the optical scanning angle (refer to Figure 2.3). Second, the size of the high-resolution optical encoder is very large, 6 inches to over 10 inches in diameter is common. The scanning system normally cannot generate a sufficient torque to overcome the large mass moment of inertia of the high-resolution optical scanner. Either a special designed scanner drive electronic or an auxiliary drive device, such as a high-resolution stepper motor, is required. Third, the coupling between the encoder and the scanner can cause not only large errors in test data but also damage to the scanner through misalignment. Since both the optical encoder and the scanner are high-precision and delicate instrument, any slight angular or transverse misalignment between their shafts can create a bending moment and asynchronous angular rotations

between the encoder and the scanner. Lastly, all equipment needed are very expensive, especially for the high-resolution optical encoder. For a high-resolution absolute optical encoder, not just the size of the encoder is very large, but also the electronics for data processing and interpreting is very complicated.

Another indirect test method needs to be mentioned is to use an auto-collimator. The auto-collimator is an optical device that can be used to observe very small angular variation of a highly reflective flat surface, such as a mirror. If an auto-collimator is used to test the angle of the scanner's rotor, the setup is very simple: the auto-collimator only needs to be aimed at the scanner's mirror with a normal angle. An ultra-precision auto-collimator can have an angle-measuring accuracy in the order of microradians. Unfortunately, the ultra-precision auto-collimator has only 1° to 2° maximum angle coverage, and they are very expensive, too.

The direct scanning accuracy test usually uses a visible laser beam to be deflected to a target by the X and Y mirrors. The target can be a flat surface or a segment of circle. The positions of the focused laser spot on the target can be determined in several ways. The simplest way that does not cost anything is to mark the laser spot on the target. The target's size of this method can be very large; but the measurements are very crude. A slightly improved way is to use photosensitive mediums, such as films, to record the scanned laser spots on the target. The size of the photosensitive medium is usually limited. A CCD camera can also be used to record the laser spots on the flat target. However, the CCD camera cannot really improve the accuracy of measurements. The optical distortion of the lens and limited number of pixel elements are two of the additional problems of the CCD camera. Photodetectors are usually used in the auto-test setup. One configuration is to place a number of photodetectors along a segment of circle so that they have the same distance to the scanner which is placed at the center of the circle (Figure 4.4). In this

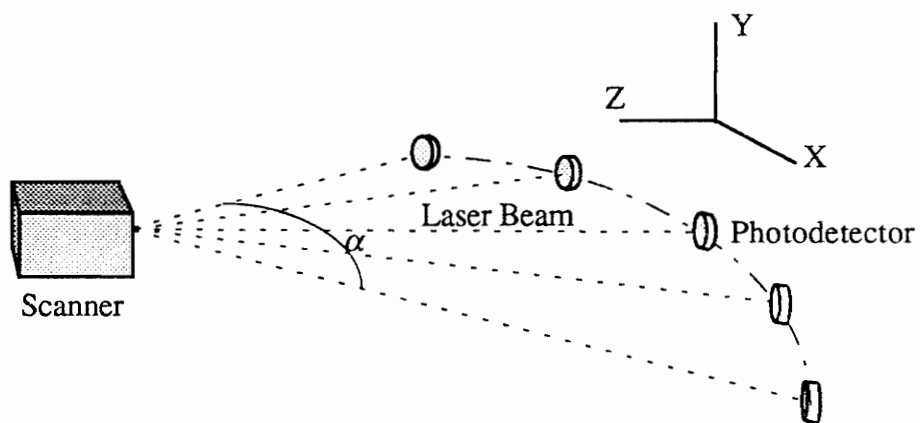


Figure 4.4 Scanning angle test with multiple photodetectors

setup, only a limited number of fixed scanning angles can be tested. Although photo sensors in matrix or linear array format have very fine pixel size, it is impractical to use them for direct scanning angle test due to the small overall size and limited number of elements. An area or lateral photo sensor outputs an analog voltage signal according to the position of the laser spot on the sensor, but this type of photo sensors usually has poor linearity.

The direct test method for scanning accuracy is simple and economic. All systematic errors from the laser and scanners are included in the test. Two distances need to be measured for scanning angle calculation. One is the distance from the scanner to the reference point on the target, and the other is from the position of the scanned laser spot on the target to the reference point. For a flat target that is parallel to the X-Y plane, the reference point naturally is the home position of the laser spot on the target, which is the center of the scanning field. Thus, the traces of the scanned laser spots on the target are perpendicular to the home position of the laser beam which is parallel to the Z-axis.

There are two major difficulties that prevent the direct method to be very accurate for scanning angle test. The first one is to accurately set up the target normal to the home position of the laser beam. For a non-orthogonality error of 1° , the error in the calculated scanning angle at 20° can be about 2,100 μrad . This error will be discussed in the next chapter. The second one is to precisely measure the distances. Given some numbers about the measurements may be helpful to make senses out of this measuring problem. Refer to Figure 4.5, assume the laser beam scans in the X direction only. Let Z be the distance from the scanner to the target with a measurement error ϵ_z , X be the distance from the scanned laser spot to the reference point with a measurement error ϵ_x , and α be the scanning angle with a computing error ϵ_α .

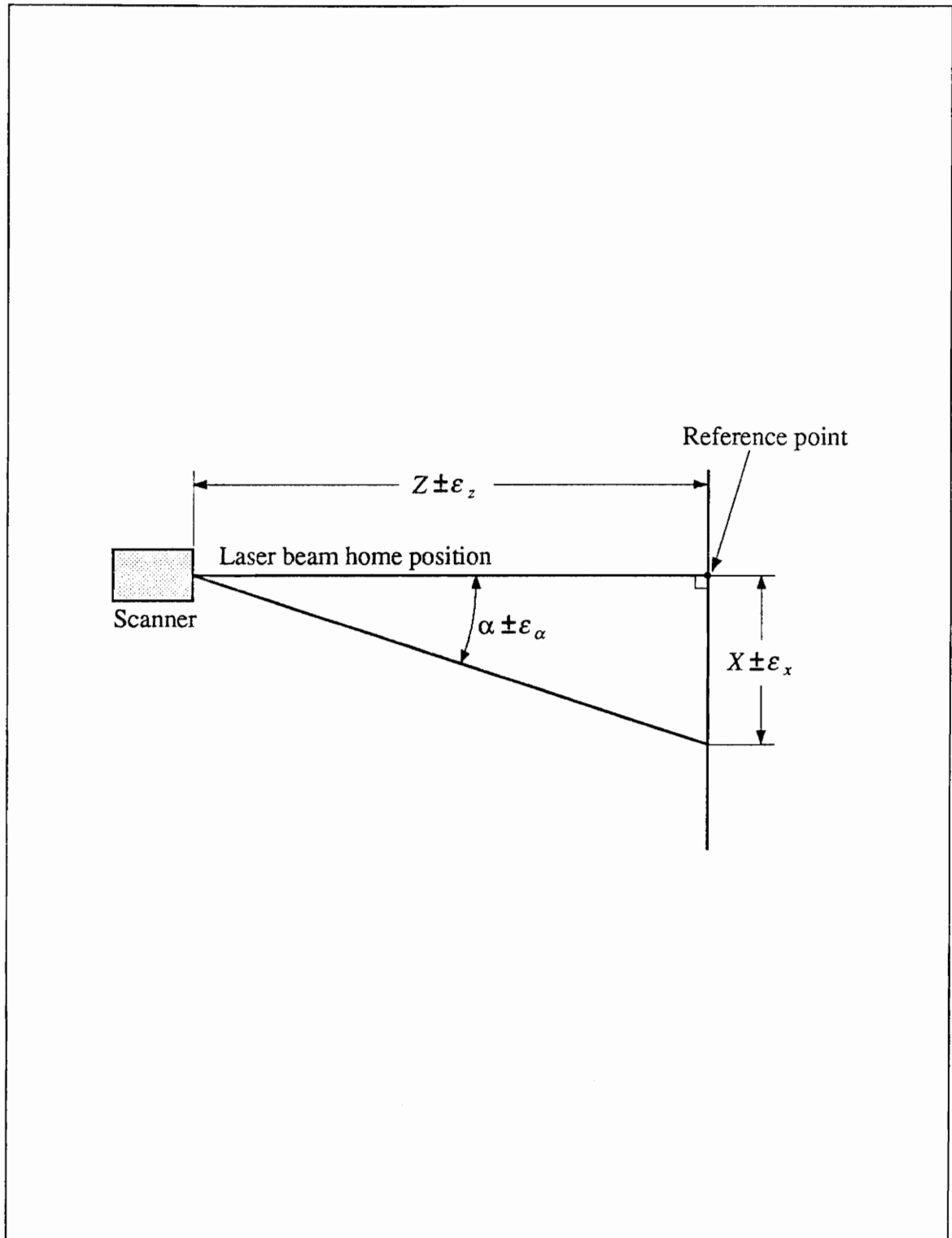


Figure 4.5 Errors in the distance measurements and scanning angle calculation

First, if ε_z is ignored, then the calculated scanning angle error, ε_α , caused by the measurement error, ε_x , can be approximated by the following equation

$$\varepsilon_\alpha \cong \frac{\varepsilon_x}{Z} \quad (4.6)$$

For $\varepsilon_\alpha = 10 \mu\text{rad}$ and $\varepsilon_x = 1 \text{ mm}$, the target needs to be 100 m away from the scanner, and the size of the target needs to be 73 x 73 m to cover 40° full scanning field. If the target is 10 m away from the scanner, the precision of ε_x measurement needs to be 0.1 mm over 7.3 m target size for the scanning angular accuracy of $10 \mu\text{rad}$. It is obviously a difficult task, but one should hold judgment until the other measurement error ε_z is analyzed. If ε_x is ignored, the relationship between ε_z , Z , ε_α , and α can be expressed as

$$\frac{\varepsilon_z}{Z} = \frac{\tan \alpha - \tan(\alpha + \varepsilon_\alpha)}{\tan(\alpha + \varepsilon_\alpha)} \quad (4.7)$$

For $\varepsilon_\alpha = 10 \mu\text{rad}$ and $\alpha = 20^\circ$, the precision of measurement, ε_z , needs to be better than 0.3 mm if the target is 10 m away from the scanner. This tolerance requirement sounds a little bit easier to reach since it is three times ε_x . The truth is just opposite. this is because the distance Z is not from the reference point to any point on the scanner but to the laser reflecting point on the mirror. For the X scanner, this distance includes the distance between the laser reflecting points on the X and Y mirrors and the distance from the reflecting point of the Y mirror to the reference point on the target. The reflecting points on the mirrors depend on laser alignment, and they are not well-defined fine points, because the laser beam is usually expanded before it enters the scanner. Actually, the

reflection of the laser beam on the mirror surface is hardly visible due to the extreme flatness and reflectivity of the mirror. Making things worse, the laser beam reflecting point travels on the mirror surface as the mirror rotates because of the offset between the mirror surface and the axis of rotation. It is not hard to imagine the difficulty of this measurement, if it is not impossible to make a such precise measurement.

A parallel-shift method is proposed for the scanning accuracy test. This method also uses a laser beam for the measurement, so it can be categorized as a direct method. However, it can avoid all the difficulty of the measurements discussed above. Figure 4.6 illustrates the test method used here.

The idea of this method is very simple: if the scanner is moved a distance, ΔZ , from position A to A' with out changing the scanning angle, α , of the laser beam, then the parallel shift of the laser beam causes the laser spot on the target plane to move a distance, ΔX , from position B to B'. If ΔX and ΔZ are perpendicular to each other, then the scanning angle, α , can be easily calculated

$$\alpha = \tan^{-1}\left(\frac{\Delta X}{\Delta Z}\right) \quad (4.8)$$

Since both are the distances of motions, the scanning angle calculated by the Equation (4.8) is independent of the distance between the scanner and the target. The distance of motion can be accurately controlled or measured by a linear translation stage of which precision of 1 μm is very common. This method does not need to have a large size target, nor a large space for the test. It is relatively inexpensive with a good accuracy. If a photodetector is mounted on a linear stage that travels along the X direction, then all the drift errors and repeatability of the scanner can be tested using the same setup. This

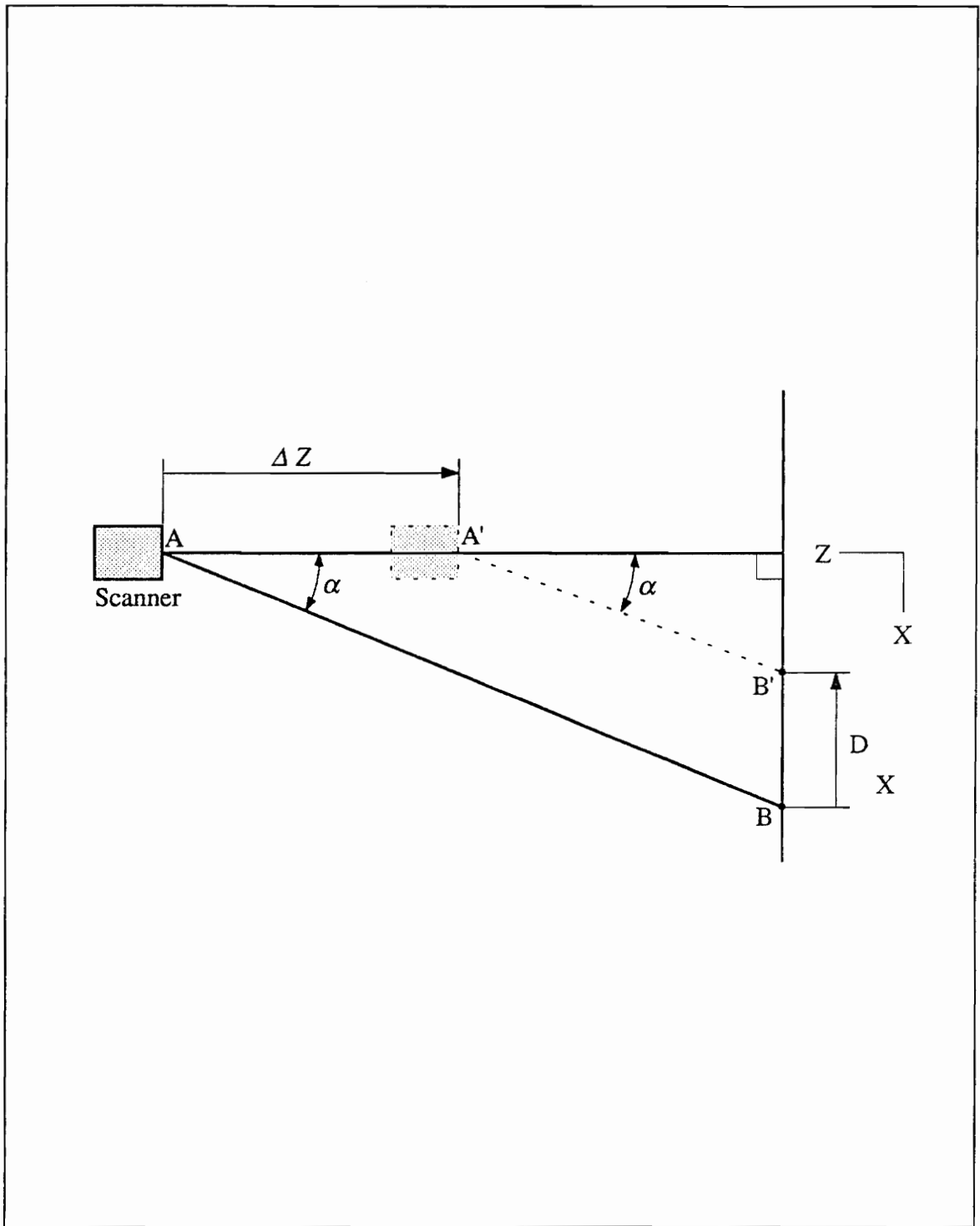


Figure 4.6 The parallel-shift method for scanning accuracy test

method can also be easily adapted for an automated test procedure. The shortcomings of this method are the inability to test the non-orthogonality error of the X and Y scanners and expensive for automation and ultra-high accuracy.

4.3. Construction of the Test Setup

The setup of the scanning time test is fairly simple. The D/A Out, Position Signal, and Position Error lines of the DE2488's diagnostic connector, along with the ATN line of the IEEE-488 interface bus, total four lines were connected to a Tektronix 2214 Digital Storage Oscilloscope. The oscilloscope has four input channels with a DC to 20 MHz analog bandwidth. It has the capability of storing 16,384 points for a waveform for each channel with maximum sampling rate of 16 megasamples per second. It can output the waveform data to a printer, a plotter, or a computer through its RS-232C serial interface. A Hewlett-Packard LaserJet III was used to plot the waveforms of the monitored signals.

The scanning times are directly measured from the plots. The IEEE-488 bus data transmission time is about 0.2 ms for one-step scan vector commands which include JX, JY, and EC. The DE2488 latency is about 1.5 ms. When the Jump commands are executed with the maximum Jump Size (32767 LSB) and minimal Step Period (0.21 ms), it is difficult to separate the DAC time, travel time, and settling time. Under these commands, the DAC time and travel time appear very short; the scanner settling takes the most of the step response time, especially for a short step size. The shortest response time is about 4.5 ms for a step size of 1^0 (1638 LSB) or about 12.5 ms for a step size of 20^0 (32767 LSB). As mentioned in the previous section, it is very difficult to tell if the scanner settles to a part in 10,000 within the measured response time, and it is impossible to know from the plot when the mirror actually stops wobbling. Several timing plots with different DE commands are included in Appendix C.

The setup for scanning accuracy testing requires more instruments than for scanning time testing. The primary guideline for the setup was to utilize available equipment and to minimize the cost. Figure 4.7 shows the top view of the setup. The test rig was set up on a regular work-bench which has a composite wood top. The size of the work-bench top is about 0.72 x 1.82 m. Two optical rails, X and Z rails, are mounted orthogonal to each other on the bench top. The lengths of the X and Z rails are 1.22 m and 1.82 m, respectively. The Z translation stage that travels in the Z direction has 100 mm travel range and can be positioned any place on the Z rail. The X translation stage that travels in the X direction has 25 mm travel range and can be mounted anywhere along the X rail. A reference block that has two precisely machined perpendicular sides is used to set the motions of the X and Z stages orthogonal to each other. Both the X and Z translation stages are manually driven by micrometers that have the resolution of 1 μm . They are manufactured by the Newport. On the top of the X stage, a right-angle bracket holds up the Y translation stage that travels in the vertical direction with a travel range of 25 mm.

The photodetector is made by the Oriel Corp. It has 5 x 5 mm detecting area. In order to precisely determine the position of the laser spot, a 25- μm pinhole is placed in front of the detector. The photodetector is mounted on a rod that is held on the Y stage. So it can travel in the X and Y directions by driving the X and Y translation stages and can face any direction by rotating the rod. The output of the detector is a DC voltage that is proportional to the laser energy. The photodetector's output is monitored by a Hewlett-Packard 3478A multimeter that has 5 1/2-digit resolution with 100 nanovolt sensitivity.

On the top of the Z translation stage, a laser-scanner base holds the scanner unit and the laser unit. The base can be mounted in two orthogonal positions for the separate tests of the X and Y scanners. The scanner unit is the General Scanning's G3B X-Y Scan Head. The laser unit consists of two translation stages, a laser beam expander, a Vee-block laser

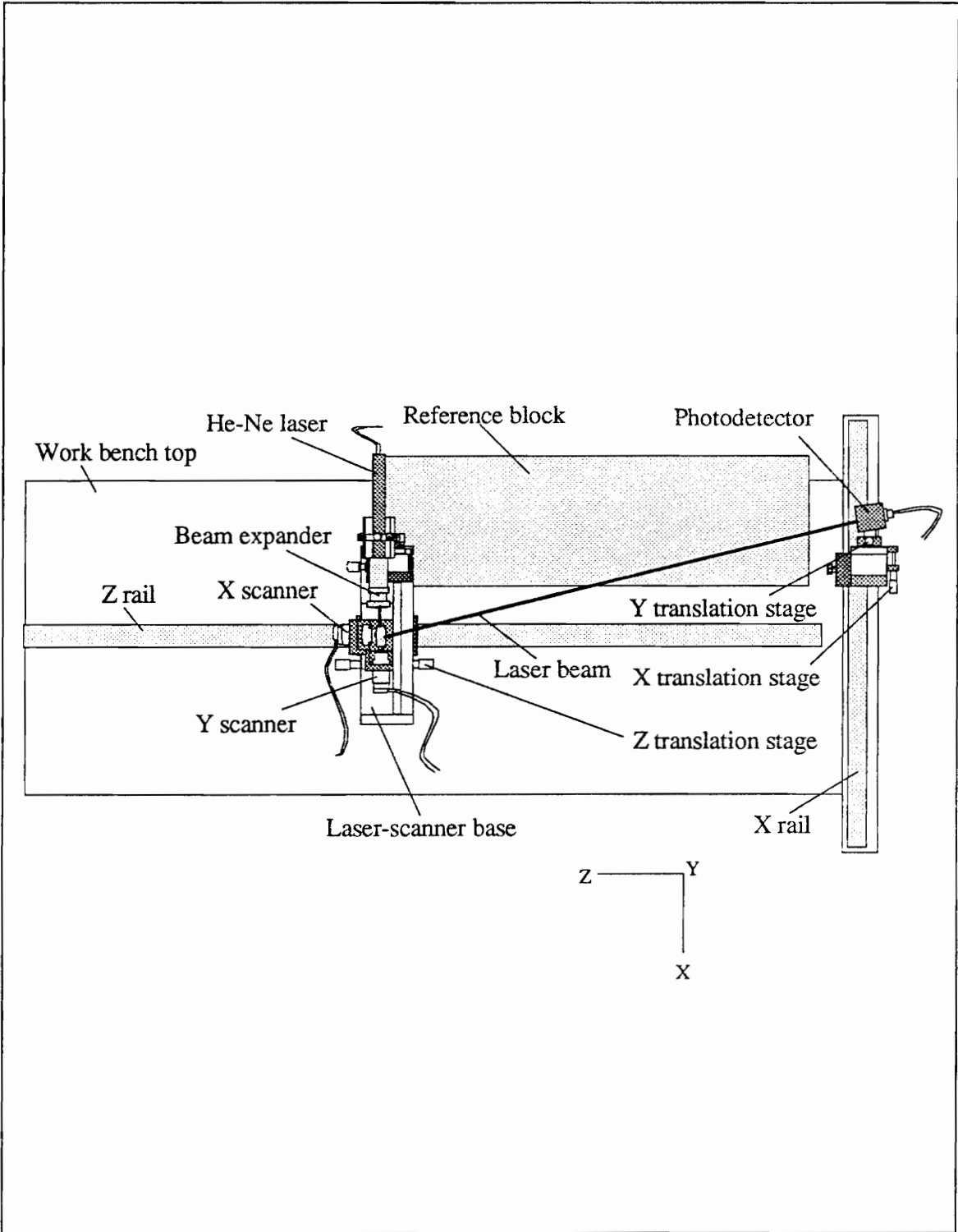


Figure 4.7 Top view of the setup for the X scanner accuracy test

holder, and a He-Ne laser. See Figure 4.8 for details. The laser is made by Uniphase and has cylindrical house with a separate power supply. According to the manufacturer's specifications, the laser has a minimal power output of 0.5 mW, $\pm 2.5\%$ power stability, ± 10 μ rad pointing stability, 0.48 mm beam output diameter, 1.7 mrad divergence, and 99% TEM₀₀ mode purity (TEM₀₀ is the lowest-order transverse laser mode, or the fundamental laser mode). The laser beam is expanded to 10 times of the output diameter by Edmund Scientific's laser beam expander that is mounted in front of the laser. The laser head and the beam expander are held by the Vee-block. A rod that supports the Vee-block is mounted on two orthogonal stages. The incident angle of the laser beam can be changed by rotating the rod. The position of the laser beam can be translated in the directions that are parallel and perpendicular to the axis of rotation of the X scanner by the two stages. The photographs of the scanning accuracy test setup can be found in Appendix D.

Here is how this test setup works. When the scanning angle of the X scanner is tested, the X mirror is set to the testing angle by sending the DE Jump commands to the DE2488 scanner controller, while the Y scanner remains at home position. The laser beam is expanded and focused by the beam expander. Then it is deflected by the X and Y mirrors. If the position of the photodetector is properly adjusted by driving the X and Y translation stages, the center of the focused laser spot can just pass through the pinhole and strike the photodetector to generate the maximum output voltage. This is because the TEM₀₀ mode laser beam has a Gaussian intensity distribution that has the maximum intensity at the center of the laser beam. Now the position of the photodetector is recorded at the first time. Then the laser-scanner unit is moved along the Z direction with a precise distance, ΔZ , by driving the Z translation stage. The laser beam will be parallel shifted accordingly. If the second position of the laser beam's center is found and recorded as the first position, then the distance between the first and second positions is the ΔX . Thus, the

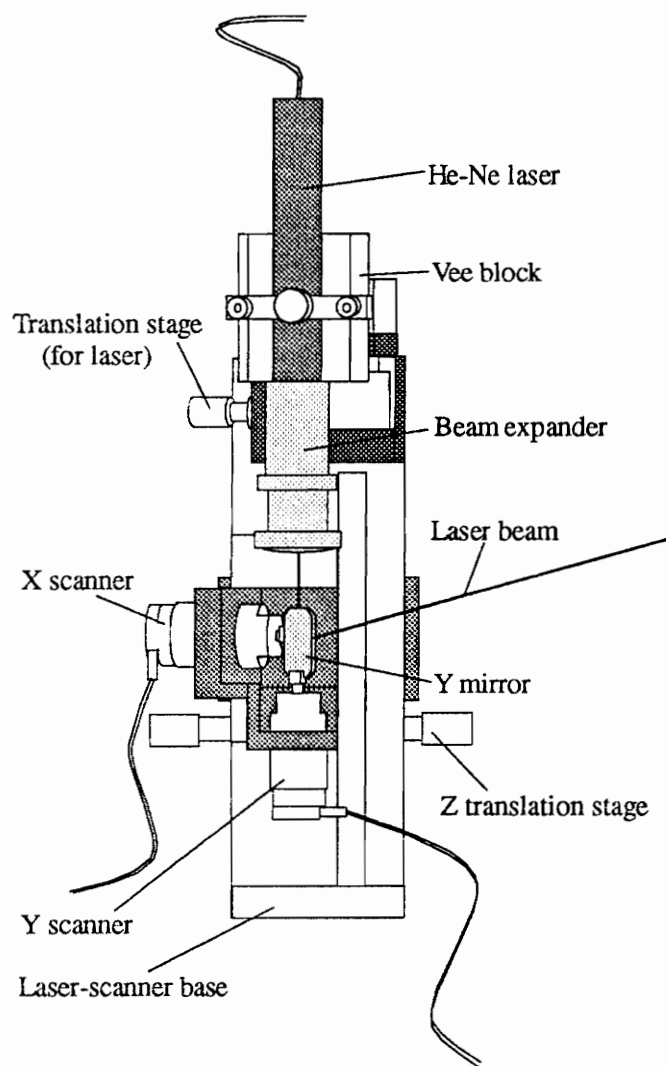


Figure 4.8 Top view of the laser-scanner unit

scanning angle of the X scanner can be calculated by using Equation (4.8). The Y scanner can be tested in the same manner. The only difference from the X scanner test is to rotate the laser-scanner unit from horizontal position to vertical position. For the repeatability and drift tests, also two positions of the laser beam's center, before and after the motions of the scanner, are recorded and subtracted. In these cases the laser-scanner unit remains stationary.

The scanning angle test results are included in Appendix F. Since the tests involve a number of errors, it needs an entire chapter to discuss the errors and the test results, which is followed.

CHAPTER FIVE

ERROR ANALYSIS FOR SCANNING ACCURACY TEST AND TEST RESULTS

The purpose of the scanning accuracy test is to quantitatively determine the errors that affect scanning accuracy. It is inevitable that the scanning accuracy test itself involves a number of errors. For the parallel-shift scanning angle test method, almost every component used in the test, including the scanner and scanner controller, has the potential to contribute an error into the scanning accuracy test. It is very important to identify these errors and their effects before the results of the scanning accuracy test can be correctly interpreted. Obviously, these testing errors set the bandwidth for the resolvable scanning accuracy. In other words, the determined scanning accuracy of the scanner cannot be better than the accuracy of the test, even though the true scanner's performances may be much better than the test results. Therefore, the overall error in test should be kept at least below the specified scanning accuracy. Furthermore, only if the overall error in test is much lower than the calibrated nonlinearity error of the scanner, computer correction of nonlinearity error to improve scanning accuracy is possible.

5.1 Errors in Scanning Accuracy Test

Naturally, errors exist in every product or procedure. For the parallel-shift scanning angle test, laser alignment, mirror surface offset, and thermal drift are just some of the error sources. Some of the errors have no real effect on scanning angle test. Some of them may be magnified by the test. The others may be small enough to be neglected. Only through careful examination each of the errors can one objectively determine the reliability of the test and the needs for the improvement of the test hardware or procedure.

5.1.1 Error in Laser Alignment

The mirrors' home positions of the X and Y scanners are set in the manufacturing of the instrument. The reference for laser alignment used by the General Scanning is two holes on the bottom of the X-Y bracket. The line passing these two reference holes is parallel to one side of the X-Y bracket that is also parallel to the X-Y plane. This side then is used as a reference to align the laser for the test setup. In Figure 5.1, a dial indicator is mounted on a translation stage. By driving the stage, one can precisely align the laser cylinder parallel to the reference side of the X-Y bracket. An alternative is to align the edge of the Vee block laser holder parallel to the reference side of the X-Y bracket. According to the laser manufacturer's specification, the laser beam is aligned to the outside diameter of the housing within 1 milliradian (0.057°). Although the General Scanning cannot provide the tolerance of setting mirror's home positions, an overall laser beam angular alignment error of 1° should be a reasonable upper limit. This error only changes the home position of the scanner output laser beam, but has no effect on the scanning angle test (see Section 5.1.2).

Angular alignment of the laser beam is only half of the laser alignment job. The other half is to position the laser beam onto the mirrors. In order to position the input laser beam, the mirror's axis of rotation needs to be located first. For dynamically ideal mirror mounting (refer to Figure 3.2), the center line of the mirror should coincide with the axis of rotation but the mirror surface will be above this axis. Since the mirror is mounted symmetrically about its center line with high precision, the axis of rotation can be located by moving the laser spot across the mirror surface.

Figure 5.2 shows how to locate the axis of rotation. As described in Section 4.3, the laser is mounted on a set of orthogonal translation stages. One of the stages can laterally shift the laser beam in the direction that is parallel to the mirror's axis of rotation. The

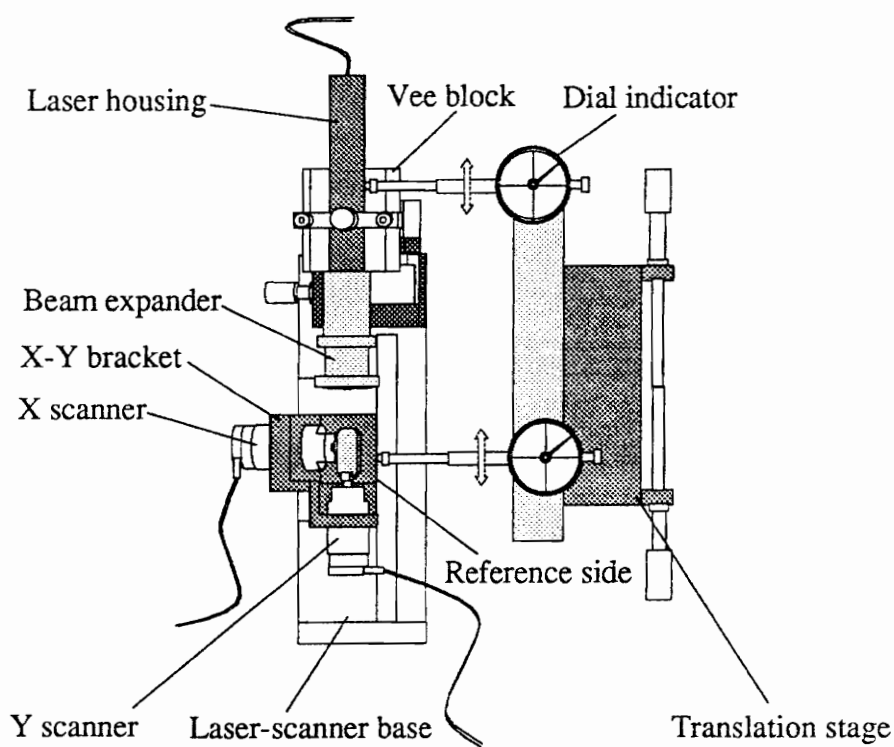


Figure 5.1 Setting the laser parallel to the X-Y bracket

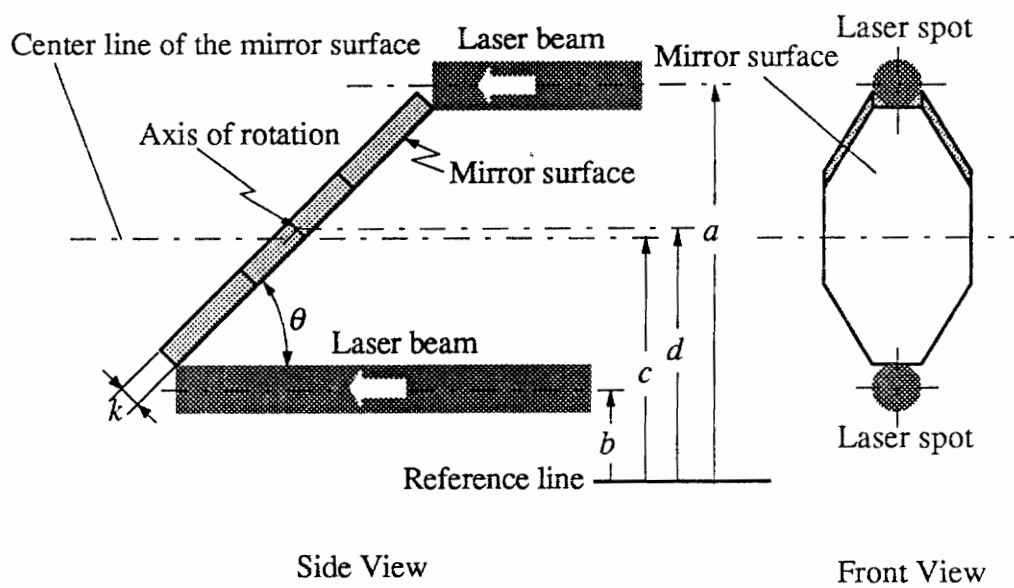


Figure 5.2 Locating the axis of rotation

other stage laterally shifts the laser beam in the direction that is perpendicular to the axis of rotation. If the readings of the stage's micrometer are a and b when the laser beam is laterally shifted just off the top and bottom edges of the mirror, respectively, then the location of the center line of the mirror surface, c , is at half way between a and b . The location of the axis of rotation, d , can be found by

$$d = \frac{a+b}{2} + \frac{k}{2} \cos \theta, \quad (5.1)$$

where k is the thickness of the mirror and θ is the incident angle of the laser beam on the mirror. However, this method involves some assumptions. First, the geometric center line of the mirror is assumed coincident with the axis of rotation. Second, the laser beam is assumed collimated, that is, its diameter does not vary with the distance from the laser. This is true for the test apparatus, but may not be true in the final end user product. Third, that the cross-section of the laser beam is assumed a perfect circle. The last assumption is that the laser angular alignment is accurate. Since the errors corresponding to violation of these assumptions are quite small, it should be easy to locate the axis of rotation within an accuracy of a half millimeter. The optimal position of the center of the input laser beam, however, should intersect the center line of the mirror surface rather than the axis of rotation. This minimizes the scanning error caused by the offset between the mirror surface and the axis of rotation. This will be discussed in the following section.

An alternative to positioning the input laser beam or to confirm the laser beam's position is to directly measure the position of the input laser beam relative to the base of the X-Y bracket. The blueprint of the X-Y scan head provided by the General Scanning shows the tolerance for the location of the X mirror's center relative to the base is 0.02

inch (or 0.5 mm). However, the error in the input laser beam position has no effect on the scanning angle test. It only increases the parallel-shift error of the laser beam during scanning. This will be discussed in the following section.

5.1.2 Error Due to Mirror Surface Offset

For the dynamic balance, the mirror is mounted symmetrically with respect to the axis of rotation (refer to Section 3.1.1). Since the incident point of the laser beam cannot be on the axis of rotation, it travels on the mirror surface as the mirror rotates. Figure 5.3 shows the situation. The mirror position A is the home position that forms an angle, θ , with the input laser beam. When the mirror rotates an angle, $\alpha/2$, about the axis of rotation to the position B, the output laser beam scans an angle, α . However, since the intersecting point of the input laser beam and the mirror's front surface changes position as the mirror rotates, the output laser beam scans and is also shifted a distance, e , in the direction parallel to the input laser beam. This parallel shift error, e , of the scanned laser beam can be found according to

$$e = \frac{d \sin \frac{\alpha}{2} + \frac{k}{2} \sin \theta \left(1 - \cos \frac{\alpha}{2} \right)}{\sin \left(\theta - \frac{\alpha}{2} \right) \sin \theta}, \quad (5.2)$$

where k is the mirror thickness and d is the distance from the center of the mirror surface to the input laser beam. In Figure 5.3 we can see that when the parallel-shift error, e , at $\alpha = 20^\circ$ is the same as at $\alpha = -20^\circ$, e has the minimal value. The optimal location of the laser, d_{op} , can be solved by equating Equation (5.2) that is evaluated at $\alpha = 20^\circ$ and $\alpha = -20^\circ$

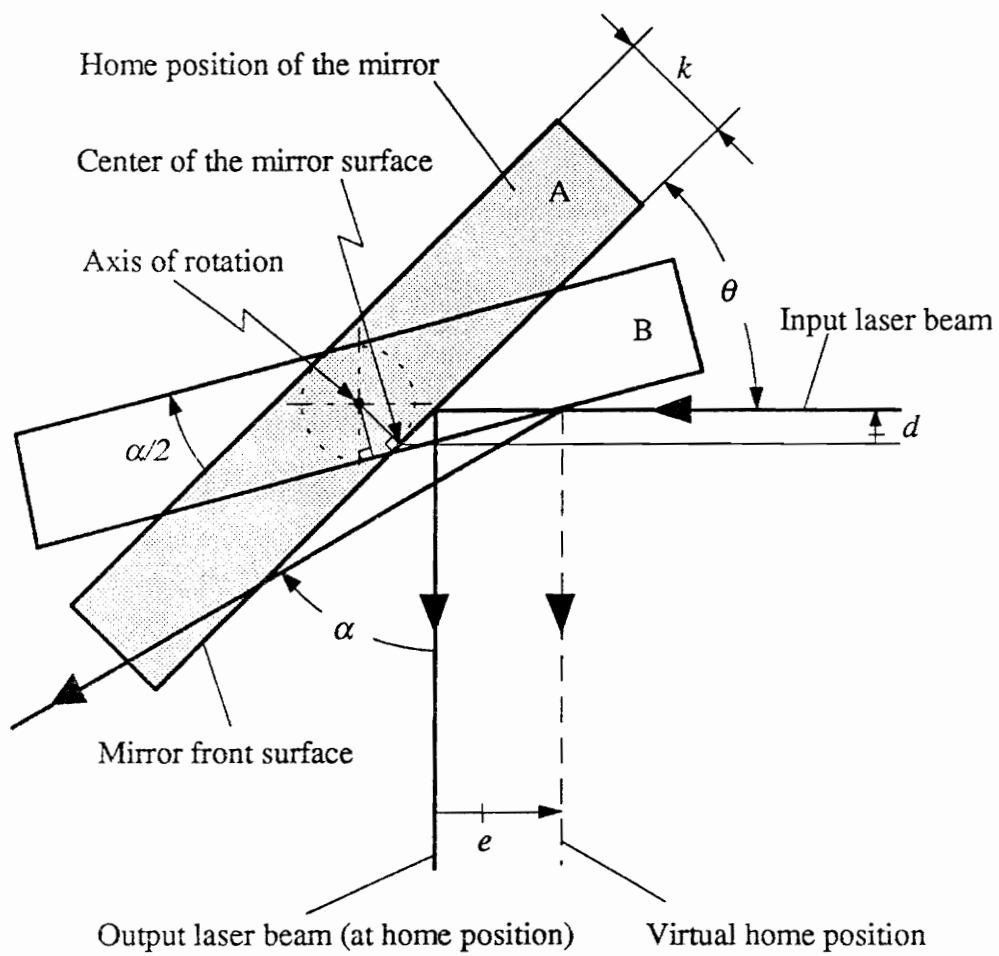


Figure 5.3 The parallel-shift error of the scanned laser beam

$$\frac{d_{op} \sin \frac{20^\circ}{2} + \frac{k}{2} \sin \theta \left(1 - \cos \frac{20^\circ}{2} \right)}{\sin \left(\theta - \frac{20^\circ}{2} \right) \sin \theta} = \frac{d_{op} \sin \frac{-20^\circ}{2} + \frac{k}{2} \sin \theta \left(1 - \cos \frac{-20^\circ}{2} \right)}{\sin \left(\theta - \frac{-20^\circ}{2} \right) \sin \theta} \quad (5.3)$$

or

$$d_{op} = \frac{k}{2} \cos \theta \left(1 - \frac{1}{\cos 10^\circ} \right) \quad (5.4)$$

The nominal angle between the input laser beam and the mirror surface at the home position, θ , is 45° for the X scanner and 53.5° for the Y scanner. For $k = 3$ mm, $d_{op} = -0.016$ mm for the X scanner and $d_{op} = -0.014$ mm for the Y scanner. Figures 5.4 and 5.5 are the plots of the laser beam parallel-shift errors according to Equation (5.2) for the X and Y scanners, respectively. Three cases are plotted for each scanner. The first case is that the input laser beam is aimed at the center of the mirror surface ($d = 0$). The other two are of the input laser beam 0.5 mm above and 0.5 mm below the center of the mirror surface ($d = 0.5$ mm and $d = -0.5$ mm, respectively). For $\theta = 45^\circ$ and $d = 0.5$ mm, the output laser beam is shifted laterally 0.2538 mm when it scans 20° , which corresponds to an angular error of $224 \mu\text{rad}$ for a test object is 1 m away or $22.4 \mu\text{rad}$ when 10 m away from the scanner. This error certainly affects the scanning accuracy, especially when the test object is close to the scanner. However, since the test method for the scanning accuracy measures the true scanning angle only, the laser beam parallel-shift error does not affect the determination of scanning angles. The method to reduce this laser beam parallel-shift to improve scanning accuracy will be discussed in the next chapter.

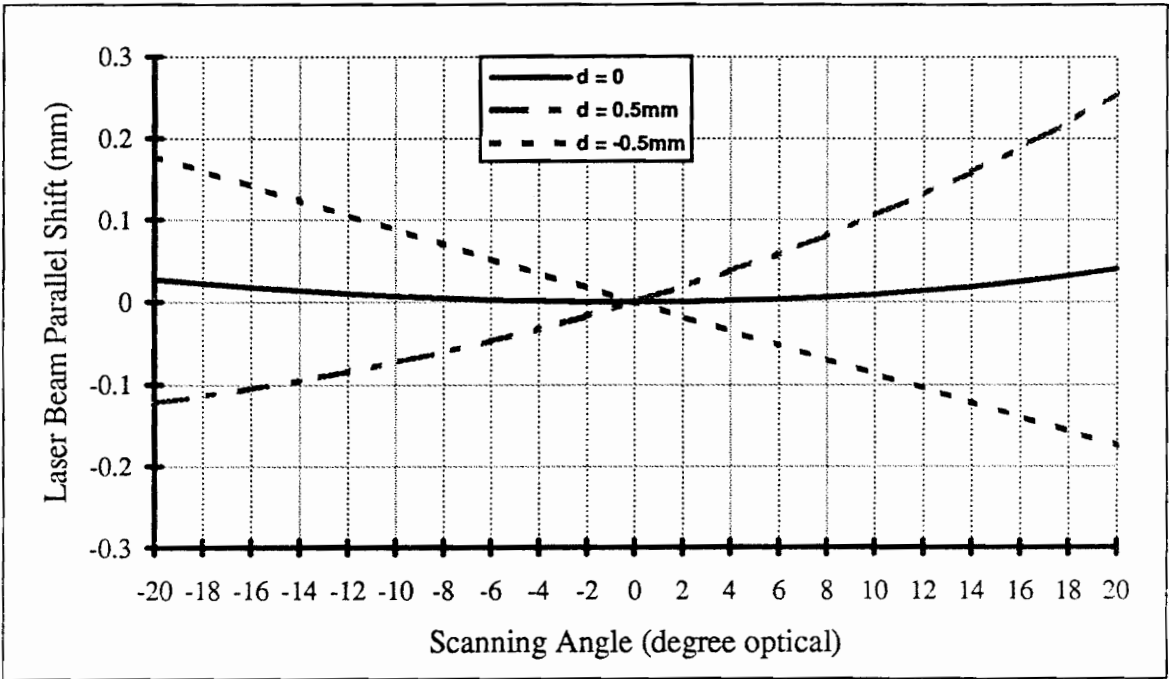


Figure 5.4 Theoretical laser beam parallel-shift error for the X scanner

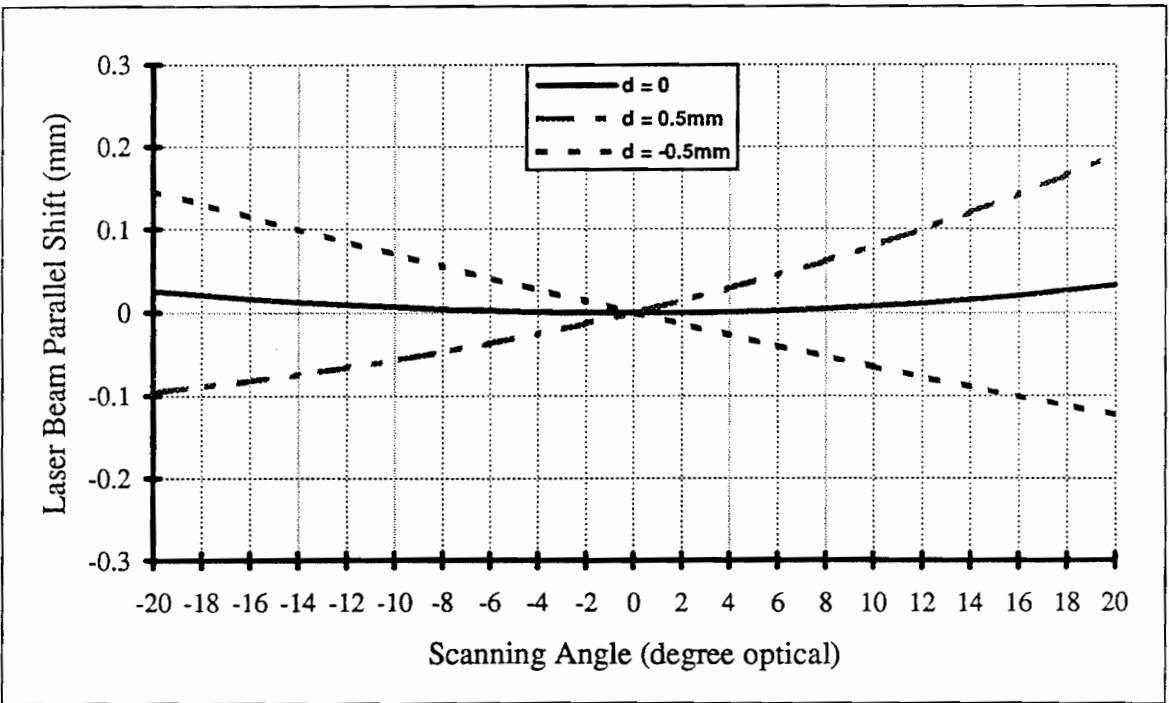


Figure 5.5 Theoretical laser beam parallel-shift error for the Y scanner

5.1.3 Error in Determining the Position of the Focused Laser Spot

The position of the focused laser spot is determined by the photodetector, along with the X and Y stages (refer to Section 4.3). A 25- μm pinhole is set in front of the detector to allow only partial laser radiation passing through. The output voltage of the photodetector reaches the maximum when the center portion of the laser beam passes through the pinhole and strikes on the detecting area. The multimeter (Hewlett-Packard 3478A) used to display the output of the photodetector is set to have a resolution of 0.0001 VDC. Although the maximum resolution of the multimeter is 0.00001 VDC, it is too sensitive to the noise of the detecting circuit for this maximum resolution.

When the scanner is about 1 m away from the photodetector, the maximum output of the detector is about 0.4700 VDC without the pinhole or 0.3600 VDC with the pinhole for the fine focused laser beam. This implies that about 76.6% of the total laser energy passes through the pinhole when the center of the laser beam coincides with the pinhole's center. Since 99% of the laser beam is of the Gaussian TEM₀₀ mode, the cross-section intensity profile of the laser beam is a bi-normal distribution function. Figure 5.5 represents the change of the laser energy that passes through the pinhole due to the displacement of the pinhole as a projection into a single flat plane normal distribution. When the pinhole is centered with the laser beam, the laser energy passing through the pinhole corresponds to the shaded area between $z = -1.19$ and $z = 1.19$, where z is defined as the percentile of the standard normal distribution. If the pinhole is laterally displaced by a distance, δ , the shaded area that corresponds to the passing laser energy will be between $z = \delta_z - 1.19$ and $z = \delta_z + 1.19$, where δ_z is the change of the variance that corresponds to the pinhole displacement δ . The minimal change of the laser energy that can be detected by the photodetector depends on the sensitivity of the multimeter. For this test setup, the 0.0001 VDC multimeter resolution over the maximum output of 0.3600 VDC gives a

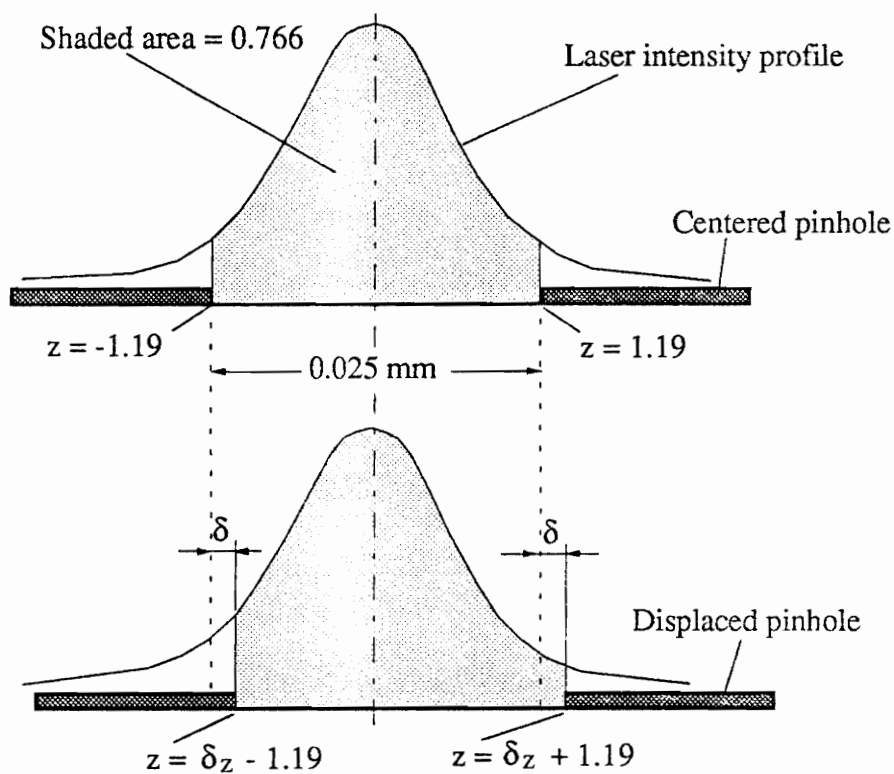


Figure 5.6 Change of laser energy due to the displacement of the pinhole

sensitivity of 0.0278%. This sensitivity corresponds to an area change of 0.000278 for the normal distribution function. The change of the variance, δ_z , for the area change then is 0.034. This gives the minimal pinhole displacement, δ , of 0.4 μm . This is only an approximation due to the fact that both the pinhole and the cross-section of the laser beam are circles, not flat planes. Besides, the intensity of the laser beam usually is not a perfect bi-normal distribution function due to the laser noise and the distortion caused by the beam expander and the mirrors. In the experiment for determining the laser beam's position, the photodetector was slowly moved across laser beam by driving the X stage. When the output of the photodetector reached the maximum value, the position of the photodetector was recorded. The same procedure was repeated 10 times for each laser beam position. The 3σ value of the measurements about the mean position of the laser beam is about 5 μm , where the σ is the sample standard deviation. This uncertainty involves the multimeter sensitivity, resolution of the stage's micrometer, backlash of the stage, drift of the laser and scanner, and vibration of the workbench and the test setup.

For the thermal drift and repeatability tests, the angular error in the test that is caused by the uncertainty error is small if the distance between the scanner and the photodetector is large. For instance, the uncertainty error of 5 μm for the determination of the laser beam's position gives only 5 μrad angular error for a distance of 1 m between the scanner and the detector. However, the uncertainty error has a large impact on the setup for the scanning angle test. This is because the accuracy of the scanning angle test depends on the travel ranges of the X and Z translation stages, not on the distance between the scanner and the detector (refer to Equation (4.8)). The maximum travel range is 25 mm for the X stage and 100 mm for the Z stage. The uncertainty error of 5 μm in ΔX can cause an angular error of 64 μrad in the scanning angle computation (using Equation (4.8)), if the

full travel range is used. The angular error can be even higher if only part of the travel range is used in the scanning angle test.

5.1.4 Laser Beam Angular Drift Error

The error due to the laser beam drift perhaps is the most serious problem for this test setup. The angular drift of the laser beam with respect to the photodetector comes from several sources.

The first source of drift is the laser itself. This drift should be less than 10 μrad according to the manufacturer's specification. The actual laser drift is confirmed to be within 5 μrad for a 30 minutes period by using the test setup. It seems that the laser drift is small and random. Because of the uncertainty error of determining the laser beam's position, the test accuracy for the laser drift cannot be better than 5 μrad . Also, the laser drift test with a longer period is not reliable because it would involve the thermal drift due to other components of the setup since there is little control of the room temperature.

The second cause of the laser beam drift is from the drift of the scanners. The scanner's position transducer and the DE controller are sensitive to the change of the temperature. According to the General Scanning's specifications, the minimal drift of the G3B scanner (with temperature control) is 10 $\text{ppm}/^{\circ}\text{C}$ for gain drift and 10 $\mu\text{rad}/^{\circ}\text{C}$ for zero drift, which gives a total drift of 15 $\mu\text{rad}/^{\circ}\text{C}$ at 20° scanning angle. There is no temperature control for the DE controller. Also, the General Scanning does not specify the drift on the output of the DE controller. Figure 5.7 shows the laser beam angular drift that corresponds to the measured DAC output drift of the X servo and the position output drift of the X scanner. Figure 5.8 shows the similar drifts for the Y servo and the Y scanner. In Figure 5.7 the X servo's DAC output and the X scanner's position output at each sample point were measured at the room temperature of 19°C and 27.5°C with the HP 3478A

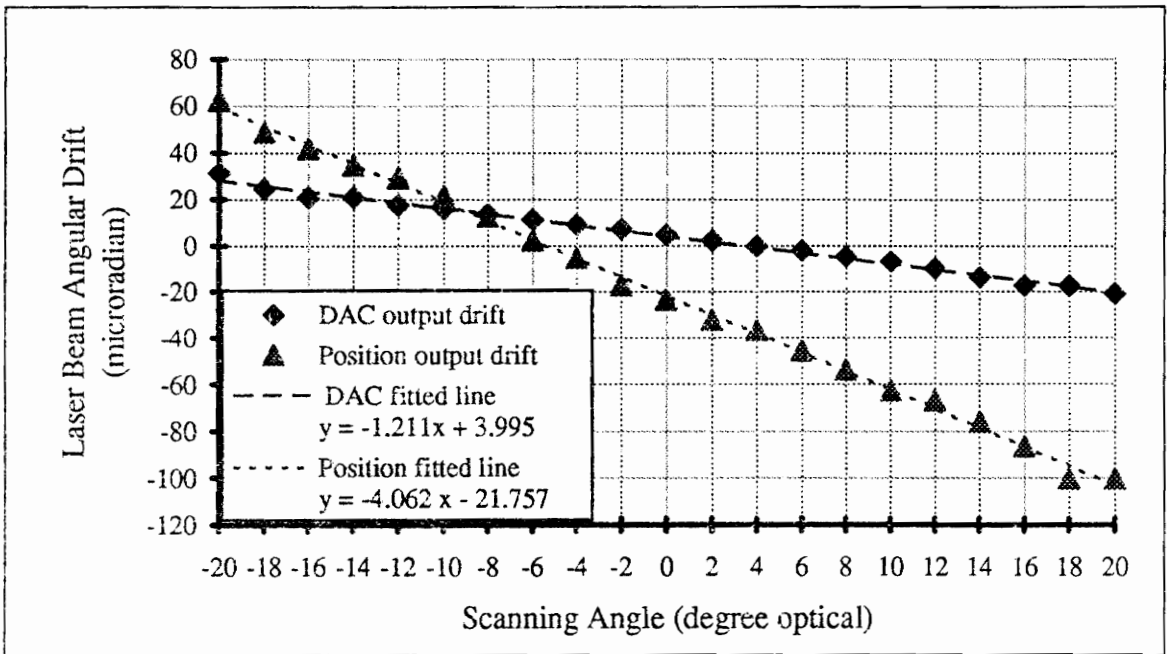


Figure 5.7 Measured thermal drift of the X scanner's servo and position sensor (from 19°C to 27.5°C room temperature)

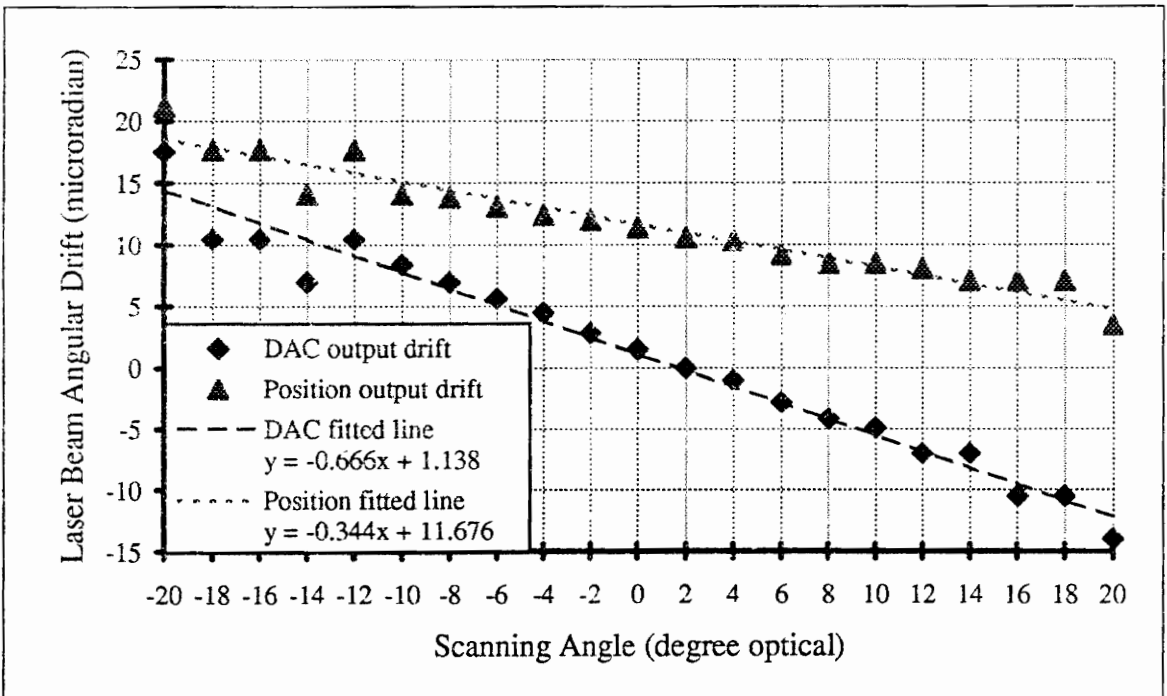


Figure 5.8 Measured thermal drift of the Y scanner's servo and position sensor (from 20°C to 27.5°C room temperature)

Multimeter. The difference of the outputs at these two room temperatures for each sample point was multiplied by the calibration factor to obtain the corresponding laser beam angular drift. The accuracy of the measurement was limited by the precision of the multimeter to about $\pm 3.5 \mu\text{rad}$ on each data point. The same procedure was followed to obtain the data for the Y servo and scanner in Figure 5.8, except the measurements were made at the room temperature of 20°C and 27.5°C . In Figures 5.7 and 5.8 the measured data for each output were fitted to a straight line by the least-squares technique. The slope of each fitted line is the gain drift in the unit of microradians per optical degree. The intercept of each line is the zero drift in the unit of microradian. The gain drift and zero drift for each output are listed in Table 5.1 with the units converted to $\text{ppm}/^\circ\text{C}$ and $\mu\text{rad}/^\circ\text{C}$, respectively.

Table 5.1 Measured thermal drift of the servo and position sensor of the scanners
(Extracted from data in Figures 5.7 and 5.8)

Output	Gain Drift ($\text{ppm}/^\circ\text{C}$)	Zero Drift ($\mu\text{rad}/^\circ\text{C}$)	Total Drift ($\mu\text{rad}/^\circ\text{C}$) (for $\pm 20^\circ$)
DAC of the X servo	-8.2	0.5	3.3
Position sensor of the X scanner	-27.4	-2.6	12.1
DAC of the Y servo	-5.1	0.2	1.9
Position sensor of the Y scanner	-2.6	1.6	2.5

It can be seen that part of the drift of the position sensor output is caused by the drift of the DAC output. The measured position sensor drift can be used as an approximation of the scanner's drift, but it might not represent the actual angular drift of the scanner. The actual drift of the scanner can be detected by measuring the drift of the laser beam. This presents some difficulties in the current test setup because of the other drifts involved,

such as the laser drift and the thermal effect of the work-bench. The laser drift appears small and random as discussed previously. The thermal effect of the work-bench is much more complicated. It may be the most serious cause of the drift of the laser beam during the scanning angle test. The work-bench has a 45-mm-thick wooden top. The frame of the work-bench is made of structure steel and sheet metal. The work-bench top is firmly mounted on the frame along all four edges. There is no support under the middle of the work-bench top. The Z rail is made of aluminum and mounted on the center of the work-bench top (refer to Figure 4.7). Since the thermal conductivity of aluminum is almost 1,200 times higher than that of wood, the response to the change of room temperature is much greater for the rail than for the bench top. The difference in thermal expansion of the rail and the bench top causes the bench top to bend, which has the same effect on the laser beam as if were drifting due to temperature change. To qualitatively determine the thermal effect of the work-bench, two experiments were conducted. The laser-scanner unit was set at horizontal position in one experiment and at vertical position in the other experiment. In order to eliminate the effect of the scanner's drift, a front-surface plane mirror was firmly set between the laser and the scanner to deflect the laser beam directly to the photodetector. Prior to the experiments, the room was cooled down by the use of an air conditioner. After the air conditioner was turned off, the room temperature rose gradually and was monitored by using a digital thermometer with a resolution of 0.1°C . The drift of the focused laser spot related to the detector's position was measured by moving the X and Y translation stages (refer to Figure 4.7). The distance between the laser unit and the photodetector was about 1.4 m which gave an angular accuracy of $3.6\text{ }\mu\text{rad}$ for the laser beam position error of $5\text{ }\mu\text{m}$. The data were taken approximately every half hour. Figures 5.9 and 5.10 shows the results of these two experiments. The ranges and rate of the changes of room temperature for two experiments were not the same for lack of effective

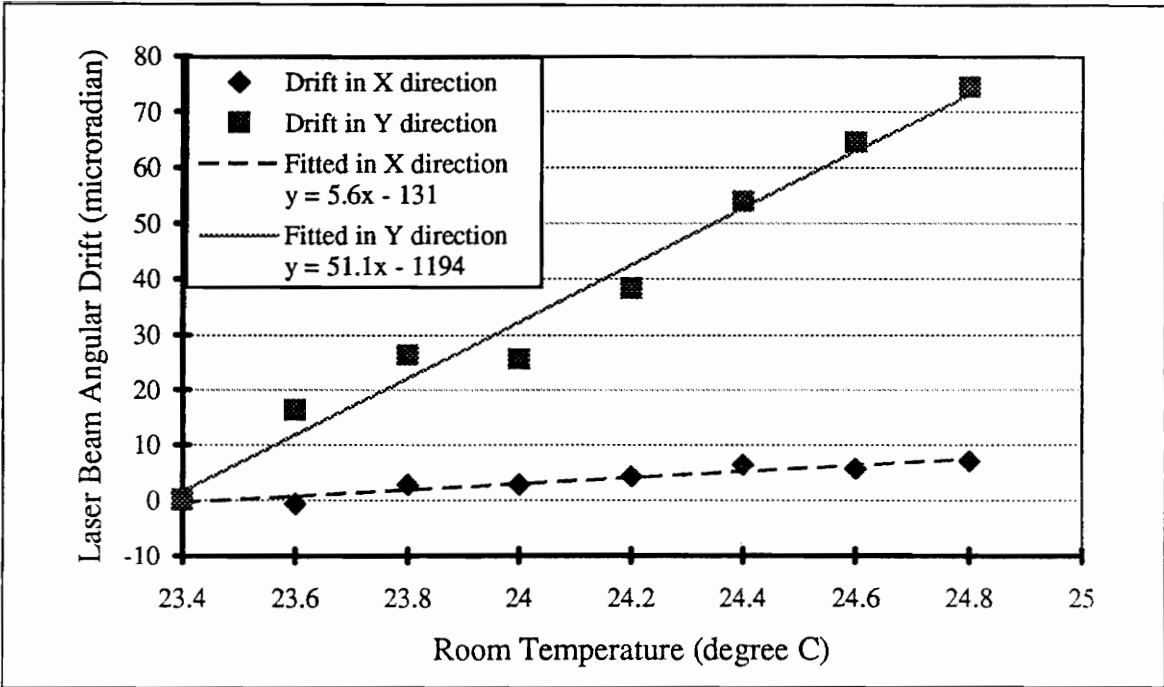


Figure 5.9 Measured thermal drift of the laser beam without the scanners (Laser-scanner unit at vertical position)

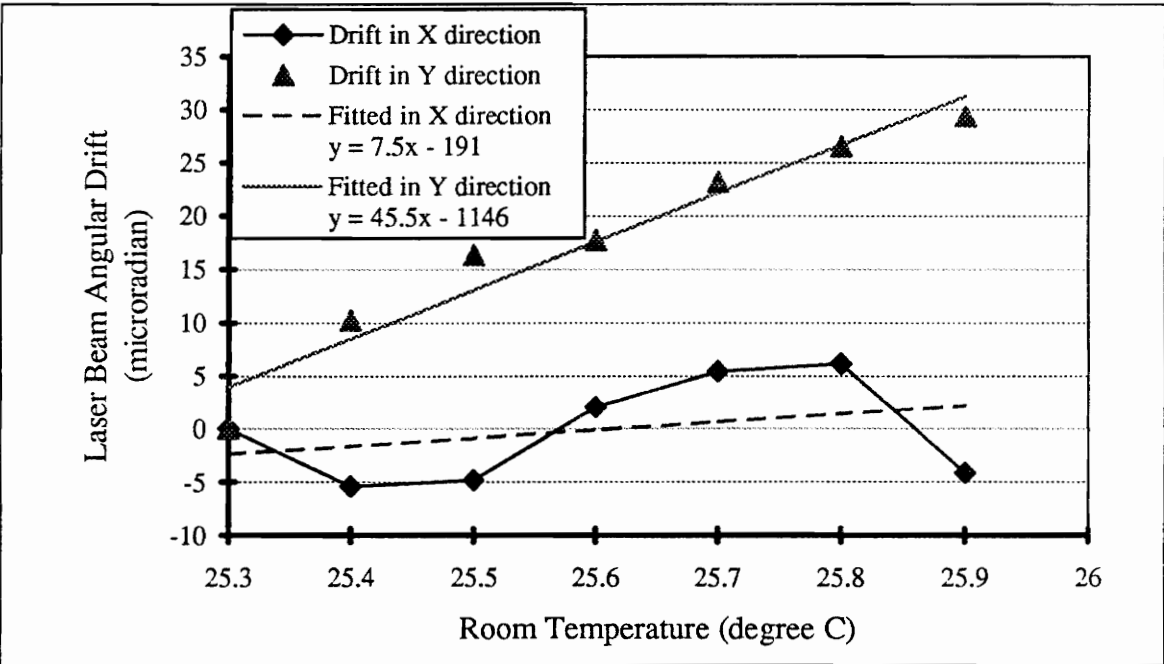


Figure 5.10 Measured thermal drift of the laser beam without the scanners (Laser-scanner unit at horizontal position)

means to control the room temperature. Although the scanner drift was not included in the test, the laser drift was unable to be singled out from the test results. However, the results of the experiments still showed some consistencies of the measured laser beam drift in the X and Y directions regardless of the position of the laser-scanner unit. From Figures 5.9 and 5.10, the laser beam drift in the X direction was small, $5.6 \mu\text{rad}/^\circ\text{C}$ drift at the vertical position and $7.5 \mu\text{rad}/^\circ\text{C}$ drift at the horizontal position of the laser-scanner unit. The main part of the X-direction laser beam drift is most likely contributed by the laser drift. The laser beam drift in the Y direction was much larger and obviously related to the change of room temperature that produced the thermal effect of the bench top. The measured laser beam drift in the Y direction was about $51.1 \mu\text{rad}/^\circ\text{C}$ at the vertical position and $45.5 \mu\text{rad}/^\circ\text{C}$ at the horizontal position of the laser-scanner unit.

The laser beam drift can give a serious problem to the scanning angle test, especially the drift in the X direction. Figure 5.11 illustrates the effect of the laser beam drift in the scanning angle test. Suppose the scanning angle to be tested is α when the scanner is at position A. When the scanner travels a distance, ΔZ , to position A', the focused laser spot at the X-Y plane should move from position B to B'. However, if the laser beam drifts an angle, ε_α , in the X direction, the laser spot will be at position B'' instead of B', and the measured movement of the laser spot in the X direction will be $(\varepsilon_x + \Delta X)$. If the distance between the scanner and the X-Y plane is Z, then $\varepsilon_x \approx \varepsilon_\alpha Z$. The angular error in the calculated scanning angle, ε_{ac} , according to Equation (4.8), will be

$$\varepsilon_{ac} = \tan^{-1} \left(\frac{\Delta X + \varepsilon_\alpha Z}{\Delta Z} \right) - \alpha \quad (5.5)$$

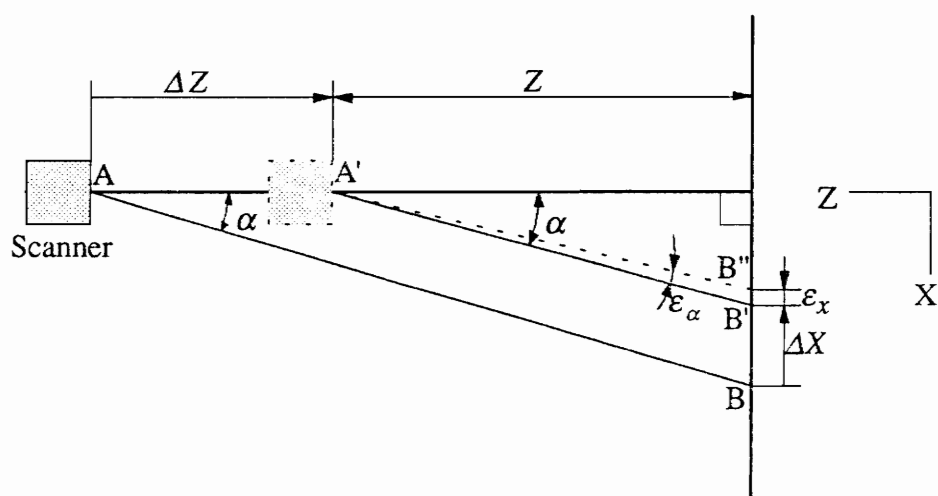


Figure 5.11 The effect of the laser beam's thermal drift in the scanning angle test

When the scanning angle, α , is small ($\alpha = 0$ is the worst case) and when the laser beam angular drift, ε_α , is small (the usual case), Equation (5.5) becomes

$$\varepsilon_{\alpha c} \approx \varepsilon_\alpha \frac{Z}{\Delta Z} \quad (5.6)$$

That is, the laser beam angular drift error is magnified in the scanning angle test by the ratio of the distance between the scanner and the photodetector to the distance traveled by the scanner unit! If in the test setup, Z is 1,000 mm, ΔZ is 50 mm, and the laser beam angular drift, ε_α , in the X direction is only 10 μ rad, the calculated error, $\varepsilon_{\alpha c}$, in the scanning angle can be as large as 200 μ rad. Unfortunately, the minimal ratio of the distance between the laser-scanner unit and the photodetector over the travel range of the laser-scanner unit is around 20 for the current test setup. This dilemma is caused by the limited maximum travel of the stage that moves the laser-scanner unit, and by the minimal distance between the laser-scanner unit and the photodetector which is limited by the minimal focus length of the beam expander.

5.1.5 Non-orthogonality Error of the X and Z Translation Stages

In all the equations for computing the scanning angle, the movements of the X and Z translation stages, ΔX and ΔZ , are assumed to be orthogonal to each other. In the reality, it is impossible to set these two stages perfectly orthogonal. The effect of the non-orthogonality error of the X and Z stages in the scanning angle test certainly cannot be neglected. Figure 5.12 shows the effect of this error in the scanning angle test. The measured laser spot movement, $\Delta X'$, instead of ΔX , is used in Equation (4.8) to compute the scanning angle. If one lets ε_x be the non-orthogonality error of the X and Z stages and

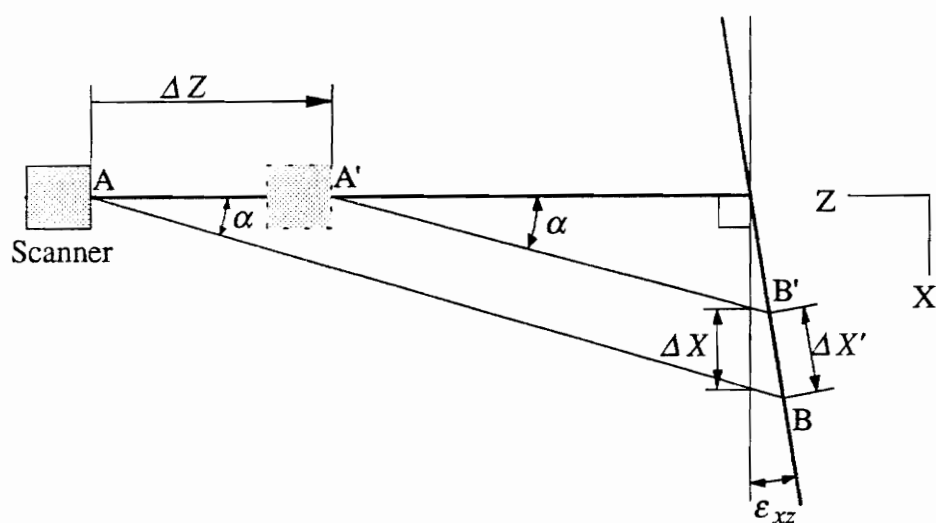


Figure 5.12 The effect of the non-orthogonality error of the X and Z stages

α be the true scanning angle to be tested, then the angular error, ε_{α} , in the calculated scanning angle can be expressed as

$$\varepsilon_{\alpha} = \tan^{-1} \left[\frac{\sin \alpha}{\cos(\alpha + \varepsilon_x)} \right] - \alpha \quad (5.7)$$

Clearly, the error in the calculated scanning angle caused by the non-orthogonality error of the stages is independent of the scanner unit travel distance and the distance between the scanner and the photodetector. For a non-orthogonality error of 0.1° ($1,745 \mu\text{rad}$) and a scanning angle of 20° , the error in the calculated scanning angle is about $205 \mu\text{rad}$. Therefore, it is crucial to reduce the non-orthogonality error for the scanning angle test. One way to reduce the non-orthogonality error of the stages is to use a reference block (refer to Figure 4.7). The two sides of the reference block that are along the X and Z rails were precisely machined to be perpendicular. According to the certificate of the milling machine upon which the aluminum reference block was manufactured, the perpendicularity of the two machined sides should be within $0.0003"/12"$, which is about 0.00143° . For a scanning angle of 20° , this perpendicularity gives only $3 \mu\text{rad}$ error in the calculated scanning angle. To set the movements of the X and Z stages parallel to the machined edges of the reference block, a dial indicator was mounted on each stage (same ideal as depicted in Figure 5.1). Obviously, the ability to adjust the stages parallel to the reference block will increase this error.

5.1.6 Other Errors in the Scanning Angle Test

In the previous analyses, it is always assumed that the home-position of the laser beam is parallel to the movement of the Z stage, ΔZ , which is the Z-axis in the scanning

angle test. In reality, accurate alignment of the home-position of the laser beam with the Z stage is difficult and is not needed. In Figure 5.13, the home-position of the laser beam forms an angle, α_h , with the Z-axis in the X-Z plane. This angle, α_h , can be treated as a scanning angle and can be determined by the exactly same method as any other scanning angle. The actual tested scanning angle, α , is then

$$\alpha = \tan^{-1}\left(\frac{\Delta X}{\Delta Z}\right) \pm \alpha_h \quad (5.8)$$

The sign of α_h in Equation (5.8) depends on the sign of the tested scanning angle, α . Since this home-position angle is very small and the time needed to measure this single angle is short, the expected error in determining this angle should be smaller than the error in determining a general scanning angle. This is because the effects of some of the errors discussed previously, such as the thermal drift and the non-orthogonality error, will be small in determining this home-position angle. However, the error in this calculated home-position angle will have the same effect on each tested scanning angle. The entire scanner calibration curve will be shifted by the error in α_h .

There is another assumption made throughout the analyses, that is the scanned laser beam is assumed parallel to the X-Z plane that is defined by the movements of the X and Z stages. Again, it is hard to accurately set the scanned laser beam parallel to the X-Z plane. The Y translation stage of the detector unit is used to solve this problem (refer to Figure 4.7). If the scanned laser beam is not parallel to the X-Z plane, the displacement of the scanner unit, ΔZ , causes the focused laser spot to shift not only in the X direction, ΔX , but also in the Y direction (refer to Figure 4.6). This laser beam shift in the Y direction, ΔY , is

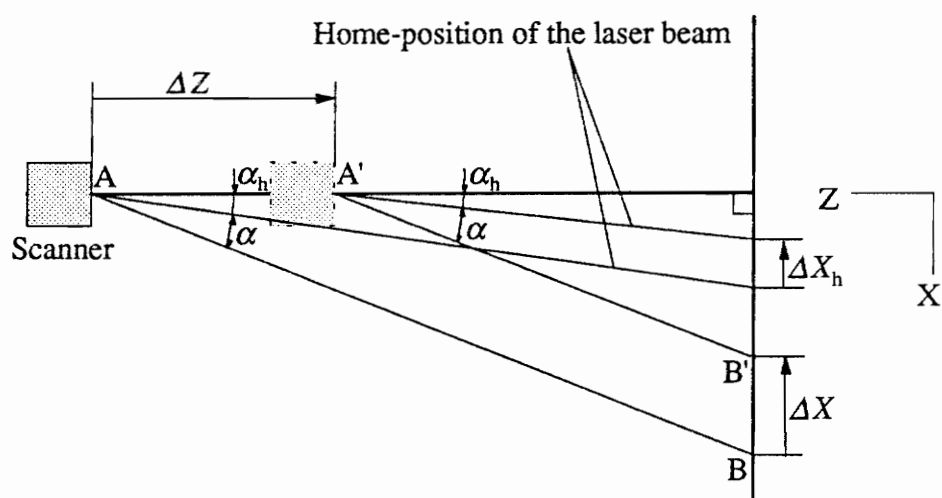


Figure 5.13 The home-position of the laser beam is not parallel to the Z-axis

measured by the Y stage. To accommodate the laser beam shift in the Y direction, Equation (4.8) can be modified as

$$\alpha = \tan^{-1} \left(\frac{\sqrt{(\Delta X)^2 + (\Delta Y)^2}}{\Delta Z} \right) \quad (5.9)$$

So this ΔY will not affect the accuracy of the scanning angle test. By carefully setting up the laser-scanner unit, ΔY can be very small comparing to ΔX . For one example, the largest measured ΔY was 0.066 mm for $\Delta Z = 50$ mm and $\Delta X = 17.968$ mm. The calculated scanning angle, α , was 19.766408° and 19.766531° by Equations (4.8) and (5.9), respectively. The difference of these two calculated angles was only about 2 μrad . Thus, the measurement error of ΔY is insignificant and can be ignored. For the same reason, the non-orthogonality error of the Y stage with respect to the X-Z plane can also be ignored.

The last error that needs to be addressed is the non-repeatability error of the scanner. To reduce the errors in the scanning angle test, such as thermal drift and uncertainty errors that are discussed in previous sections, an average from multiple tests for each tested scanning angle may be needed. The non-repeatability error can affect the convergence of the multiple-test results. A typical non-repeatability error for the G3B scanner is about 2 μrad for short term according to the General Scanning's specification. The test for this error was only able to determine that the short-term non-repeatability of both the X and Y scanners was within 5 μrad . A higher test accuracy is limited by the uncertainty error of determining the position of the focused laser spot. Also, lack of room temperature control and the laser beam drift problem prevent an accurate test for long-term non-repeatability of the scanner.

5.2 Test Results for the Scanning Accuracy

Scanning accuracy is defined as the maximum angular deviation of the scanned laser beam from its given position in space. As stated in Section 4.1.3, a number of error sources affect the scanning accuracy. Some of the errors have been analyzed in the previous sections of this chapter, along with the test results. These errors include the laser beam alignment error, the mirror surface offset error, the scanner and its controller drift error, and the non-repeatability error. Table 5.2 summarizes the test results of these errors.

Table 5.2 Test results of some errors that affect the scanning accuracy

Error Source	Magnitude	Effect on Scanning Accuracy
Laser beam angular alignment	$<1^\circ$	Only through mirror surface offset
Laser beam lateral alignment	$<0.5\text{ mm}$	Only through mirror surface offset
Laser drift	$<5\text{ }\mu\text{rad}$	$5\text{ }\mu\text{rad}$
Mirror surface offset	$<0.2538\text{ mm}$	$224\text{ }\mu\text{rad}$ for object 1 m away
Scanner and controller drift	$<11.8\text{ }\mu\text{rad}/^\circ\text{C}$	$11.8\text{ }\mu\text{rad}/^\circ\text{C}$
Non repeatability	$<5\text{ }\mu\text{rad}$	$5\text{ }\mu\text{rad}$

The main source of the error that affects the scanning accuracy may be the nonlinearity of the scanner. The only possibility to determine the nonlinearity is through the scanning angle test which also is the main objective of this work.

For the scanning angle test, the full scanning field (DE vector coordinate from 0 to 65,535 LSBs) was divided into 20 equal angular intervals of approximately 2° . For each tested scanning angle, the laser-scanner unit was moved $50,000\text{ }\mu\text{m}$. The positions of the scanned laser beam were measured 10 times before and 10 times after the laser-scanner unit was moved. The average time to test a scanning angle was about half an hour. The standard deviations of the measurement for each position were about 1 to $2.5\text{ }\mu\text{m}$ (20 to $50\text{ }\mu\text{rad}$ angular). The mean value for each tested scanning angle was used to fit a straight

line by the method of least squares. The deviations of the measured scanning angles from the best-fitting straight line were plotted as the nonlinearity error of the scanner. Figure 5.14 is such a nonlinearity plot of the X scanner from one set of test results. The slope and intercept of the line, which corresponds to the gain and offset of the scanner, are $-0.0006103^{\circ}/\text{LSB}$ and 20.009° for the X scanner, respectively. For comparison, the residuals of the linear fit for the position sensor measurement data provided by the General Scanning (see Appendix E) are also plotted. The nonlinearity plot from one set of test results for the Y scanner is in Figure 5.15. The gain and offset for the Y scanner are $-0.0006478^{\circ}/\text{LSB}$ and 21.230° , respectively. The offset of 21.230° indicated an error. Consultation with General Scanning suggested recalibration of the controller electronics.

From the plots, the differences between the test results and the General Scanning's data are quite obvious. The nonlinearity from the test results shows a zigzag pattern instead of a smooth curve as the one provided by the General Scanning. The tested nonlinearity errors for two adjacent scanning angles vary up to $300\text{ }\mu\text{rad}$. The worst thing is that the nonlinearity of the scanner from any set of test data is not repeatable. The variations from one set of test data to the other are sometimes a few hundred microradians. Since it took several hours to collect a set of test data (21 test points), and since the test setup magnified the laser beam drift error into the calculated scanning angle, the laser beam drift error was the prime suspect that was responsible for the large part of the variations and inconsistencies in the scanning angle test results. The other errors that might share some of the responsibility include the non-orthogonality error of the X and Z stages, the uncertainty error of determining scanned laser beam position, and the non-repeatability error of the scanner. As stated previously, the laser beam parallel-shift error caused by the mirror surface offset and the laser misalignment was not responsible for the inaccuracy of the test results.

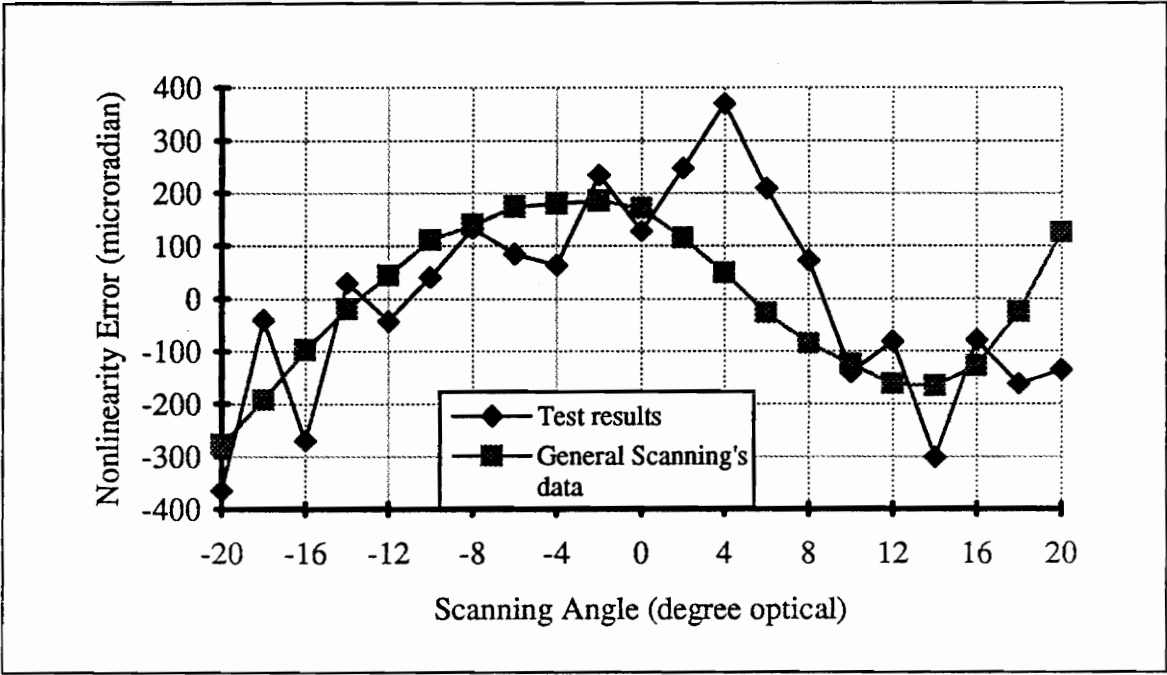


Figure 5.14 Nonlinearity plot for the X scanner from a typical set of test results (along with the calibration data from the General Scanning)

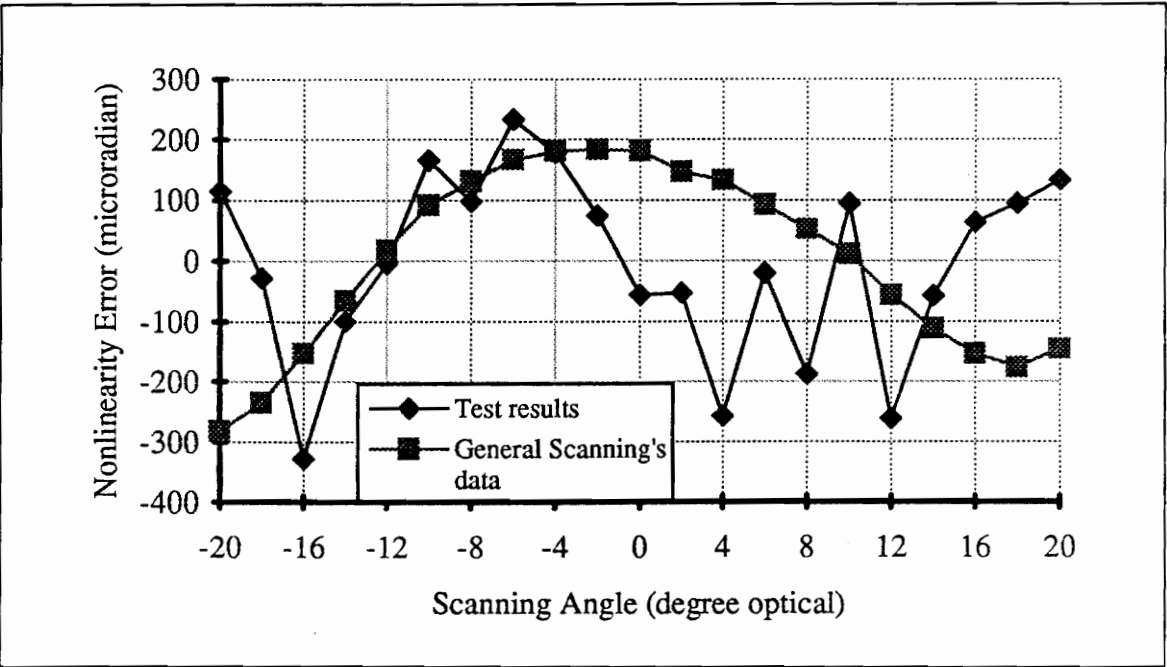


Figure 5.15 Nonlinearity plot for the Y scanner from a typical set of test results (along with the calibration data from the General Scanning)

several systematic scanning errors are not accounted by the General Scanning's test. This parallel-shift test setup can provide the test for a single scanning angle with an accuracy of $20 \mu\text{rad}$ ($\pm 1\sigma$) if a large number of measurements are made for that scanning angle. If multiple angles are measured, then significant time will elapse so that temperature change could cause the various sources of thermal drift to increase the measurement error. However, if a computer correction of the nonlinearity error is needed, the test setup needs some improvements to dramatically reduce the errors in the scanning accuracy test, which will be discussed in the next chapter.

CHAPTER SIX

IMPROVEMENT OF TEST AND SCANNING ACCURACY

The test setup used in this work provides a cost-constrained means for not only the scanning angle test but also the other scanning-accuracy-related tests as well. However, the cumulative error in the test may exceed the overall scanning accuracy requirement. Since the test data for the scanning accuracy by this setup are not very repeatable, using them for computer correction to improve scanning accuracy is not practical. Moreover, the use of the vendor supplied calibration for computer correction cannot be verified by the present system because this calibration cannot be confirmed or repeated by the current test setup. Although the test data for the linearity of the scanner may eventually converge to the true linearity of the scanner if a large number of tests are made, the time for such tests will be impractically long. If ultra-high scanning accuracy test is essential and money is no object, then almost every part of the test setup can be improved to dramatically cut down the errors in the test so that the repeatable errors in the scanning angle can be calibrated out. If the accuracy of the scanning angle test is improved by at least an order of magnitude, we can have two options to improve the scanning accuracy by computer correction. One is to use the General Scanning's calibration data for the position sensor after verification. The other is to generate a new set of calibration data for the overall scanning system. The first option can save the time and cost for the calibration. The second option may give better accuracy. Without the improvement of the test setup, it is also possible to reduce some of the errors that affect the scanning accuracy, such as the linearity of the scanner's position sensor and the laser parallel-shift error due to the laser misalignment.

6.1. Improvement in the Test Accuracy

From Chapter 5, it is clear that the uncertainty error of determining the position of the scanned laser beam and the laser beam drift error have the most effect on the test accuracy. These two errors are not totally unrelated. For instance, the uncertainty error may be reduced statistically by increasing the number of repetitive measurements, but increasing number of the measurements means increasing the time, which increases the laser beam drift error. A good improvement for the test accuracy should not trade one error for another but reduce both the errors. Most of the components used in the test setup can be improved to reduce one or both of the errors.

6.1.1 *Reducing Uncertainty Error of Determining the Laser Beam Position*

The main causes of the uncertainty error are the quality of the laser beam and the displacement sensitivity of the photodetector unit. Noises in the laser beam, the diameter and geometric shape of the focused laser beam, in-focus range, and power fluctuation are some of the laser beam quality problems that are directly related to the uncertainty error. The displacement sensitivity of the photodetector unit in this test setup is related to the diameters of the focused laser beam and the pinhole, the linearity and signal-to-noise ratio of the photodetector, the resolution of the translation stages, and the resolution of the multimeter.

The quality of the laser beam is determined by the laser and the optics. The laser used in the test setup meets most standard specifications for a commercial Ne-He laser. Some high-performance lasers with laser stabilization systems can have the laser beam stabilized within 0.1% amplitude. Two examples of commercial products are the Spectra-Physics and the AEROTECH stabilized He-Ne lasers. This type of high-performance lasers usually costs 8 to 10 times of a standard laser. Since the amplitude and frequency stabilization

give only minor improvement for determining laser position, the cost of the improvement may not be justified.

The beam expander used in the test setup is a typical reversed Galilean telescope. It consists of a negative input lens and a positive output lens. The expansion ratio (magnification) is given by the focal length of the output lens over the focal length of the input lens. There are three main advantages in using a beam expander. First, over a long distance, an expanded laser beam can be collimated or focused to a much smaller spot than an original laser beam that usually has a diverging angle of 1 to 2 mrad. Second, the expanded laser beam can reduce the contamination by the localized small imperfection in the optical path. Third, the laser angular drift can be reduced by the beam expander. However, because of the design and manufacture, the beam expander used in the test gives very high spatial noise and a large distortion to the wavefront of the output laser beam, which can be observed from the expanded laser spot. There is no lateral or angular adjustment for the mount of the beam expander. The manufacturer gives no specifications on the wavefront distortion, mechanical tolerance, and minimum focus distance of the beam expander used in the test.

A high-quality, usually expensive, beam expander can be expected to greatly improve the quality of the laser beam, thus reducing the uncertainty error. The basic requirement for a high-quality beam expander is that the wavefront distortion should be less than a quarter of wavelength so that a symmetrical and minimum sized laser spot in the far field is guaranteed. In order to have the wavefront distortion of less than $\lambda/4$, besides precision manufacturing, two design features of the beam expander are very important. First, the beam expander must be able to be adjusted laterally (X and Y translations) to compensate the centration error of the laser beam and the beam expander. Additional angular adjustments for the beam expander can produce the best possible wavefront and eliminate

the angular deflection of the output laser beam. Second, the output lens or lens group should be able to effectively cancel spherical aberrations induced by the input lens. If the beam expander is accompanied by a spatial filter, then most of the spatial noises can eliminate, and the output laser beam will have a very smooth intensity distribution profile. The configuration for a typical Keplerian beam expander with spatial filter is shown in Figure 6.1. Both the input and output lenses are positive. The pinhole is centered at the internal focal point. A multi-element output lens group can improve wavefront of the laser beam and reduce the physical length of the beam expander. The pinhole size should be about 1.5 times the $1/e^2$ diameter (the diameter at which the laser beam intensity is about 13.5% of the maximum laser beam intensity, $e = 2.718$) of the focused laser beam which is given by

$$d_f = \frac{1.27 \lambda f_{in}}{d_{in}}, \quad (6.1)$$

where d_f is the $1/e^2$ diameter of the focused laser spot, λ is the wavelength, f_{in} is the focal length of the input lens, and d_{in} is the $1/e^2$ diameter of the input laser beam.

A larger magnification ratio of the beam expander can focus a laser beam to a smaller spot. For example, a laser beam diverging to a diameter of 10 mm at 10 meters can have the diameter at that distance converged to 1 mm by a 10X beam expander, and to 0.5 mm by a 20X beam expander. A larger magnification ratio also gives a longer depth of field which is defined as the distance over which the beam diameter does not exceed 1.41 times the value at the focal point. However, the drawbacks of a large magnification ratio are the large size of the beam expander and the long attainable minimum focus distance which is

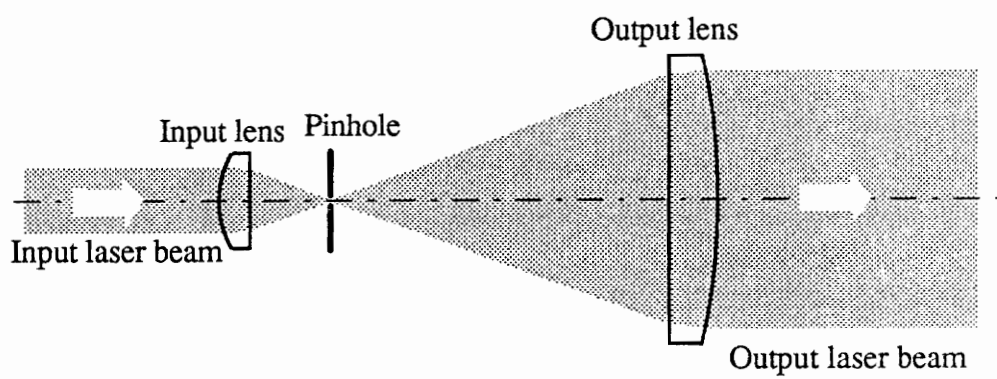


Figure 6.1 Configuration of a typical Keplerian beam expander with spatial filter

depends on the design of the beam expander. In any cases, the diameter of the expanded laser beam must not exceed 20 mm which is the pupil diameter of the scanner.

The best possible improvements for the quality of the laser beam are a stabilized laser and a high-quality beam expander with a spatial filter, angular and translation adjustments, and a large magnification ratio. Since these improvements do not come cheap, they need to be justified according to their effectiveness on reducing the uncertainty error of the laser beam's position.

A more direct approach to reduce the uncertainty error is to improve the precision of determining the position of the focused laser beam. In the original test setup, the X and Y stages need to be driven back and forth several times to seek the peak output of the photodetector for each position of the focused laser beam. This procedure not only takes much time, but also involves the insensitivity of the detector and the stages. More or less, the position of the laser beam is determined by "guessing". If the profile of the focused laser beam can be visualized with a high spatial resolution, or the center of the laser beam can be read out precisely at once, then both the test time and the uncertainty error can be reduced. A beam profiler or analyzer is needed for the job. There are two basic types of beam profilers. The first type is to use 2-D photodiode elements (matrix array). The second one is to scan the cross-section of the laser beam with a photodetector.

The Laser Beam Analyzer manufactured by the Spiricon, Inc. is of the first-type beam profiler. The finest CCD camera used with the beam analyzer has 752×582 elements with the pixel size of $8.6 \times 8.3 \mu\text{m}^2$ and the maximum viewable beam dimension of 3.9 mm. The intensity profile of the laser beam can be displayed in 2-D or 3-D with the display update up to 15 Hz. Since each photodiode element is scanned electrically, this type of beam profiler is mechanically simple and relatively fast. Without any moving parts, the problems associated with mechanical vibration, noise, and wear are non-existent. The main

disadvantage is that the ultimate spatial resolution of the beam profile is limited by pixel size. One of the smallest pixel sizes of commercial CCD matrix arrays is $6.8 \times 6.8 \mu\text{m}^2$, which is manufactured by the Eastman Kodak Company (model KAF-1400). Since the position of the focused laser beam cannot be determined within the resolution that is better than the pixel size, using CCD matrix arrays certainly cannot reduce the uncertainty error. Besides, high-resolution matrix arrays and the electronic systems are relatively expensive, from \$10,000 to \$50,000.

The second type of beam profiler uses a small aperture (a slit or a pinhole) with a photodetector behind it. The aperture scans the cross-section of the measured laser beam with its position or speed precisely controlled or monitored. As the aperture crosses the measured laser beam, only a tiny part of the laser beam passes through the aperture and strikes on the detector. The outputs of the detector at different positions of the aperture are processed to extract the intensities of the laser beam for the beam profile. The spatial resolution of the beam profile is the function of the aperture size and position resolution of the aperture. Two commercial products that are claimed having sub-micron position resolution are the Optical Profiler made by the Oriel Corporation and the BeamScan made by the Photon, Inc. The Oriel's Optical Profiler can take up to 250,000 samples for a beam profile with a spatial resolution of $0.1 \mu\text{m}$. The aperture size of the slit is $2 \mu\text{m}$. The scan range is 20 mm for single axis or 4 mm for dual axes (XY) with a position resolution of $0.05 \mu\text{m}$ and a scan rate up to 10 Hz. The Photon's BeamScan has several models that can determine the intensity profile of a laser beam with a diameter of from $5 \mu\text{m}$ to 8 mm. The spatial resolution of the profile is $0.14 \mu\text{m}$ for dual axes profile if a $2\text{-}\mu\text{m}$ slit is used. The maximum update rate is 10 Hz. The Photon also manufactures an even higher resolution beam profiler called the SpotScan. The SpotScan measures the profile of a laser beam with a diameter of less than $5 \mu\text{m}$ to $25 \mu\text{m}$ and a spatial resolution of 5 nm. If the Oriel's

Optical Profiler and the Photon's BeamScan have the claimed performance, they will be the ideal devices to determine the position of the focused laser beam. The uncertainty error can be expected to be reduced by up to 50 times. The even greater improvement is that the test time for each scanning angle can be reduced from a half hour down to a few seconds. This certainly minimizes the laser beam drift error. Another advantage of using such a beam profiler is that the quality of the laser beam can be readily visualized, so the necessity of laser and optics improvements can be determined. It is possible that even the beam expander is not needed for the test setup. The cost for this type of beam profiler is about \$6,000 to \$10,000, which is surprisingly lower than the cost of the CCD type of the beam profiler.

An alternative to the beam profiler is to use a quadrant photodetector. A quadrant detector has four sensing elements in 2×2 matrix form. Two of the companies that provide the commercial product are the United Detector Technology (UDT Instruments) and the Silicon Detector Corp. The effective area of a quadrant detector can be a square or a circle with a diameter of 5 to 10 mm. The gap between the elements can be as small as $10\text{ }\mu\text{m}$. For the best resolution, the diameter of the measured laser beam should be as small as possible but larger than the gap. The laser beam needs to be symmetrical and to strike on all four elements. From the outputs of the individual elements, the coordinates of the laser beam's position with respect to the center of the quadrant detector can be computed with a resolution up to $0.1\text{ }\mu\text{m}$. This position resolution, however, is dependent on the several factors, such as the sensing element size, the beam diameter, gap size, quality of the laser beam, and the electronics for signal conditioning. The United Detector Technology manufactures the X-Y Optical Position Indicator that is used with the quadrant detectors for signal conditioning, computing, and displaying the position of the laser beam. The cost of the position indicator is from \$3,300 to \$5,600. The quadrant

detector costs about \$100 to \$500. Besides low cost, the advantage of using a quadrant detector is that the position of the laser beam can be read out directly with very high resolution. This will dramatically reduce the uncertainty error and test time. However there are three main drawbacks for the quadrant detector. First, the center of the laser beam must be very close to the center of the detector. Second, the laser beam needs to be symmetric and free of spatial noises. Third, the profile of the laser beam cannot be visualized.

One caution must be taken when a laser beam detecting device is chosen to be used in the test: the power threshold of damage of the detector specified by the manufacturer must not be exceeded. Since the power threshold usually is quite low, permanent damage to the detector is very possible even though a low-power laser is used.

6.1.2 Reducing the Laser Beam Drift Error

The laser beam drift error probably is the main cause for the inconsistency in the scanner linearity test. Using a high-resolution beam profiler to reduce the test time certainly is a very effective way to reduce the laser beam drift error. There are some other improvements that can reduce this error. One of the important improvements is to reduce the drift error magnified in the test setup and scanning angle calculation.

Refer to Section 5.1.4 and Equation (5.6), any laser beam angular drift error in the X direction is magnified about 20 times in the scanning angle test and calculations. Since the parallel-shift method for the scanning angle test is independent of the distance between the scanner unit and the photodetector unit, the magnification ratio can be reduced either by increasing the travel distance of the Z stage or by decreasing the distance between the laser-scanner unit and the photodetector unit or both (refer to Figure 4.7).

To increase the travel distance of the scanner unit, a minor modification for the current setup would be replacing the X stage with a travel range of 50 mm, so that the full travel range of 100 mm of the Z stage is utilized. A better improvement would occur by replacing both the X and Z stages with longer travel ranges and digital micrometers. A digital micrometer can avoid the readout error and largely improve the read speed. The travel range of a manually-driven linear stage with a micrometer is usually limited to 150 mm. For the travel range is longer than 150 mm, a motor-driven linear stage which can travel up to 1,500 mm is needed. With an optical encoder, a sub-micron resolution and accuracy for a motor-driven linear stage is common. However, a motor-driven linear stage system can cost anywhere from \$2,000 to \$20,000 depending on the travel range and accuracy of the stage. Not only do long travel range, motor-driven linear stages improve the position resolution and accuracy, but they also reduces further the test time. Furthermore, if the scanning accuracy test needs to be automated, motor-driven stages are necessary.

There is only one problem in shortening the distance between the scanner unit and the photodetector: the laser beam cannot be focused onto the detector if the optical path from the beam expander to the detector is shorter than the minimum attainable focus distance of the beam expander. If a high-resolution beam profiler is used, the beam expander may not be needed, or the laser beam may not need to be focused to a fine spot. Otherwise, an additional focusing lens may be needed. Decreasing the distance between the scanner and the detector and increasing the travel range of the Z stage could result in the ratio of these two distances being cut from 20 to less than 2. Under these conditions the laser beam drift will not have much effect on the scanning angle test and calculation.

The workbench used in the test setup is not designed for precision laser and optical works. Besides the thermal effect of the workbench discussed in Section 5.1.4, the lack of

sufficient damping and vibration isolation for the workbench causes the laser beam to shake for any small disturbances around the test setup, such as closing a door. An optical bench with a good vibration isolation and thermal stability should be able to improve the consistence for the scanning accuracy test results.

6.2. Improvements for the Scanning Accuracy

The errors in a scanning angle can be separated as two parts: repeatable and random errors. The repeatable errors will not change with time and environment and are basically caused by the imperfection existent in the mechanical and electrical hardware of the scanner system. The random errors, on the other hand, may vary with time, temperature, or anything else. They include the non-repeatability and thermal drift errors of the scanner system. There is not much we can do other than control the temperature to reduce the thermal drift. Fortunately, the random errors of scanning angles for the DE2488/G3B are remarkable low. The repeatable errors may be reduced or corrected if they can be accurately determined first. Two of the repeatable errors that contribute the major part of the scanning angle error can be theoretically reduced. The first one is the laser beam parallel-shift error caused by the mirror surface offset and the laser misalignment. This error does not affect the accuracy of the scanning angle test but does affect the scanning accuracy. The other is the nonlinearity of the scanner's position transducer.

6.2.1 Reducing the Laser Beam Parallel-Shift Error

The laser beam parallel-shift error caused by the laser misalignment and the mirror surface offset with the axis of rotation was discussed in Section 5.1.2. This error can have a large impact on the scanning accuracy if the tested object is very close to the scanner unit. That is, the parallel-shift error will look like an angular shift error. The scanners'

nonlinearity test data, both provided by the General Scanning and obtained from the scanning angle test, do not involve the laser beam parallel-shift error. If we assume that the mirror is precisely mounted about the axis of rotation, then the amount of the laser beam parallel shift for a given scanning angle is directly related to the position of the input laser beam, both the angular and lateral laser alignments. Figure 6.2 shows how to determine the parallel-shift error of the scanned laser beam. First, three scanning angles, α_1 , α_2 , and α_3 , are set and determined by using the parallel-shift method for the scanning angle test discussed in Section 4.2.2. One of the scanning angle, say α_1 can be the maximum angle (about 20°), and the other two can be around 18° and 16° . The scanned distances, X_1 and X_2 , that correspond to the scanning angles from α_1 to α_2 and from α_2 to α_3 respectively, are precisely measured by the photodetector and the X stage. The measured distances, X_1 and X_2 , can also be expressed as

$$X_1 = Z(\tan \alpha_1 - \tan \alpha_2) + (e_1 - e_2) \quad (6.2)$$

and

$$X_2 = Z(\tan \alpha_2 - \tan \alpha_3) + (e_2 - e_3) \quad (6.3)$$

where Z is the distance between the scanner unit and the target plane, and e_1 , e_2 , and e_3 are the laser beam parallel-shift errors corresponding to the scanning angles α_1 , α_2 , and α_3 , respectively. The distance, Z , does not need to be measured or determined. The laser beam parallel shift errors, e_1 , e_2 , and e_3 , can be expressed by Equation (5.2) with α replaced by α_1 , α_2 , and α_3

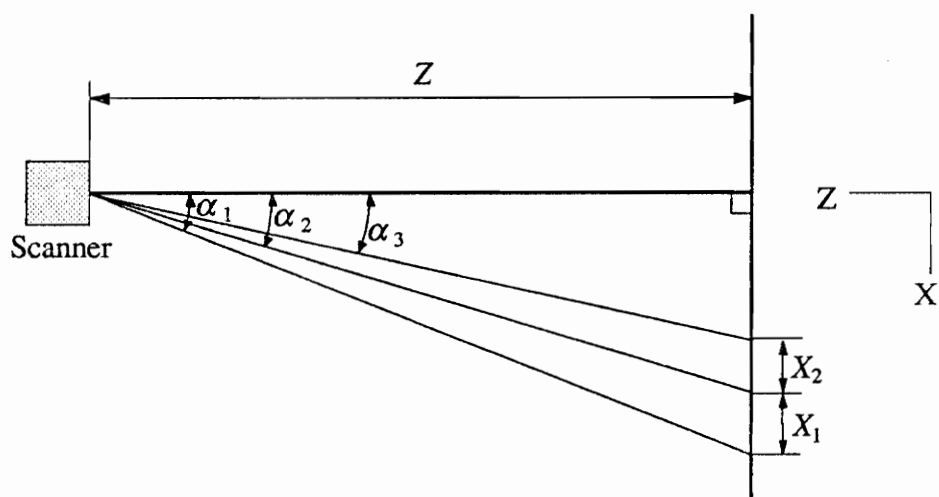


Figure 6.2 Determining the parallel-shift error of the scanned laser beam

$$e_1 = \frac{d \sin \frac{\alpha_1}{2} + \frac{k}{2} \sin \theta \left(1 - \cos \frac{\alpha_1}{2} \right)}{\sin \left(\theta - \frac{\alpha_1}{2} \right) \sin \theta} \quad (6.4)$$

$$e_2 = \frac{d \sin \frac{\alpha_2}{2} + \frac{k}{2} \sin \theta \left(1 - \cos \frac{\alpha_2}{2} \right)}{\sin \left(\theta - \frac{\alpha_2}{2} \right) \sin \theta} \quad (6.5)$$

$$e_3 = \frac{d \sin \frac{\alpha_3}{2} + \frac{k}{2} \sin \theta \left(1 - \cos \frac{\alpha_3}{2} \right)}{\sin \left(\theta - \frac{\alpha_3}{2} \right) \sin \theta} \quad (6.6)$$

where d is the distance from the center of the mirror surface to the input laser beam (the lateral alignment error of the input laser beam), k is the mirror thickness, and θ is the angle between the mirror's surface at the home position and the input laser beam (refer to Equation (5.2) and Figure 5.3). In Equations (6.4) through (6.6), the angle θ is dependent on the laser angular alignment. If the laser beam can be aligned to the nominal angle within an angular error of 1° , the laser angular alignment error can be neglected since it has little effect on the laser beam parallel-shift error, and the nominal angle can be used. Substituting Equations (6.4) through (6.6) into Equations (6.2) and (6.3) and eliminating Z from the equations, one can solve the only unknown d

$$d = \frac{RX_2 - X_1 + \frac{k}{2}(P_{12} - RP_{23})}{RF_{23} - F_{12}} \quad (6.7)$$

where

$$R = \frac{\tan \alpha_1 - \tan \alpha_2}{\tan \alpha_2 - \tan \alpha_3},$$

$$F_{12} = \frac{\sin(\alpha_1 - \alpha_2)}{\sin\left(\theta - \frac{\alpha_1}{2}\right)\sin\left(\theta - \frac{\alpha_2}{2}\right)},$$

$$F_{23} = \frac{\sin(\alpha_2 - \alpha_3)}{\sin\left(\theta - \frac{\alpha_2}{2}\right)\sin\left(\theta - \frac{\alpha_3}{2}\right)},$$

$$P_{12} = \frac{\sin\left(\theta - \frac{\alpha_2}{2}\right) - \sin\left(\theta - \frac{\alpha_1}{2}\right) + \cos \theta \sin(\alpha_2 - \alpha_1)}{\sin\left(\theta - \frac{\alpha_1}{2}\right)\sin\left(\theta - \frac{\alpha_2}{2}\right)},$$

and

$$P_{23} = \frac{\sin\left(\theta - \frac{\alpha_3}{2}\right) - \sin\left(\theta - \frac{\alpha_2}{2}\right) + \cos \theta \sin(\alpha_3 - \alpha_2)}{\sin\left(\theta - \frac{\alpha_2}{2}\right)\sin\left(\theta - \frac{\alpha_3}{2}\right)}.$$

With knowing d , the laser beam parallel-shift error, e , at each scanning angle can be determined From Equation (5.2).

After determining the lateral alignment error, d , of the input laser beam, one can realign the laser or correct the laser beam parallel-shift error through the scanning control command. However, since the effect of the laser beam parallel-shift error to the scanning angular accuracy is the function of the distance between the scanner unit and the object the computer correction of this error may not be very convenient. It is advisable to reduce the laser lateral alignment error as small as possible.

6.2.2 Reducing the Nonlinearity Error of the Scanner

If the scanner's linearity data obtained from the scanning accuracy test are reliable and accurate, computer corrections to improve the scanning accuracy are possible. The nonlinearity error, by the definition, is the deviation of the scan data from a straight-line fit. Therefore, using other curve fitting methods to describe the scanner angular calibration, one should be able to reduce the so-called nonlinearity error of the scanner by using the curve fit to describe the calibration..

The polynomial regression is a simple, yet effective curve fitting method, in which the least-squares technique is extended to fit the scanning angle test data to an m^{th} -degree polynomial:

$$\alpha = a_0x^0 + a_1x^1 + a_2x^2 + \cdots + a_mx^m \quad (6.7)$$

where α is the expected scanning angle, a_m is the coefficient of x^m , and x is the digital coordinate of the scanning angle command. If the measured scanning angle corresponding to x_i is α_i , then the sum of the squares of the residuals is

$$S = \sum_{i=1}^m (\alpha_i - a_0 x^0 - a_1 x^1 - a_2 x^2 - \dots - a_m x^m)^2 \quad (6.8)$$

If we take the derivative of Equation (6.8) with respect to each of the coefficients, a_0 to a_m , and set these derivatives equal to zero, then we obtain m linear equations for solving the coefficients from a_0 to a_m in Equation (6.7). After the coefficients are determined, one can use numerical method, such as the Newton-Raphson method [30], to obtain the input digital command, x , which is the root of the following equation:

$$\alpha - (a_0 x^0 + a_1 x^1 + a_2 x^2 + \dots + a_m x^m) = 0 \quad (6.9)$$

Unfortunately, the scanning angle test data obtained from this test setup are not very consistent due to the large errors involved in the scanning angle test. So the polynomial regression cannot improve the scanning accuracy by fitting these test data. For the computer correction of the commands to the DE scanner controller to effectively reduce the scanning error, we can either verify General Scanning's calibration data or generate a set of new data that could be depended up for the polynomial fitting. If we assume that the calibration data of the scanners' position transducers provided by the General Scanning are reliable and accurate, then we can fit these calibration data with the polynomial regression to reduce the nonlinearity errors of the position transducers. Figure 6.3 shows the third-order and fourth-order polynomial fitted curves of the measured data provided by the General Scanning for the X scanner's position transducer. The original measured data can be found in Appendix E. In order to show the differences among the curves and measured data, the magnitudes of the plots are suppressed by subtracting the linearly fitted line from all the values. Figure 6.4 is the similar plots for the Y scanner. For the polynomial fitting of these data higher than the fourth-order, there are little improvements on the position

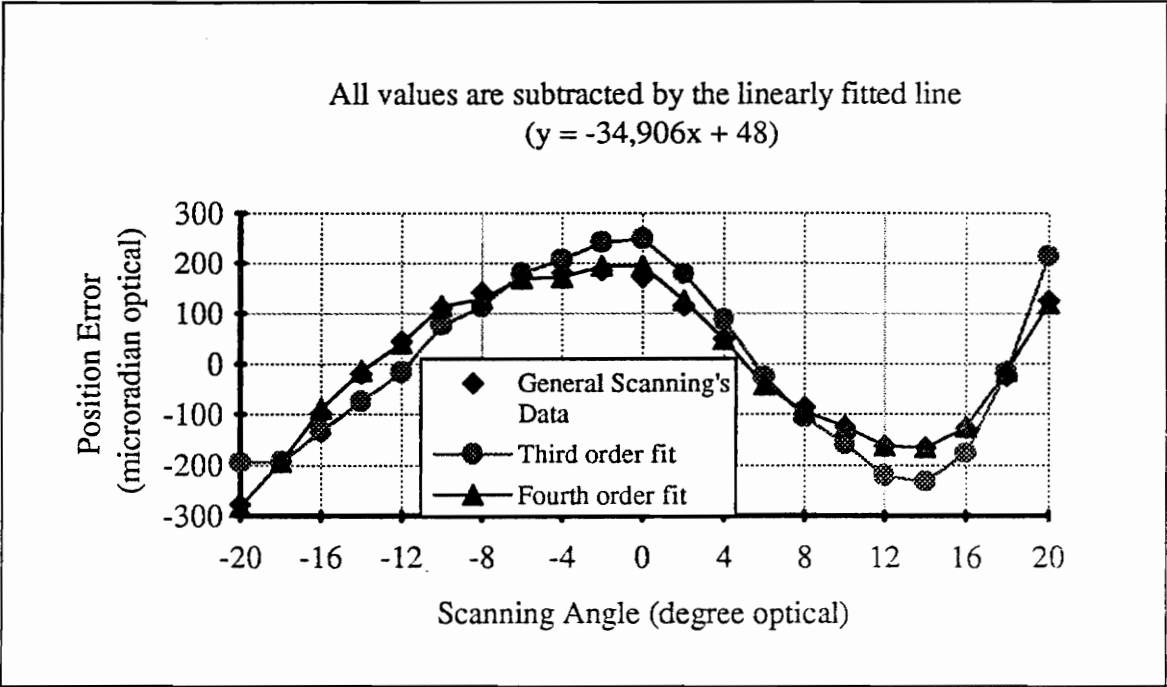


Figure 6.3 Polynomial fitted curves of the measured data for the X scanner's position sensor
(The original measured data are provided by the General Scanning)

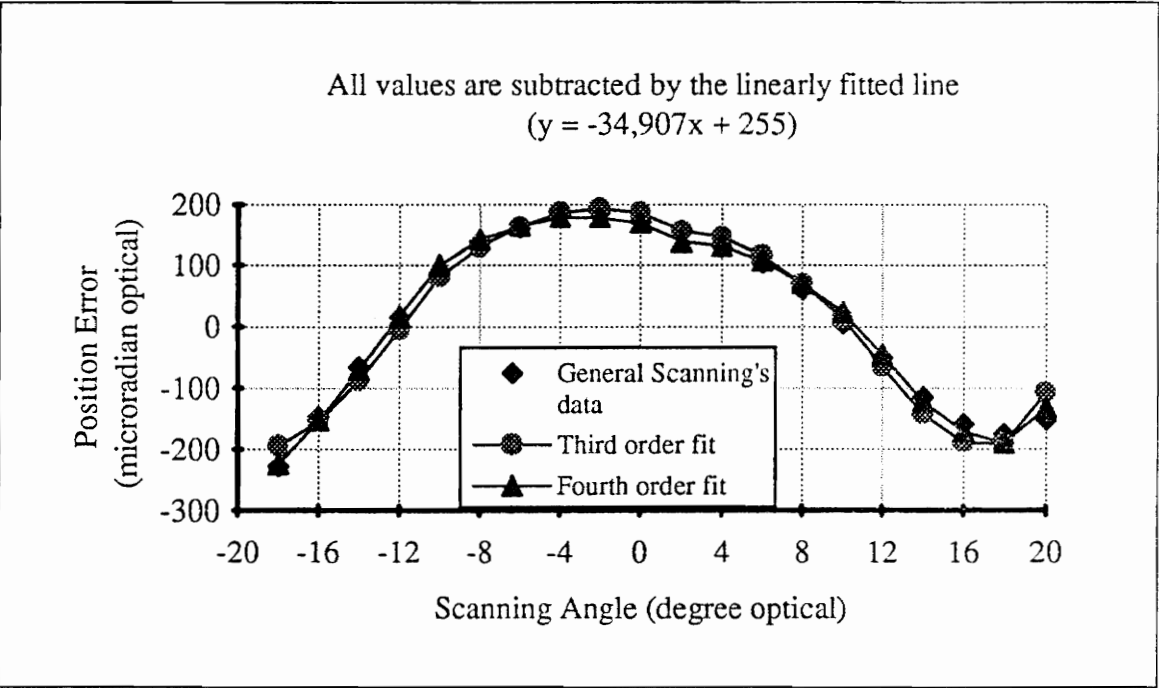


Figure 6.4 Polynomial fitted curves of the measured data for the Y scanner's position sensor
(The original measured data are provided by the General Scanning)

accuracy. The fourth-order polynomial fitting can cut down the position error to about 20 μ rad or lower optical for both scanners' position transducers. Figures 6.5 and 6.6 show the residuals from Figures 6.3 and 6.4, respectively. The coefficients of the polynomial fitting for the X and Y scanners from the General Scanning's data are listed in Table 6.1.

Table 6.1 The coefficients of the polynomial fitting for the X and Y scanners (from General Scanning's data, refer to Equation (6.7))

		1st-order	2nd-order	3rd-order	4th-order
X scanner	a_0 (degree optical)	1.46E-2	9.25E-3	9.27E-3	6.06E-3
	a_1 ($^{\circ}$ /LSB)	-6.10E-4	-6.10E-4	-6.09E-4	-6.09E-4
	a_2 ($^{\circ}$ /LSB ²)		1.36E-11	1.36E-11	4.10E-11
	a_3 ($^{\circ}$ /LSB ³)			-9.41E-16	-9.41E-16
	a_4 ($^{\circ}$ /LSB ⁴)				-2.78E-20
Y scanner	a_0 (degree optical)	2.78E-3	-5.43E-3	-5.90E-3	-6.95E-3
	a_1 ($^{\circ}$ /LSB)	-6.10E-4	-6.10E-4	-6.10E-4	-6.10E-4
	a_2 ($^{\circ}$ /LSB ²)		2.32E-11	2.54E-11	3.53E-11
	a_3 ($^{\circ}$ /LSB ³)			-4.63E-16	-3.70E-16
	a_4 ($^{\circ}$ /LSB ⁴)				-9.42E-21

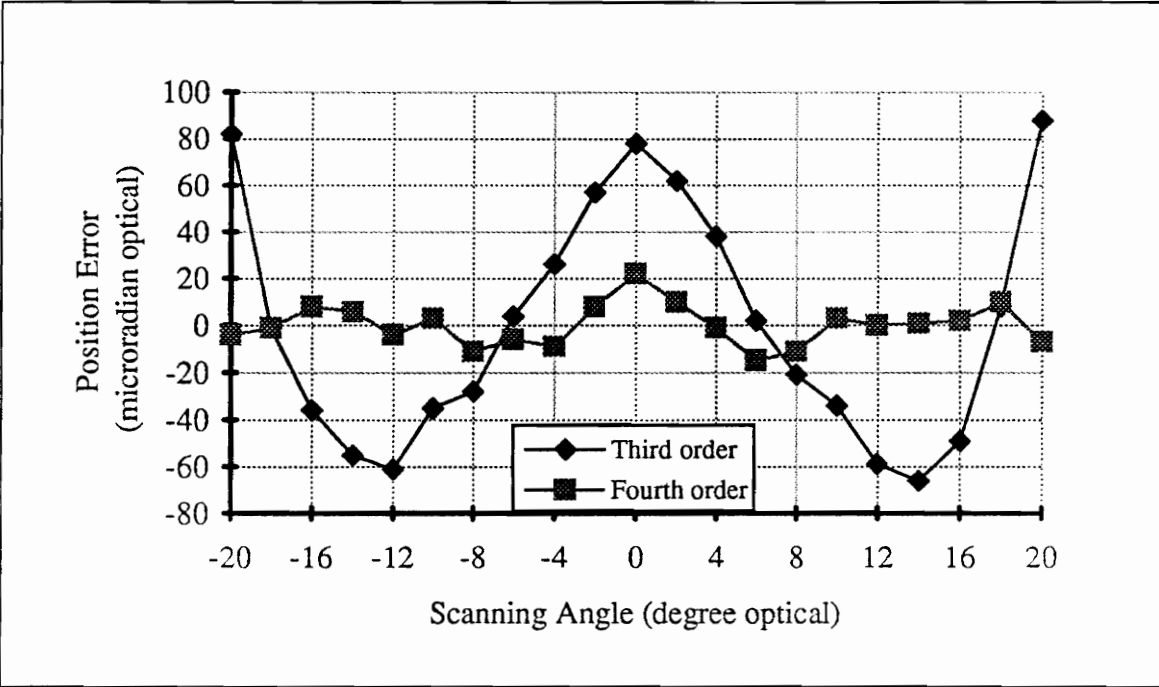


Figure 6.5 Plots of the residual position errors from Figure 6.3 for the X scanner

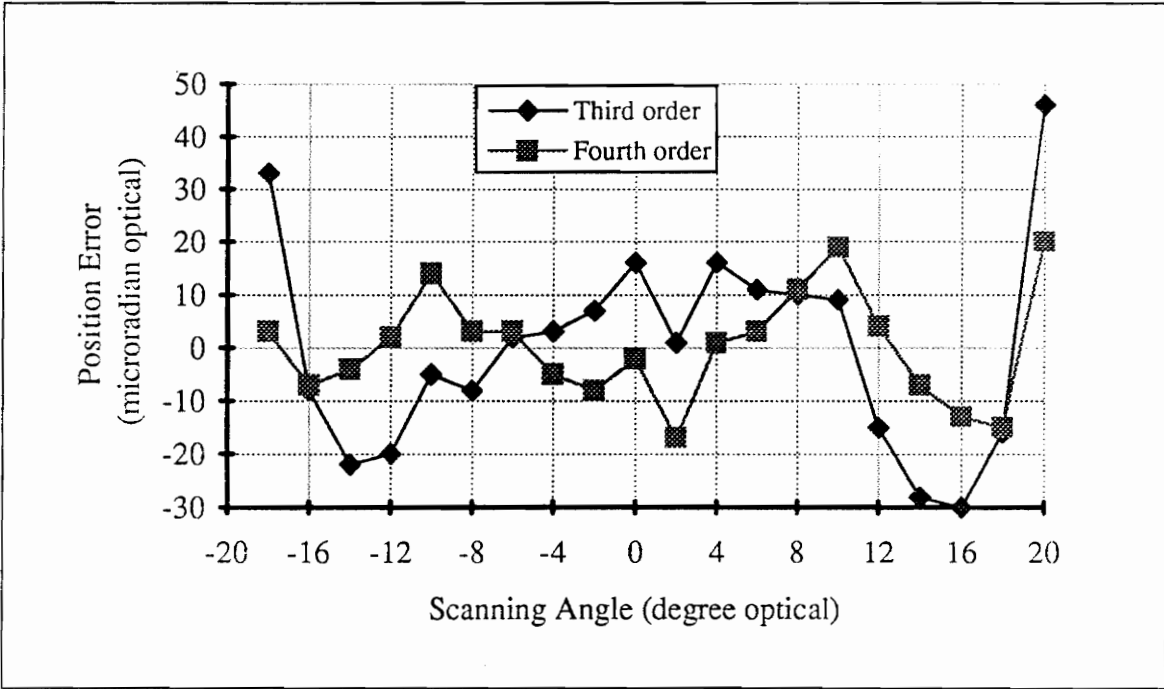


Figure 6.6 Plots of the residual position errors from Figure 6.4 for the Y scanner

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

The LDV technique is showing a bright future for experimental modal analysis. The G3B/DE2488 is a state-of-the-art laser scanning system that can provide positioning accuracy, speed, and flexibility for the LDV and modal testing. The overall step response time of the scanner can meet our requirement. The short-term non-repeatability error and the thermal drift of the G3B/DE2488 have been confirmed to be within the manufacture's specifications which are very low. However, both the calibration data from the General Scanning and the scanning angle test results from this work show that the nonlinearity error of the X and Y scanners are three times the G3B's specification and two times the requirement for the modal testing. The computer correction on the scanner's nonlinearity error is needed to have the overall scanning accuracy meet the requirement.

Other than the G3B/DE2488 scanning system, the laser and optics for the LDV can also affect the scanning accuracy. A laser with high pointing stability is essential. The laser alignment is very important to reduce the laser beam parallel-shift error that can have effects on the scanning accuracy if the test object is close to the scanner. If this laser beam parallel-shift error needs to be reduced, besides realigning the laser, computer correction is also possible since it is a deterministic function. However, in a commercial instrument it will be difficult to determine the position of the input laser beam relative to the center line of the mirror, d - see Equations (5.2) and Figure 5.3. Figure 6.2 shows that d may be determined using a test setup such as described in this thesis. However, field replacement of the laser or the scanner would require return of the instrument to the factory for test and adjustment of d , unless the entire laser assembly with scanners is a factory prealigned and removable subsystem that could be replaced in the field.

The setup for the scanning accuracy test was a new concept and was cost-constrained. It can effectively provide the tests for the scanning time, non-repeatability, and the drift of the scanning system. The accuracy for the scanning angle test, however, is limited due to the qualities of the instrument used in the setup. The test data of the nonlinearity of the scanner are not good enough for computer correction. Also, the time needed for the scanning accuracy test is too long.

To improve the accuracy of the scanning angle test, some modifications of the test setup are needed. The first priority for improvement would be to replace the photodetector with a high-resolution beam profiler, because it not only would improve the test accuracy but also would reduce the testing time. A good candidate would be the Oriel's Optical Profiler (\$6,250). A high-resolution beam profiler can also help to determine if other improvements are needed, such as a laser. The second improvement should be the use of a long-travel-range digital or motor-driven translation stages for the X and Z stages. Again, these can reduce both the testing error and time. There are a number of linear stage manufacturers. One of the choices is AEROTECH's ATS100 Series Linear Positioning Stages. Two models, ATS100-75 (75-mm travel range) and ATS100-200 (200-mm travel range), can be used as the X and Z stages in the setup. The cost of these two stages with an accuracy of $1\mu\text{m}/100\text{mm}$ and $0.1\mu\text{m}$ resolution is \$7,760. The controller (UNIDEX 12 Series) and drivers (DAV4008) for the stages cost \$5,310. The combination of the beam profiler and motor-driven translation stages (cost \$19,320) can automatize the scanning accuracy test and calibration processes with an ultra-precision. If the profile of the focused laser beam is assumed to be well-defined (smooth, symmetrical, and stable), that is, if the position of the focused laser beam can be determined with a resolution of $0.1\mu\text{m}$, then the angular error in the scanning angle computation due to the uncertainty error can be expected within $1\mu\text{rad}$, which is a

tremendous improvement compared with the original error of 64 μrad (refer to Section 5.1.3). The total laser beam drift error can be expected to have little effect on the scanning angle test under this new arrangement. The third choice for improvement would be to use an optical bench. It would provide a good environment for a consistent scanning accuracy test by reducing the effects of the vibration and change of temperature of the surroundings. An optical bench manufactured by the Oriel that has 4'x6'x8" table top with mounts costs \$4,055. Other tables may have better static and dynamic properties. The other improvements would be to using a stabilized laser (\$2,625 for the AEROTECH stabilized He-Ne laser) and high-quality beam expander with spatial filter (\$1,079 for the Oriel's 20X beam expander with spatial filter). However, the needs for the improvements of the laser and the beam expander are much dependent on the quality of the laser beam that could be determined by the beam profiler.

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APPENDIX A

Example of "C" Program for Driving the G3B/DE2488 Scanning System Through the HP 9000 Computer

```
#include <dvio.h>           /*header file for device I/O control*/
#include <fcntl.h>          /*header file for file control*/
#include <stdio.h>          /*standard buffered I/O stream file*/
#include <string.h>         /*header file for character string operations*/
#include <errno.h>          /*error indicator for system calls*/

main( )
{
    int eid, eid1, status;      /*define variables*/
    char buf[BUFSIZ];

    if ((eid = open("/dev/de2488", O_RDWR)) == -1)    /*open auto-addressing
                                                         device file*/
    {
        printf("open /dev/de2488 failed, errno = %d\n", errno); /*if failed, print
                                                                    message*/
        exit(2);          /*then exit the program*/
    }

    read(eid,buf,sizeof buf);      /*read the message from DE2488*/
    printf("%s\n", buf);           /*print the message*/

    if ((eid1 = open("/dev/de_raw", O_RDWR)) == -1)    /*open the raw device file*/
    {
        printf("open /dev/de2488 failed, errno = %d\n", errno); /*if failed, print
                                                                    message*/
        exit(2);          /*then exit the program*/
    }

    if ((status = hpib_spoll(eid1, 23)) == -1)    /*conduct serial poll on DE2488*/
    {
        printf("error during serial poll\n");      /*if failed, print message*/
        exit(1);          /*then exit the program*/
    }

    write(eid, "JS200\r\0JD2\r",
           sizeof("JS200\r\0JD2\r"));      /*send DE commands Jump*/
                                           /*Size and Jump Delay*/
}
```

/*Note: "write" subroutine will automatically
appends a NULL character to the end of string*/

```
write(eid, "JX0\r\0JY0\r\0EC\r",          /*move laser beam to lower right*/  
      sizeof("JX0\r\0JY0\r\0EC\r"));      /*corner of field*/  
  
write(eid, "JX0\r\0JY65535\r\0EC\r",      /*move to upper right corner*/  
      sizeof("JX0\r\0JY65535\r\0EC\r"));    
  
write(eid, "JX65535\r\0JY65535\r\0EC\r",  /*move to upper left corner*/  
      sizeof("JX65535\r\0JY65535\r\0EC\r"));   
  
write(eid, "JX65535\r\0JY0\r\0EC\r",      /*move to lower left corner*/  
      sizeof("JX65535\r\0JY0\r\0EC\r"));    
  
printf("commands are sent!\n");           /*print message for the end*/  
close(eid1);                             /*close device file*/  
close(eid);  
}
```

APENDIX B

Example of LabVIEW Program for Driving the G3B/DE2488 Scanning System Through the Macintosh Computer

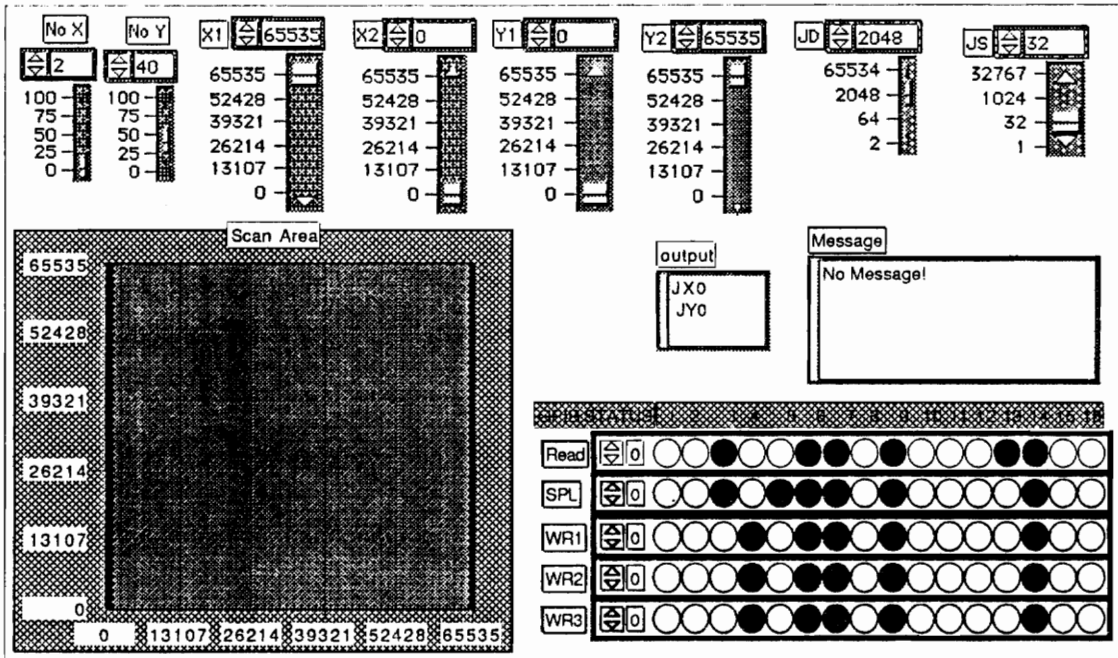


Figure B.1 Front panel of the LabVIEW program

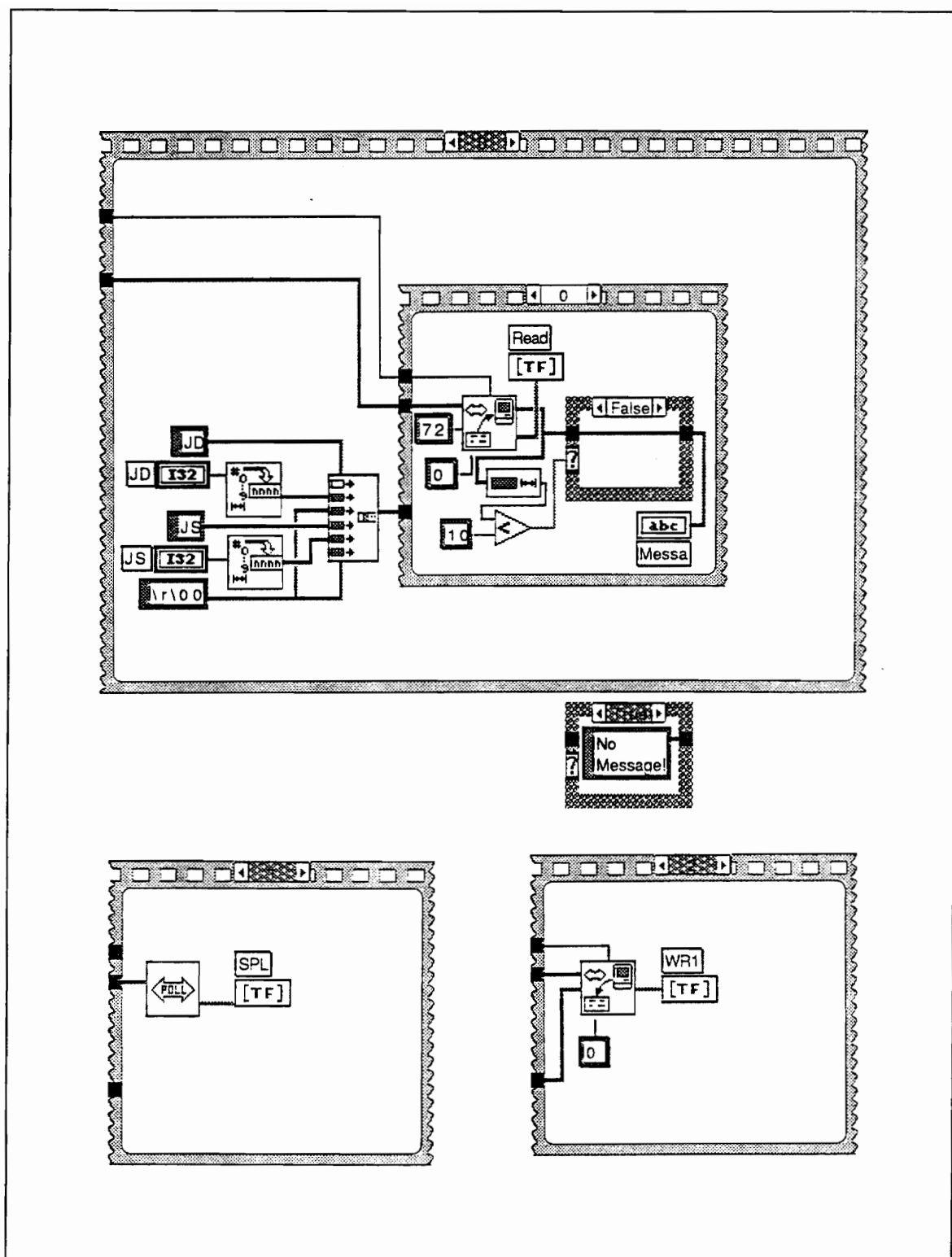


Figure B.2 Block diagram of the LabVIEW program (1)

APENDIX C

Test Results of the Scanning Time of the G3B/DE2488

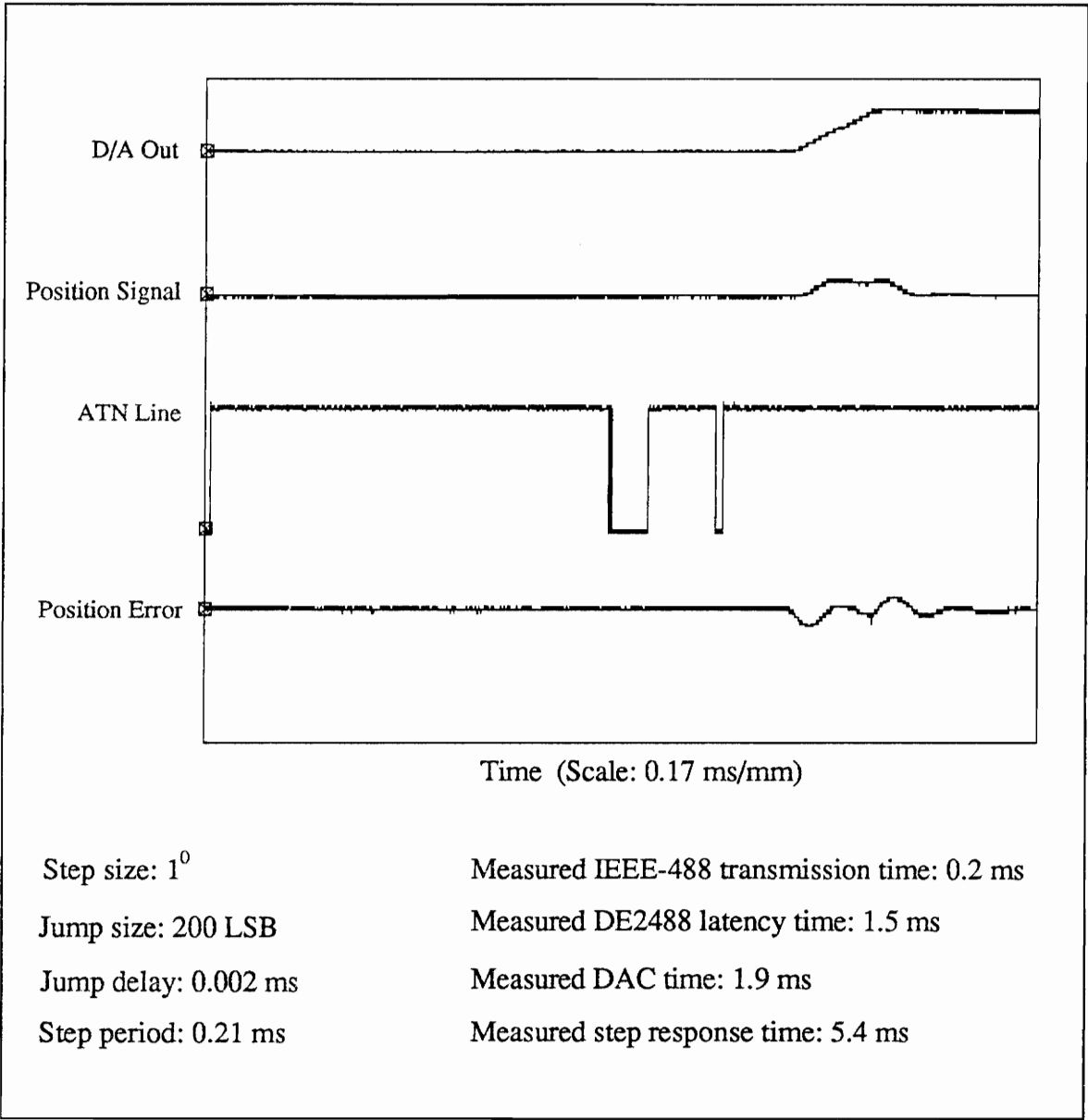


Figure C.1 Test result of the scanning time of the G3B/DE2488 (1)

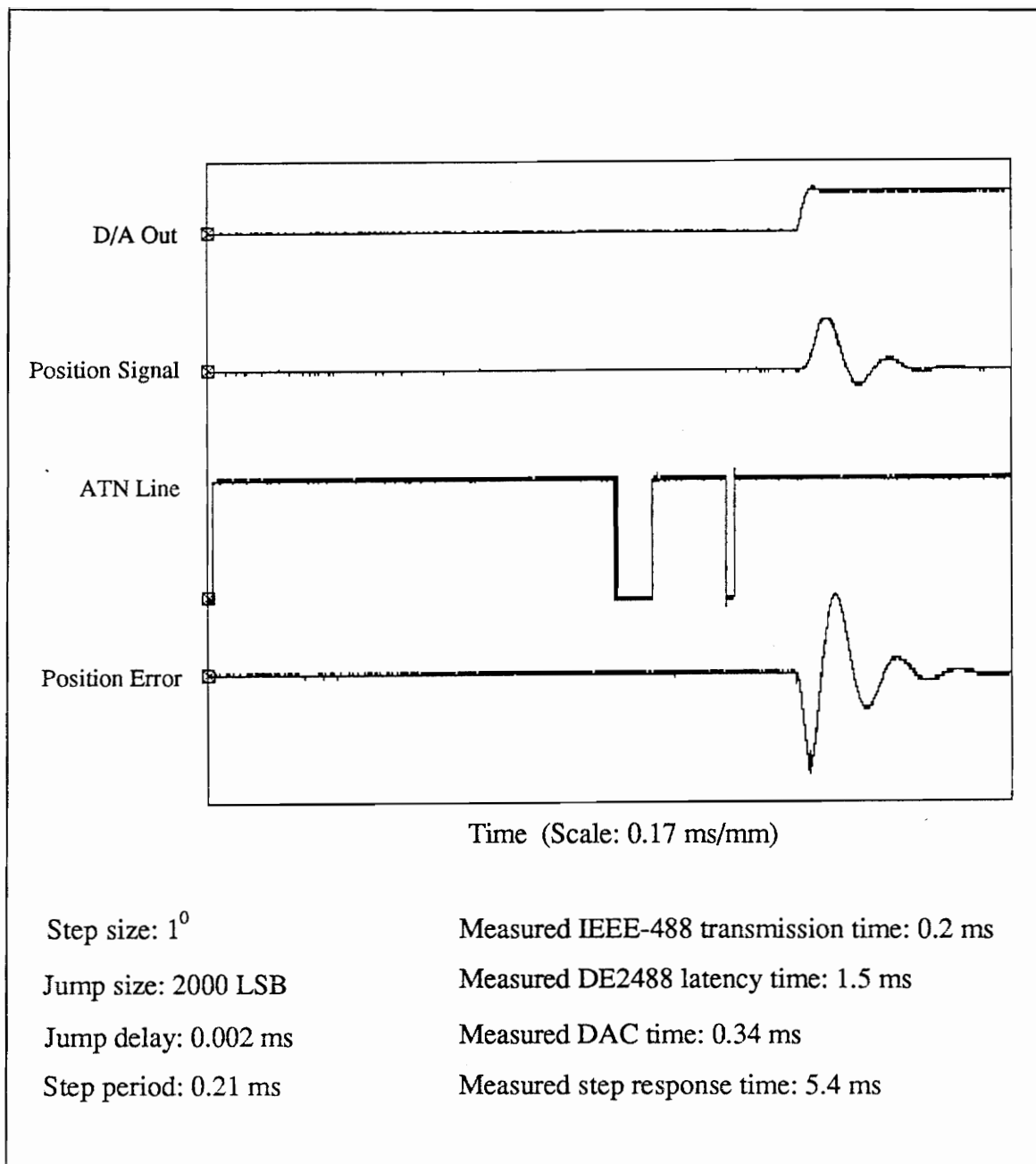
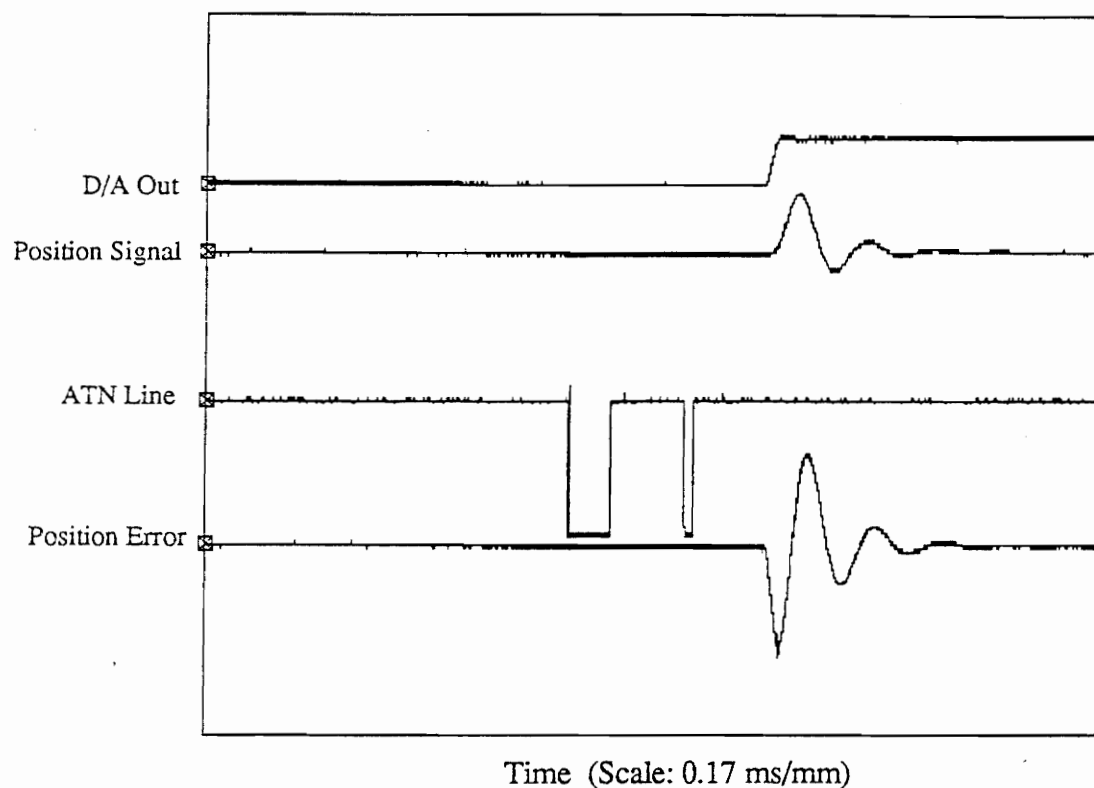


Figure C.2 Test result of the scanning time of the G3B/DE2488 (2)



Step size: 1°

Jump size: 32767 LSB

Jump delay: 0.002 ms

Step period: 0.21 ms

Measured IEEE-488 transmission time: 0.2 ms

Measured DE2488 latency time: 1.5 ms

Measured DAC time: 0.34 ms

Measured step response time: 4.5 ms

Figure C.3 Test result of the scanning time of the G3B/DE2488 (3)

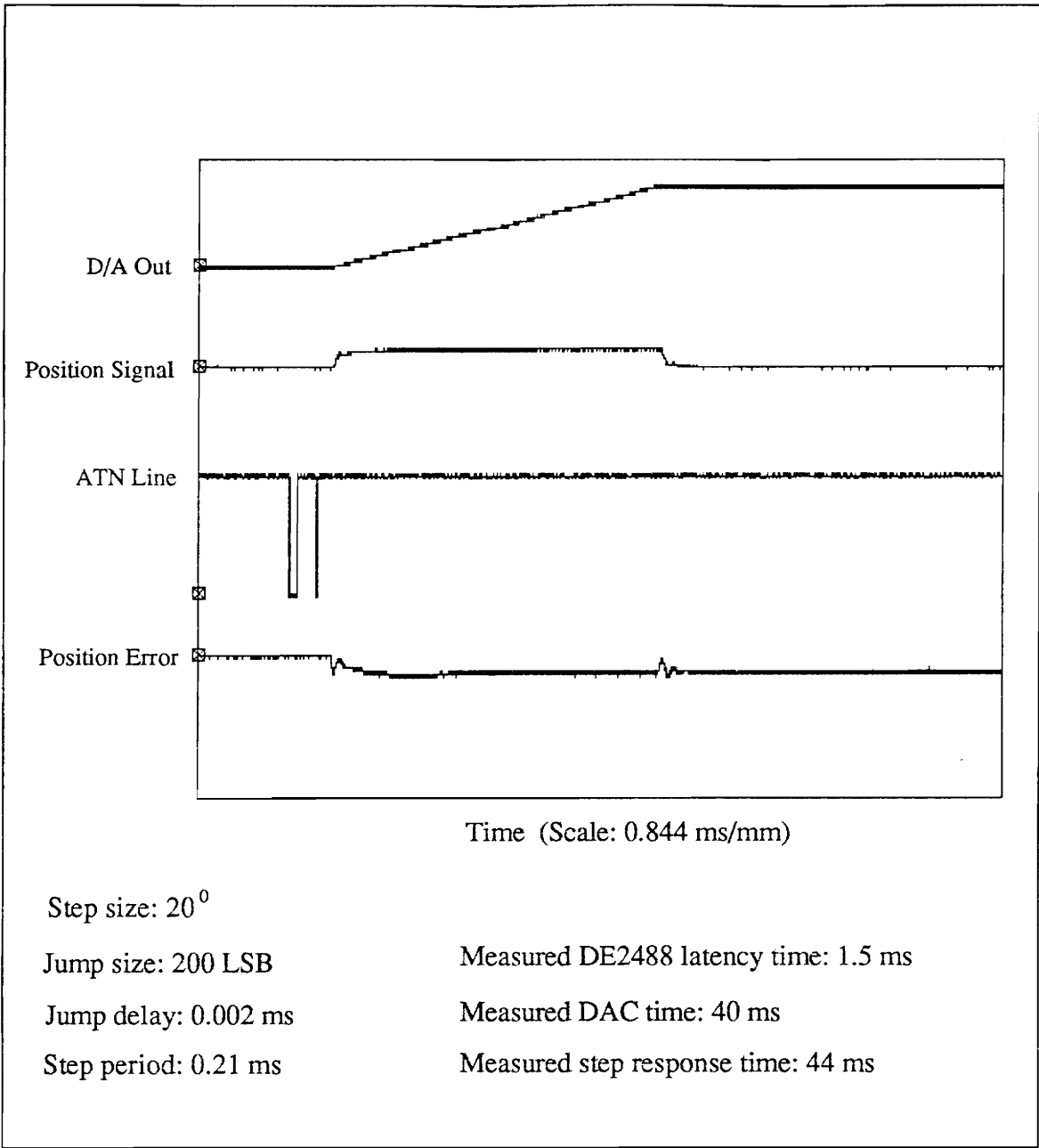
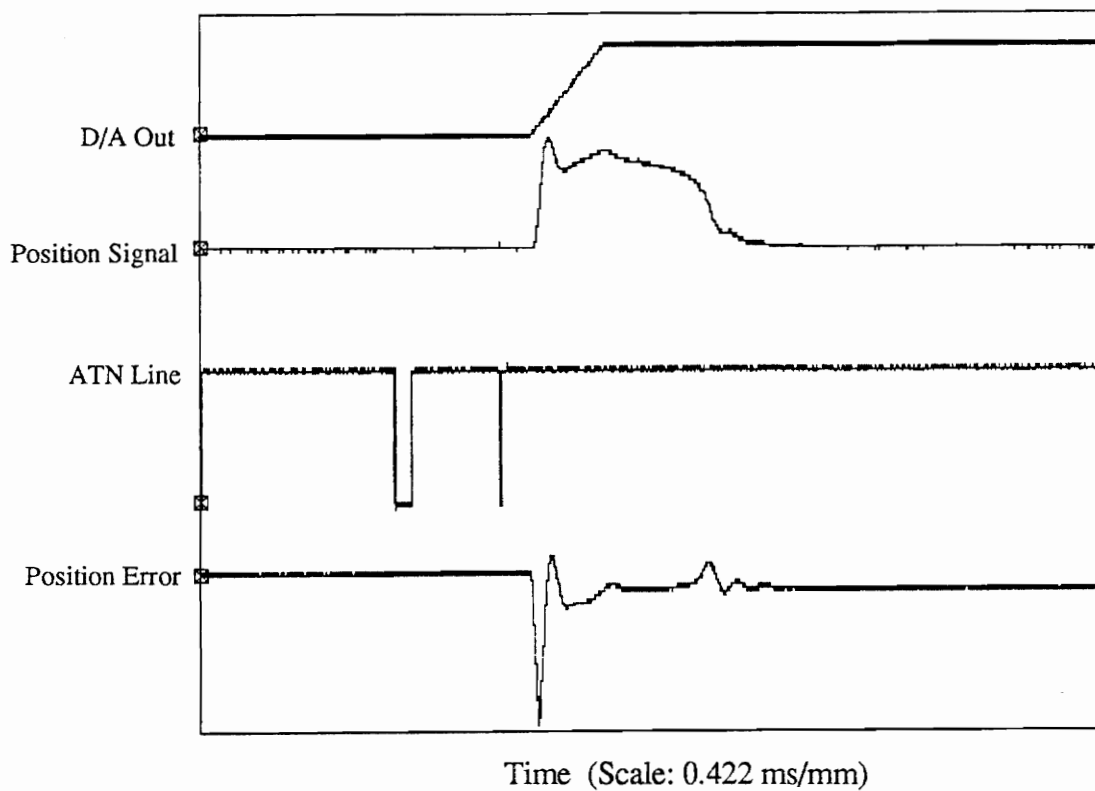


Figure C.4 Test result of the scanning time of the G3B/DE2488 (4)



Step size: 20^0

Jump size: 2000 LSB

Jump delay: 0.002 ms

Step period: 0.21 ms

Measured DE2488 latency time: 1.5 ms

Measured DAC time: 3.8 ms

Measured step response time: 14 ms

Figure C.5 Test result of the scanning time of the G3B/DE2488 (5)

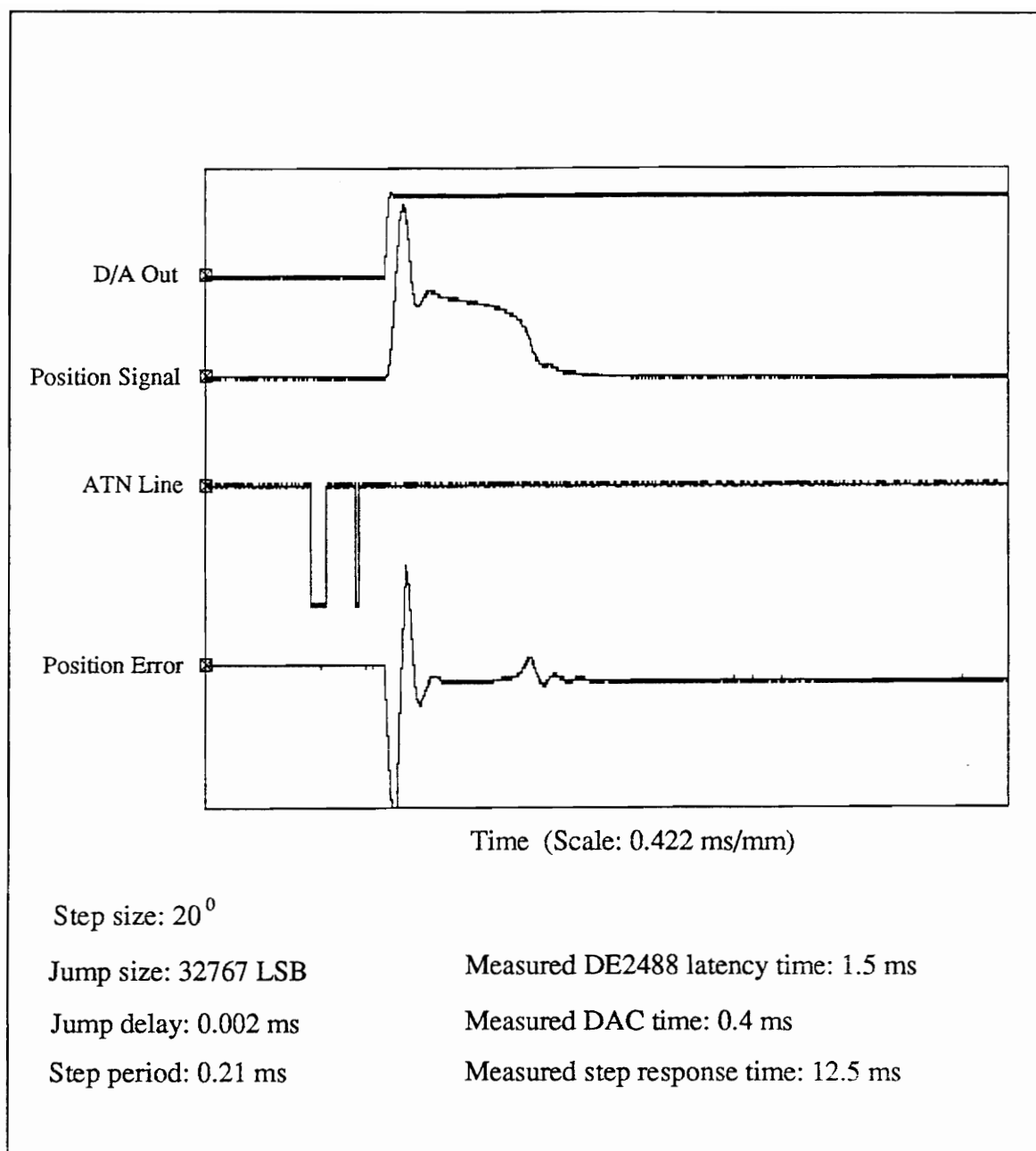
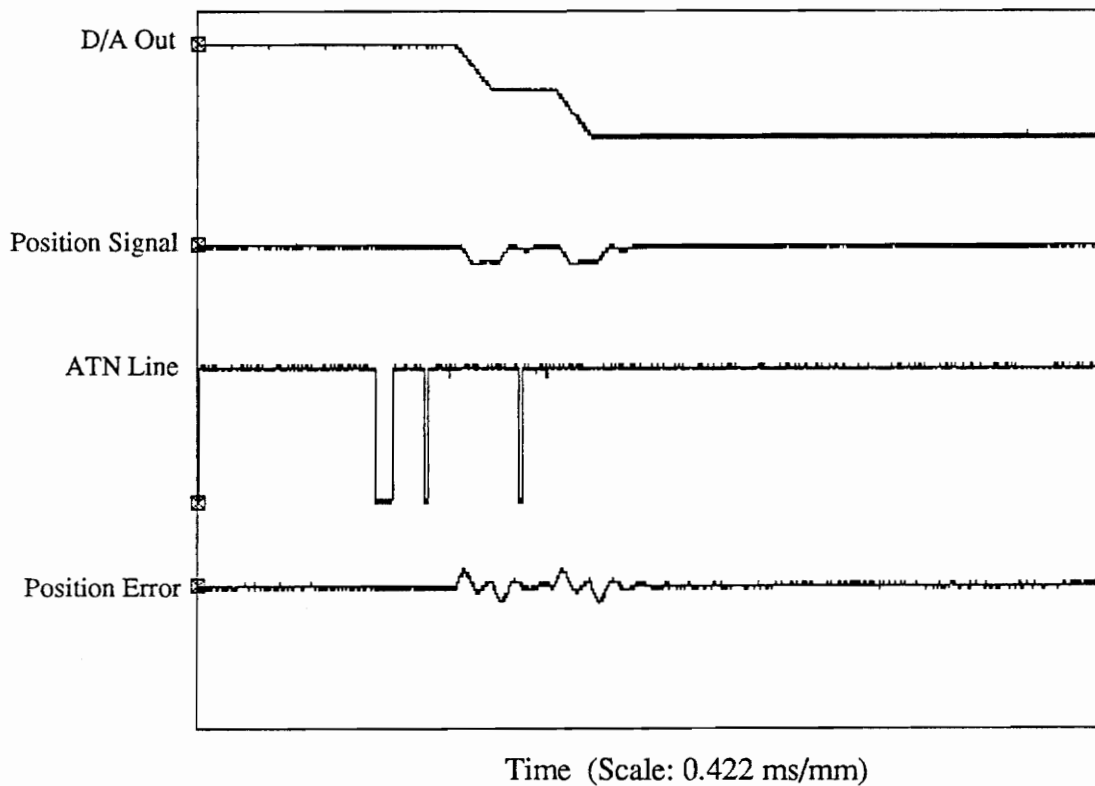


Figure C.6 Test result of the scanning time of the G3B/DE2488 (6)



Step size: $1^0 \times 2$

Jump size: 200 LSB

Jump delay: 2 ms

Step period: 0.21 ms

Measured DE2488 latency time: 1.5 ms

Measured DAC time: 2.1 ms $\times 2$

Measured step(2) response time: 11 ms

Figure C.7 Test result of the scanning time of the G3B/DE2488 (7)

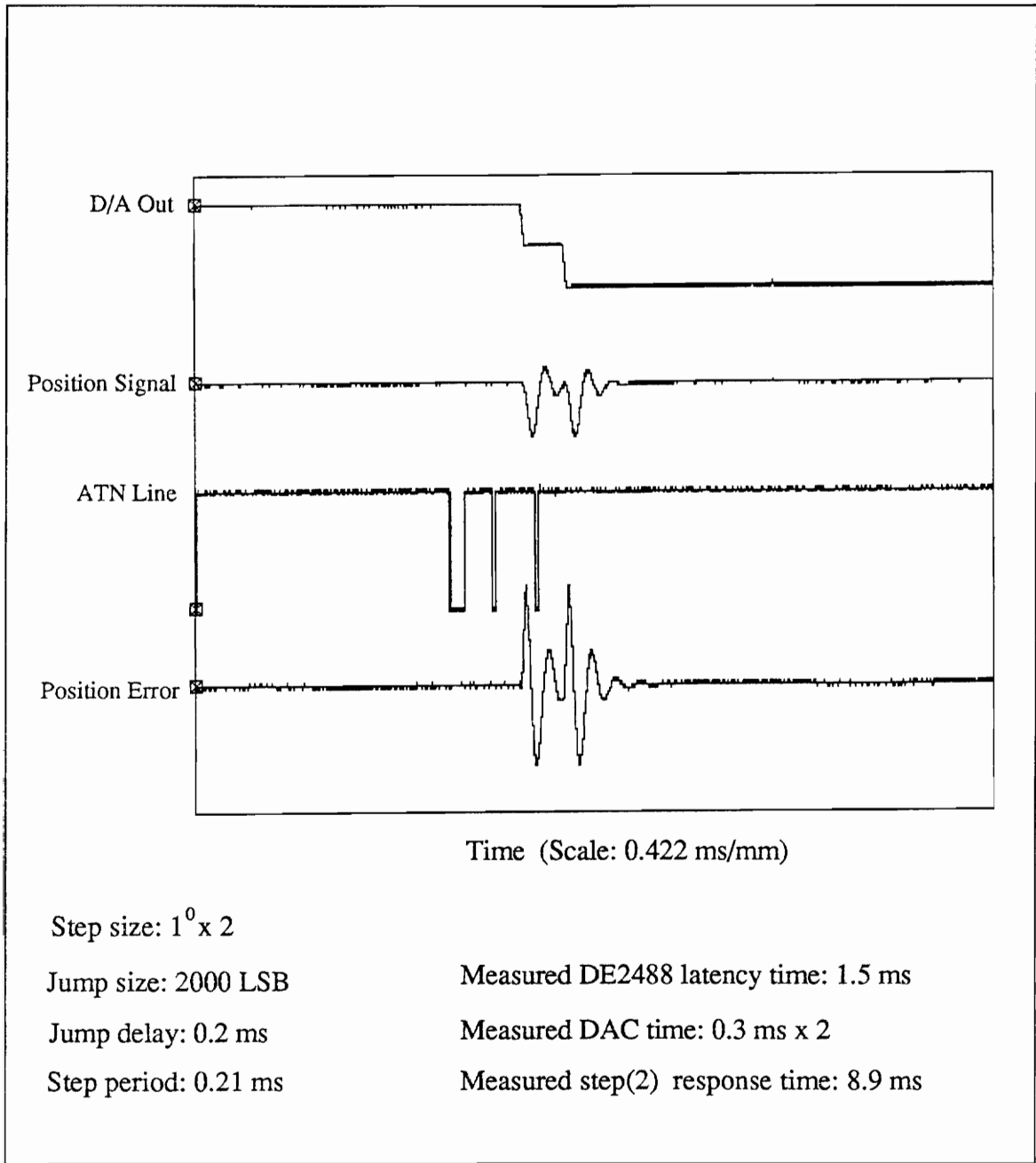


Figure C.8 Test result of the scanning time of the G3B/DE2488 (8)

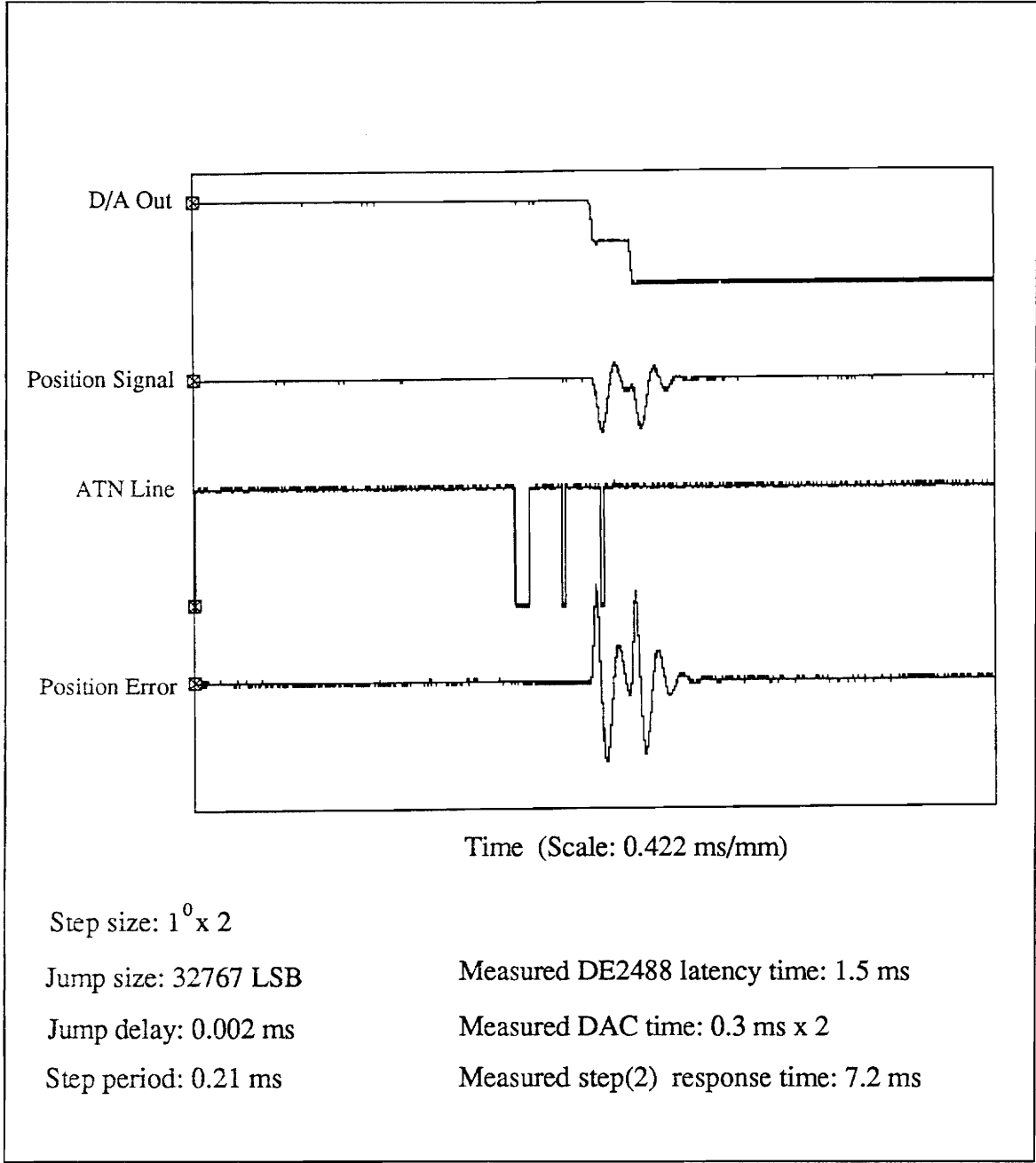
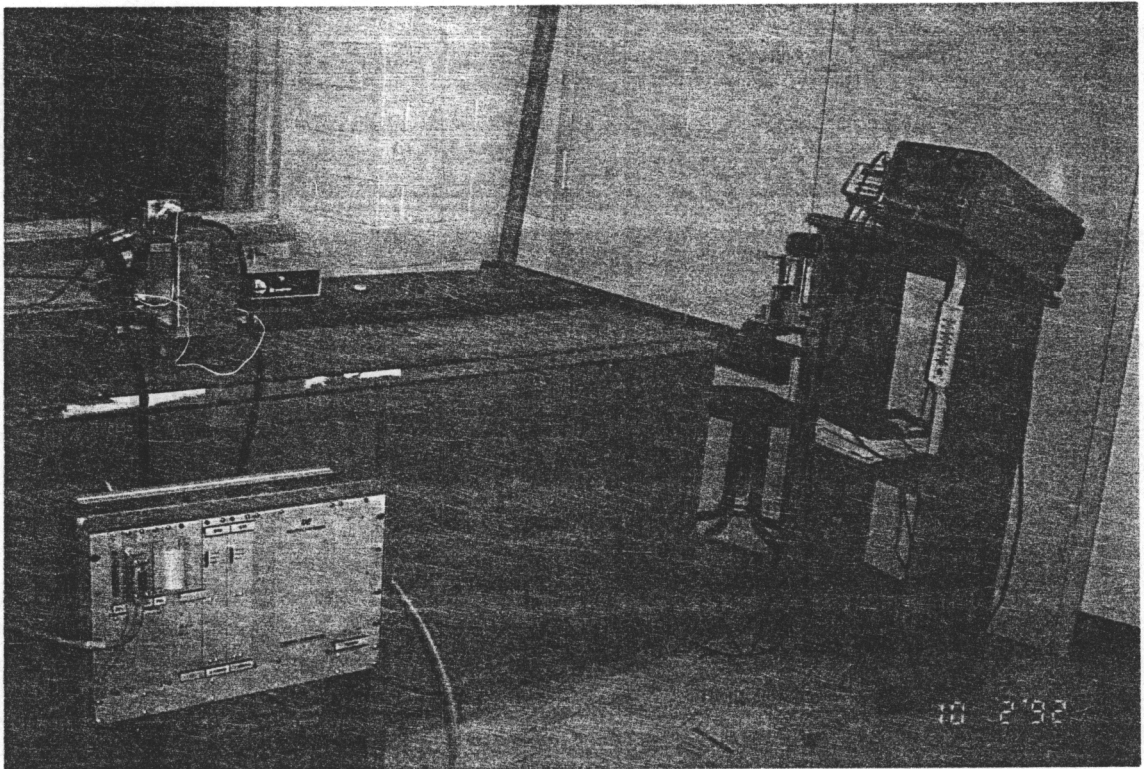


Figure C.9 Test result of the scanning time of the G3B/DE2488 (9)

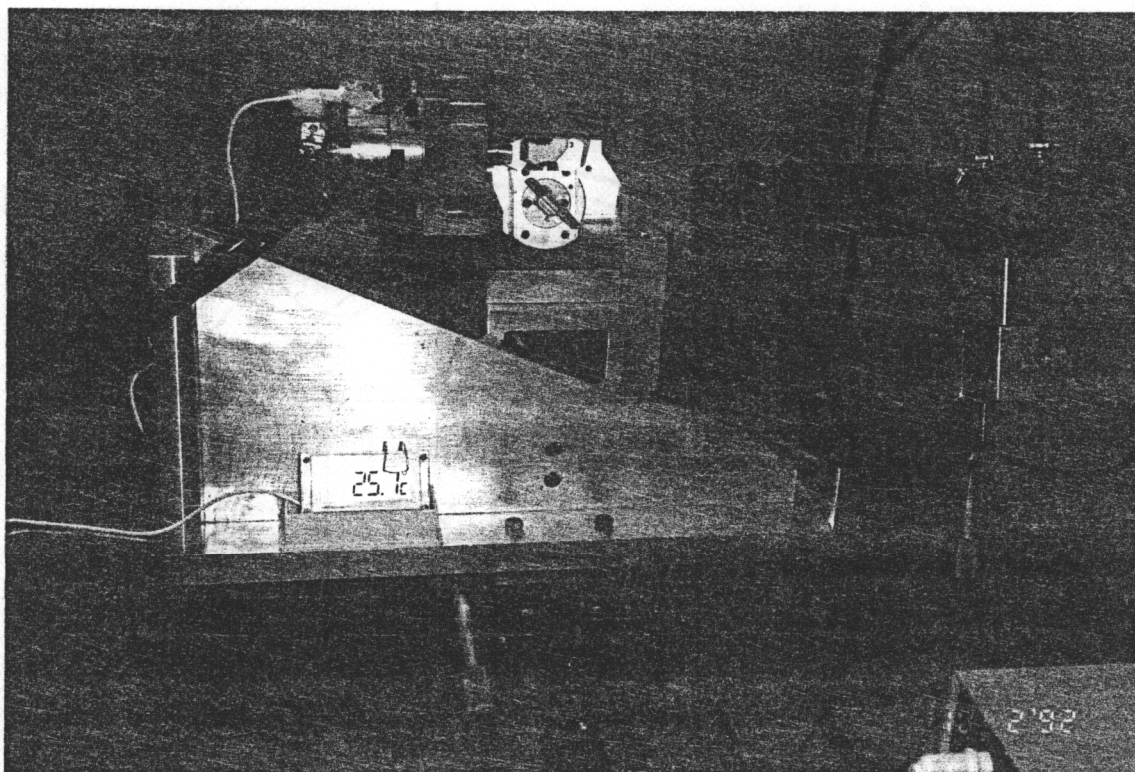
APENDIX D

Photographs of the Setup for the Scanning Accuracy Test



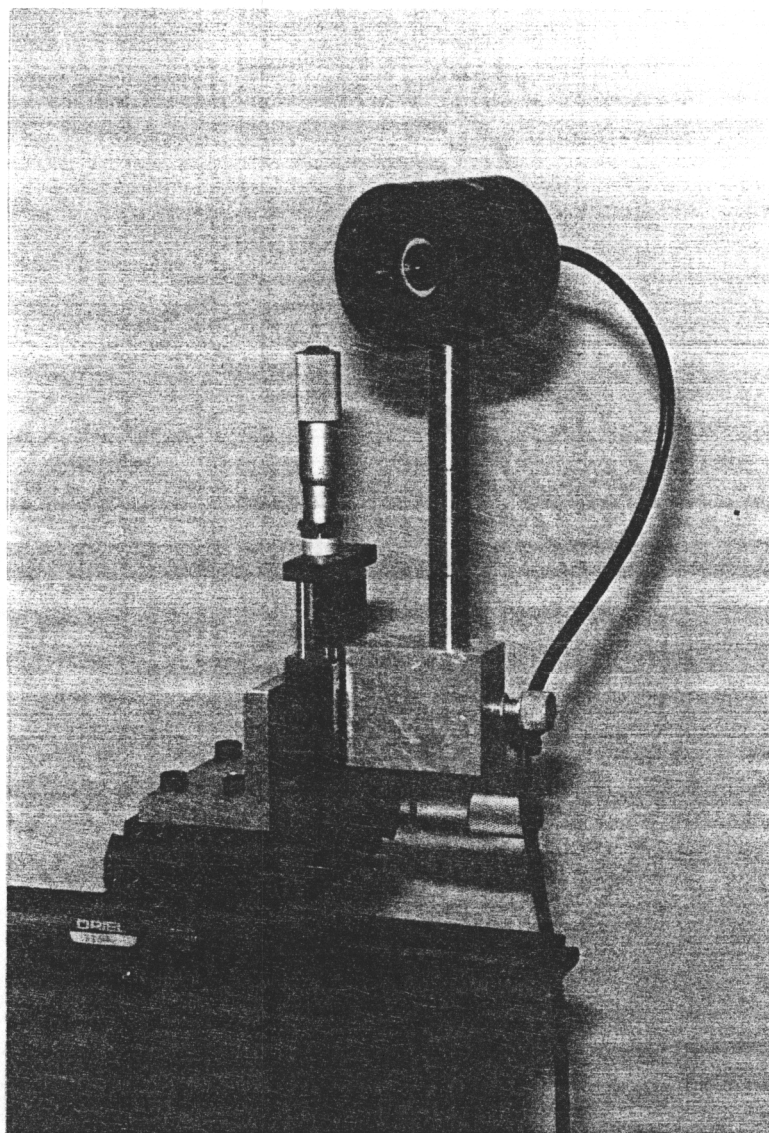
Full view of the setup

Figure D.1 Photograph of the setup (1)



The laser-scanner unit (at horizontal position, with the Z stage)

Figure D.2 Photograph of the setup (2)



The photodetector unit (with the X and Y stages)

Figure D.3 Photograph of the setup (3)

APPENDIX E

Measurement Data for G3B Position Sensors from General Scanning Inc.

X scanner (S/N 604920)		Y scanner (S/N 604919)	
Angle (degree)	Raw position (VDC)	Angle (degree)	Raw position (VDC)
-10.00035	1.87414	-9.00148	1.65943
-9.00204	1.68688	-8.00344	1.47518
-8.00400	1.49962	-7.00568	1.29095
-7.00568	1.31239	-6.00764	1.10670
-6.00709	1.12519	-5.00933	0.92244
-5.00822	0.93792	-4.01046	0.73826
-4.00907	0.75080	-3.01103	0.55400
-3.00937	0.56355	-2.01133	0.36981
-2.00911	0.37635	-1.01107	0.18557
-1.00858	0.18910	-0.01054	0.00131
-0.00776	0.00190	0.99027	-0.18282
0.99416	-0.18528	1.99136	-0.36712
1.99663	-0.37251	2.99245	-0.55128
2.99911	-0.55969	3.99410	-0.73554
4.00131	-0.74691	4.99574	-0.91979
5.00295	-0.93413	5.99766	-1.10396
6.00432	-1.12131	6.99986	-1.28245
7.00513	-1.30856	8.00150	-1.47249
8.00455	-1.49578	9.00204	-1.65664
9.00204	-1.68298	10.00174	-1.84092
9.99786	-1.87013		

APPENDIX F

Scanning Angle Test Results for the X and Y Scanners

Table F.1 Scanning angle test results for the X scanner

Digital Input	Test 1 (degree optical)	Test 2 (degree optical)	Test 3 (degree optical)	Test 4 (degree optical)	Test 5 (degree optical)	Average (degree optical)
0	-20.016	-19.987	-20.013	-19.988	-19.984	-19.998
3277	-18.017	-18.001	-18.011	-17.984	-17.994	-18.001
6554	-16.012	-15.995	-16.008	-16.007	-15.986	-16.002
9830	-14.015	-14.002	-14.007	-13.990	-13.985	-14.000
13107	-12.013	-12.009	-12.014	-11.990	-11.983	-12.002
16384	-10.016	-9.999	-10.007	-9.993	-9.990	-10.001
19661	-8.003	-8.005	-7.998	-7.998	-7.988	-7.998
22937	-5.996	-6.005	-6.004	-6.008	-5.997	-6.002
26214	-3.986	-3.997	-3.995	-4.001	-3.991	-3.994
29491	-1.993	-1.996	-2.000	-2.000	-1.993	-1.996
32767	0	0	0	0	0	0
36044	1.999	2.001	1.996	1.993	1.989	1.996
39321	3.997	4.004	4.003	3.990	3.989	3.997
42598	5.998	6.008	5.990	5.992	5.980	5.994
45875	8.001	8.004	7.998	7.987	7.973	7.993
49151	9.996	10.008	9.988	9.988	9.987	9.993
52428	11.991	12.016	11.986	11.975	12.010	11.96
55705	13.996	14.006	13.978	13.982	13.996	13.992
58982	15.979	16.006	15.970	15.953	15.994	15.980
62258	17.992	18.005	17.982	17.973	17.988	17.988
65535	19.973	20.000	19.983	19.956	19.967	19.976

Table F.2 Scanning angle test results for the Y scanner

Digital Input	Test 1 (degree optical)	Test 2 (degree optical)	Average (degree optical)
0	-21.236	-21.222	-21.229
3277	-19.105	-19.093	19.099
6554	-16.965	-16.980	-16.973
9830	-14.856	-14.837	-14.847
13107	-12.739	-12.739	-12.739
16384	-10.626	-10.615	-10.621
19661	-8.499	-8.499	-8.499
22937	-6.385	-6.367	-6.376
26214	-4.258	-4.232	-4.245
29491	-2.130	-2.114	-2.122
32767	0	0	0
36044	2.117	2.120	2.119
39321	4.257	4.246	4.252
42598	6.367	6.380	6.374
45875	8.499	8.493	8.496
49151	10.605	10.605	10.605
52428	12.748	12.741	12.745
55705	14.860	14.866	14.863
58982	16.975	16.981	16.978
62258	19.096	19.097	19.097
65535	21.217	21.194	21.206

VITA

Xinzuo Li (李心佐) was born in Jiangsu Yixin (江苏宜兴), People's Republic of China on October 31, 1959. He is the youngest child of Li, Xun (李勋) and Wang, Yixing (王仪型). He spent his childhood in his hometown. He graduated from Nanjing Mechanical and Electrical Technical Institute (南京机电学校), Nanjing, China in July 1981.

In July 1982, he moved to Los Angeles, California. He received his Bachelor of Science in Mechanical Engineering from the California State University at Los Angeles in September 1989. He went on to attend graduate school at Virginia Polytechnic Institute and State University, studying mechanical engineering. On December 7, 1991, he married Christina Yonbong Chong (郑然奉) at Virginia Tech Chapel. He completed the requirements for his Master of Science degree in Mechanical Engineering in November, 1992.

He plans to continue pursuit of a Doctor of Philosophy degree in Mechanical Engineering at Virginia Polytechnic Institute and State University.

A handwritten signature in cursive script, reading "Xinzuo Li", written in black ink.

Xinzuo Li