REMOTE MEASUREMENTS OF ANGULAR ORIENTATION

OF PLANAR AND CYLINDRICAL TARGETS

A Thesis Presented

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Abstract of the Thesis

Remote Measurements of Angular Orientation of Planar and Cylindrical Targets

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This thesis presents a novel method for the remote measurement of angular orientation of stationary targets. The technique is based on obtaining a temporal signature of non-linear, reflecting image patterns that are printed on to the surface of the target. The system uses one-dimensional LASER scanning system for reading a bar pattern, which can be described by a pulse position modulation signal. Through the system, angular orientation, both azimuth and elevation, can be obtained at a distance of 1m.

A commercial barcode scan engine, controlled through a microcontroller, forms the basis of a compact angular orientation measurement system is described in this thesis. The recorded temporal signature is processed to output the angle information. Performance of the system was verified by using planar and cylindrical targets. The system has on angular resolution of $\pm 2^\circ$ for flat surfaces and cylindrical objects.

To

My Parents

Yumi Horimai and Hideyoshi Horimai

For their continuous support, encouragement and patience

And

In the memory of my grandmother

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This research was supported through a Strategic Partnership for Industrial Resurgence award (SPIR) funded by Omnitek Partners, without their generous support I could not have completed the experiments. Additionally, I would like to thank Motorola for providing the OEM version of scan engine. I would like to extend my gratitude to my committee member, Professor Murali Subbarao, for taking time off his busy schedules to examine my thesis report and give valuable advice. I would also like to thank my colleague, Shih His Yen for his benevolent aid and insightful suggestions.

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1.0 Introduction

Angular orientation measurements are very important in a variety of disciplines, particularly, in the area of autonomous robots. Speed, accuracy and easy implementation are required for measurement and adaptability to the outer environment is necessary in these fields.

Several optical methods based on interferometry [14] auto-collimation [12], the internal reflection effect [7], phase shift imaging [3], and the moiré technique [9] have been proposed for measurements of angles. However, most of these methods require careful consideration of transmitter and receiver location. The phase based method, while exhibiting high resolution, are very difficult to implement in open environments. They are particularly sensitive to the mechanical vibrations.

Commercial digital angle measurement device, inclinometer or tilt sensor, on the other hand, uses an accelerometer to determine the pitch (rotation angle around y-axis), roll (rotation angle around x-axis), and yaw (rotation angle around z-axis), angles relative to the direction of gravity. Each accelerometer axis (x,y,z) picks up a component of gravity as a function of its orientation. The three axis DC accelerometer measures the three components of gravity, g_x, g_y, and g_z with respect to the coordinate system of the accelerometer. As the accelerometer is tilted away from horizontal, the x and y axes of the accelerometer will pick up a component of the gravity acceleration [4]. Trigonometry can be used to convert this acceleration to angles relative to the gravity vector inclination angle [15]. These systems achieve the desired measurement through local sensors and encoders mounted at the point of measurement.

Wireless angle measurement systems displays angle data received from a transmitter attached to the target. Despite the lack of remote angular measuring systems, there exists a need for such systems, particularly, in the area of munitions. A recently issued patent [11], discusses the relevance of remote angular orientation measurement in this context.

For this problem to be solved, a method based on the idea of angular orientation measurements by using a bar pattern printed on the target is developed to measure angle orientation.

The main focus of this thesis is to design and fabricate a remote system for measuring the angular orientation, i.e. azimuth and elevation, of a cylindrical target at a distance of 1 m.

2.0 Theoretical background

The technique is based on obtaining a temporal signature of a non-linear, reflecting image that is painted on to the surface of the target. Angular position measurement can be achieved at a distance of 1m, for illustrative purpose the analysis below uses a one-dimensional scanning system for reading a bar pattern, which can be represented by a pulse position modulation scheme.

At first glance this pattern may be mistaken for the ubiquitous barcode found on all products, and an incorrect inference that barcode scanning solution may be tailored to meet the needs of an angular displacement sensor. However, this would be an incorrect observation as the similarity ends with shape of the bar, a barcode comprises of a sequence of fixed width space marks which can either be dark or white, corresponding to a digital 1 or 0. Scanning and non-scanning (imaging) systems are used for detection of the sequence of 1s and 0s representing the product numeric code. The emphasis of such system is on the recovery of the digital sequence from arbitrary orientation of the barcodes. Such systems cannot be easily adapted for angular measurement.

We propose a scanning based system with a novel signal processing technique for rapid recovery of angular information. A laser beam illuminates the target and a retro-reflective optical system provides the instantaneous temporal signature of the target bar pattern. The technique of measurement is based on the intellectual property assigned to Omnitek Partners, LLC (See US Patent 7,233,389) [11].

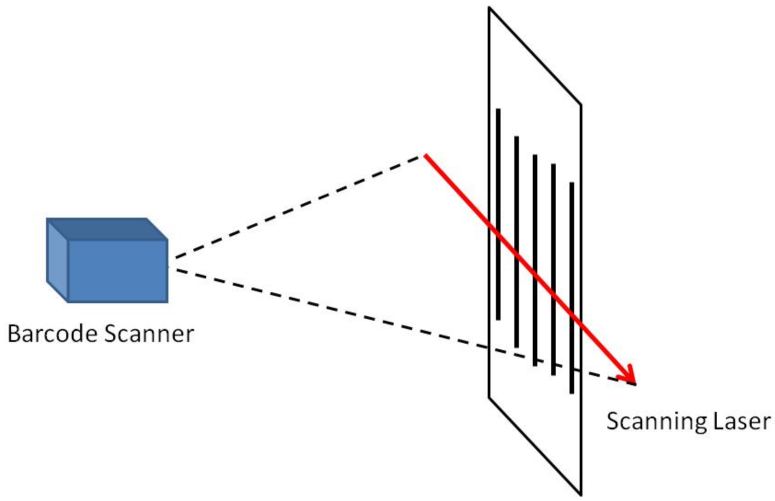


Figure 2.1 Barcode scanner scans the bar pattern on flat surface horizontally.

The retro-reflective target can be characterized by a spatial distribution f(x), which for example could be sequence of rectangular functions

$$f(\chi)= \sum_{j} \mathrm{rect}\left[\frac{\chi - X_{oj}}{W_j}\right]$$

Where Xoj and W_j are position and width of the j'th bar in the pattern, respectively.

In general, the bar position and width are functions of the elevation and azimuth angles. Thus, the elevation angle can be recovered from a measurement of the bar width, which can be accomplished by using either an imaging or a scanning technique. The former technique requires independent illumination of the target and considerable signal processing, while the latter offers considerable advantage of simplicity and space.

2.1 Calculating rotation angle in flat surface

As the laser spot moves across the target it generates a time varying signal. The signal will vary depending on the angle of scanning. The 0° rotating angle signal, v(t,0) and θ° rotation angle signal v(t,θ) is shown in the figure 2.2 and 2.3.

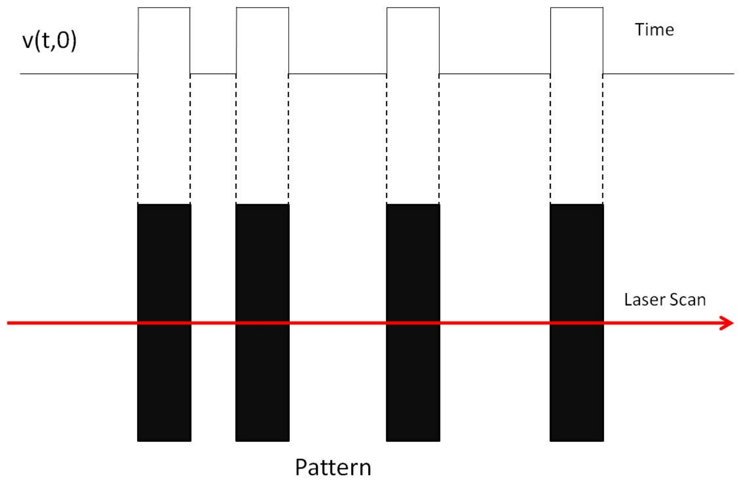


Figure 2.2 Rotating angle signal v(t,0) produced by scanning by laser scan at 0 angle

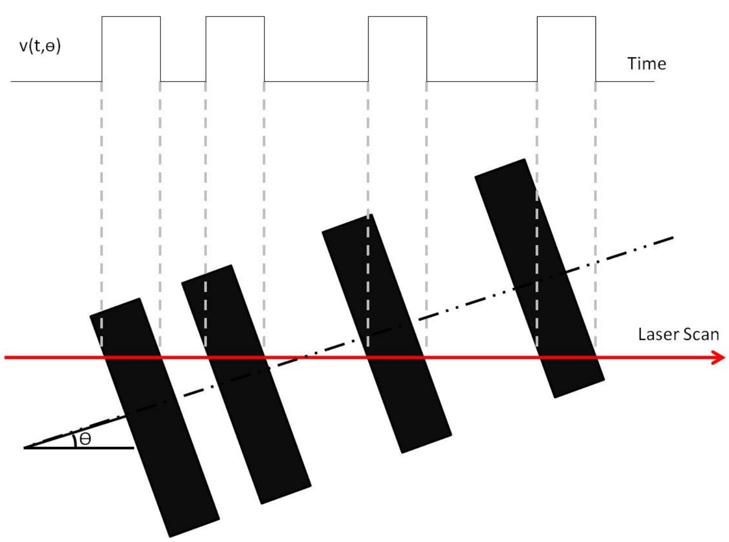


Figure 2.3 Rotating angle signal v(t,θ) produced by scanning by laser scans at θ° rotation angle

In the following equations the subscript j has been dropped for clarity. The rotation angle can be recovered from the width of bar W(θ) using the transformation

$$\theta = \cos^{-1}\left[\frac{W(0)}{uT_0}\right]$$

Where W(0) is the initial width of the bar and u is the scan velocity at the bar location and ΔT is the measured time width of the bar. This measurement requires knowledge of the scan velocity that is not constant throughout the scan. It is possible to compute a correction for the velocity error.

However, the dependence on velocity can be eliminated by normalizing the time measurement with a reference time measurement made at say $\theta=0^\circ$, giving

$$\theta = \cos^{-1}\left[\frac{W(0)}{u\Delta T}\right] = \cos^{-1}\left[\frac{u\Delta T_0}{u\Delta T}\right] = \cos^{-1}\left[\frac{\Delta T_0}{\Delta T}\right]$$

In general, the precision and sensitivity of the angular measurement can be improved by using a non-linear two-dimensional pattern and by averaging the results over several scans. The precision of the measurement is proportional to the square root of the number of scans. However, in practice, the limiting angular precision may be determined by the stability of mechanical system.

2.2 Calculating elevation angle on cylindrical surface

A laser spot scan of a cylindrical surface produces a curved trajectory, resulting in a non-linear temporal signature from a linear bar pattern on the cylindrical surface. Figure 2.4 shows a typical response from a cylinder with orientation (0,0). The laser scan line is parallel to the x-y plane.

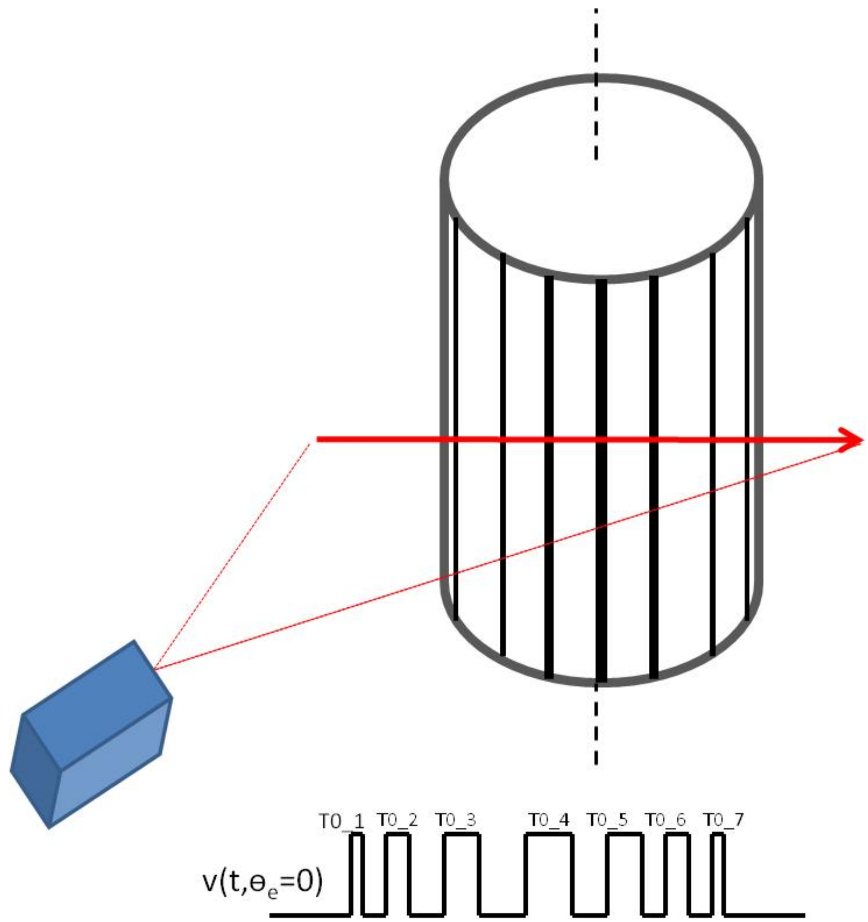


Figure 2.4 Output signal for the cylinderical object for 0° elevation angle for equally printed bar pattern

If the cylinder is elevated in an angle of θ > 0°, the scanned surface by laser will shown as a Figure 2.5

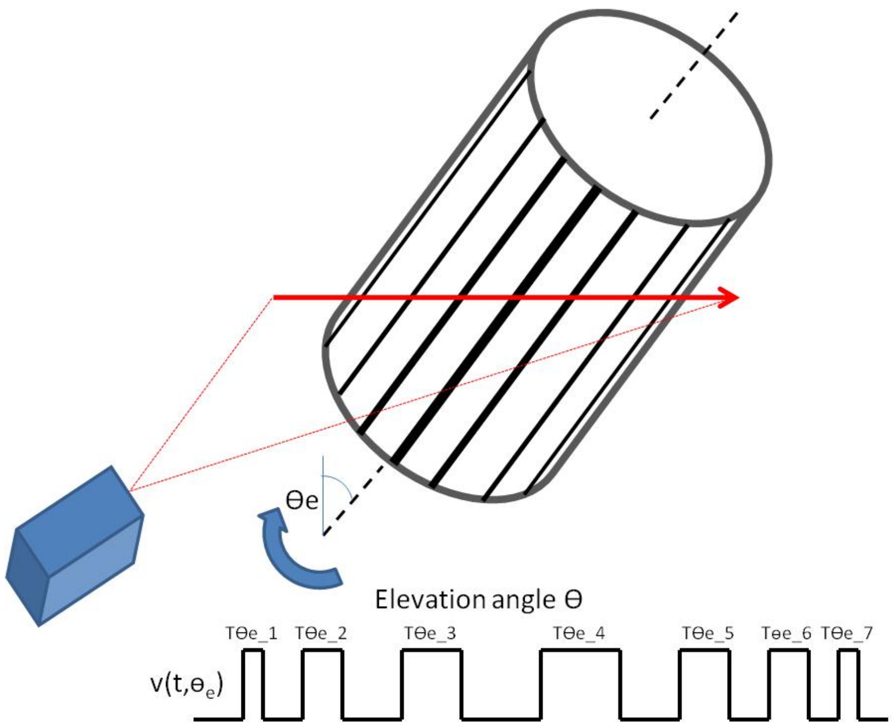


Figure 2.5 Output signal for the cylinderical object for θ° elevation angle for equally printed bar pattern

The same technique is used for calculating the elevation angle, as shown in the flat surface, by matching each $T\theta_0\_1$ to $T\theta\_1$, $T\theta_0\_2$ to $T\theta\_2$, …, $T\theta_0\_n$ to $T\theta\_n$, where θ is elevation angle, and θ_0 is 0° elevation angle.

Therefore, the elevation angle θ can be calculated as

$$\theta = \frac{\sum_{i=1}^{N} \cos^{-1}\left(\frac{T\theta_{0}\_i}{T\theta\_\mathrm{i}}\right)}{N}$$

where N is the total number of lines scanned by the scanner and $T\theta_0\_i$ is the i'th line pulse width at 0° elevation angle and $T\theta\_i$ is the i'th line pulse width at θ° elevation angle. Therefore, the elevation angle of cylindrical object is determined from simple pattern printed on the surface of the cylinder.

Azimuth angle of the cylinder can be measured by locating the laser scanner axis parallel to the radial unit vector $\hat{r}$, as illustrated in Figure 2.6. This will be perpendicular to scanner axis for the elevation angle, that is, parallel to the unit vector $\hat{\varphi}$. Therefore, the azimuth angle φ of cylindrical objects can be calculated from a simple pattern printed on the surface of the cylinder as same function as calculating the elevation angle,

$$\varphi = \frac{\sum_{i=1}^{N} \cos^{-1}\left(\frac{T\varphi_{0\_}i}{T\varphi\_\mathrm{i}}\right)}{N}$$

where N is the total number of lines scanned by the scanner and $T\varphi_0$_i is the i'th line pulse width at 0° azimuth angle and Tφ_i is the i'th line pulse width at φ° azimuth angle.

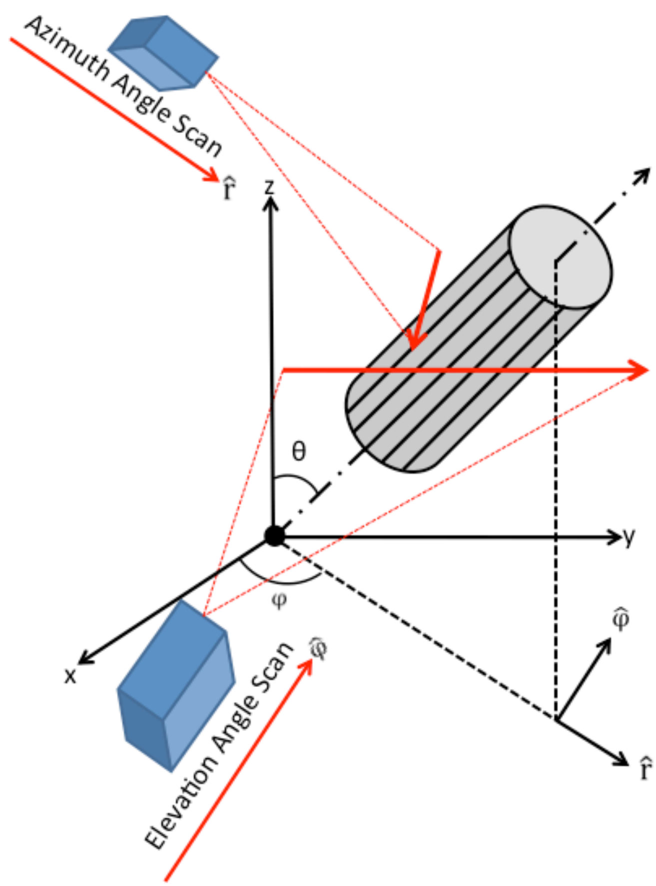


Figure 2.6 Location of the barcode scanner when measuring the elevation and azimuth angle. φ represents the azimuth angle, and θ represents elevation angle. To measure the elevation angle, scanner is positioned parallel to the azimuth unit vector, $\hat{\varphi}$. To measure the azimuth angle, scanner is positioned parallel to the radial unit vector, $\hat{r}$

3.0 Hardware implementation and setup

The measurement system comprises of three sections: 1) laser scan engine; 2) a microcontroller; and 3) All components are carefully selected to meets the goal of this project.

3.1 Barcode scanner evaluation

There are two types of commercial barcode detection systems. One uses a laser scanning system while second uses a Charge-Coupled Device (CCD) based imaging system. Laser systems are by far the most prevalent, but the CCD system has also been a commercial success. The two approached were evaluated for the purpose of orientation detection.

3.2 CCD barcode scanner

CCD barcode scanner contains illuminating Light Emitting Diode (LED), lens, and CCD image sensor. It will read the barcode in the following principle. First, light is irradiated over the barcode with illuminant LED. In this mean time, this illuminant LED is pulsed. The frequency of this pulse determines the ability to read the barcode in motion, which higher frequency pulse light has an advantage to read the barcode on the fast moving object. Then CCD image sensor will absorbs its diffused reflection light as an image. Scan the barcode image on the CCD image sensor from edge to edge, and output as an analog signal. The analog signal is then converted to digital signal. Then the digitized data is then decoded to the code according to the barcode standard.

CCD barcode scanner has 3 main characteristics, such as firm body, limited reading width, not able to read the barcode of moving object. Compared to laser barcode scanner, CCD barcode scanner does not contain moving material such as motor or breakable material such as mirror. This makes CCD barcode scanner compact, cheaper, and impact resistant [6].

The CCD barcode scanner, like a camera, focus the desired barcode image on the CCD image sensor using lens, so that if there is no focus, it is not able to read the barcode. Fuzziness due to out of focus causes the reading error, which will limit the barcode scanning distance within few centimeters [6].

The CCD barcode scanner, emits pulsed illuminant LED light towards the barcode, and reads the barcode pattern by receiving the reflected light. If the pulse duration of this illuminant LED is 1ms, and during this interval, if the barcode shifts a distance of narrow bar, the barcode image on the CCD image sensor overlaps and will be impossible to read the barcode. This is the same phenomenon of the camera shake. Therefore, if the barcode moves a distance of few milliseconds faster than the LED pulse, it is not possible to read the barcode [6]. CCD image barcode scanner is not suitable for the moving object.

LED illumination range, cannot emit the wide area as a laser barcode scanner, its maximum label width is limited to its barcode scanner size.

3.3 Laser barcode scanner

There are mainly two different types of laser barcode scanners, one which emits a collimated laser beam to the rotating polygon mirror to do the scanning, and the other one is which emit the collimated laser beam to the reciprocating motion flat surface mirror, or also known as galvano-mirror, to do the laser scanning [6]. The latter technique is used in this study. This type of barcode scanner, Figure 3.1, is mainly formed from the laser diode, galvano- mirror, and a light absorbent component.

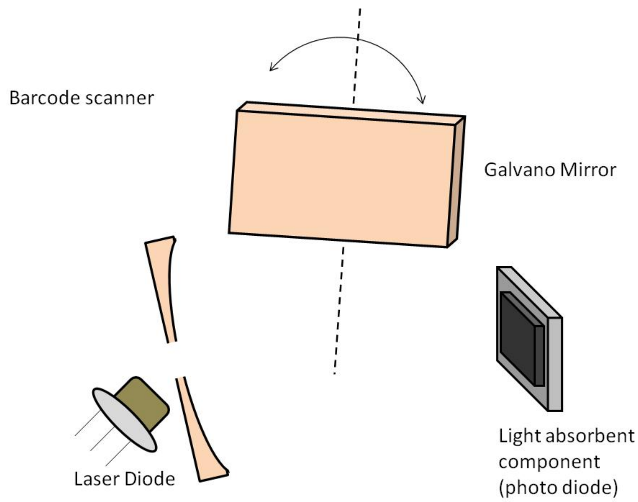


Figure 3.1 Components used in the laser barcode scanner.

A collimated laser beam, from the laser diode assembly, impinges on a reciprocating galvano-mirror, resulting a scanning pattern illustrated in Figures 3.2.

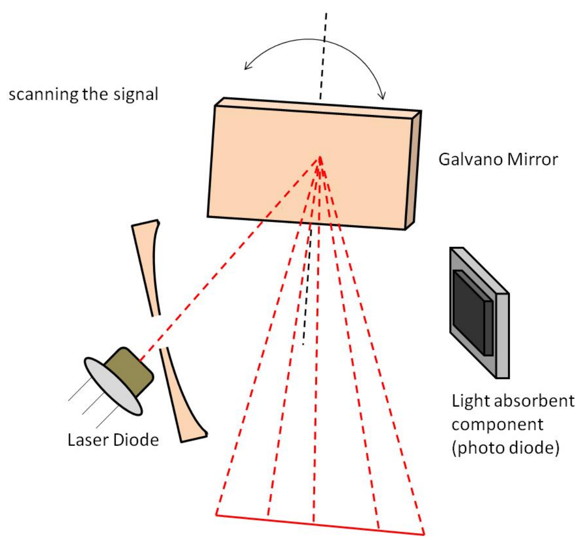


Figure 3.2 Illustration showing laser barcode scanner scans the bar pattern. Laser diode emits the collimated laser towards galvano mirror, in certain scanning angle, between the hole on parabollic mirror.

As sketched in Figure 3.3, the reflected laser light scans across the face of the barcode. A small portion of the incident light is scattered backward toward the light-absorbing medium, which converts the light signal to an analog electrical signal.

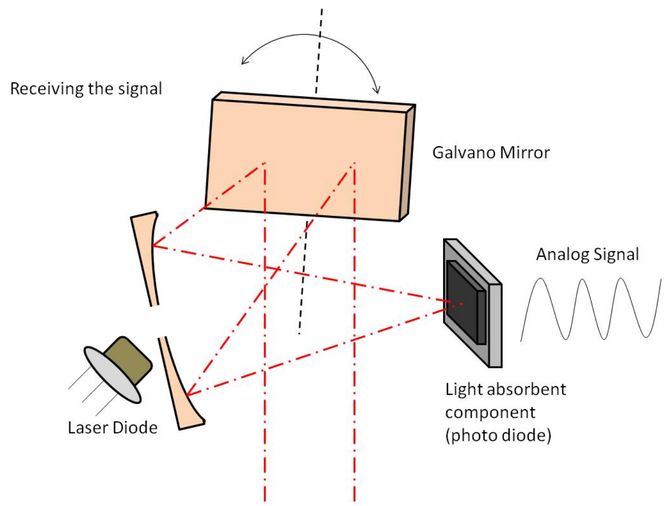


Figure 3.3 Illustration showing how barcode scanner receive the signal from bar pattern. Parabollic mirror in front of laser diode focuses the received signal towards photo diode.

The analog signal is then converted into the digital signal using an analog to digital converter (ADC), Figure 3.4. The resulting digital signals are decoded, according to the specific standard, and the product information retrieved from the enterprise data base.

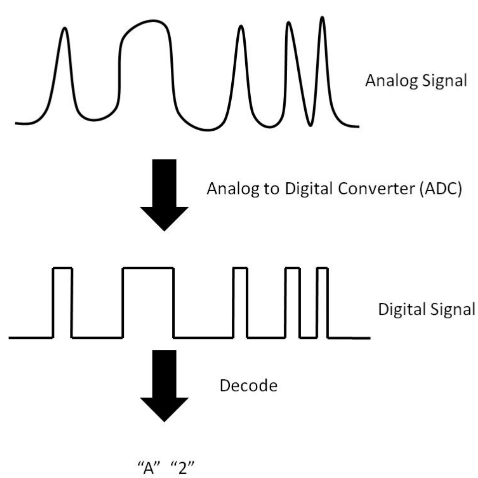


Figure 3.4 Barcode scanner converts received analog signal to digital signal,then decode to appropriate barcode with barcode standards.

The angular measurement system can exploit the technology of barcode scanners. The front part of the barcode scanner is exactly what is called for in the proposed measurements. However, commercial barcode scanners are specifically designed for identifying products based on the printed barcode, and therefore the undecoded signal is not usually saved. In the initial experiments we used the old hand-held scanners (LS7000 model year 1986) for which, after some probing, I was able to find the undecoded signal. Subsequently, Motorola graciously provided on of their latest scan engines, without the decoder. A microcontroller based hardware was designed to process the undecoded signal and recover the time signature of the bar pattern, which enabled the angular measurements to be made rapidly.

3.4 Selecting barcode scanner

Table 1 shows the advantages and disadvantages between laser and CCD barcode scanners. The laser scanner meets of the requirements for the angular measurement. It has long read distances with a high scan speed and capability to read barcodes from moving objects. In particular, the Motorola scan engine SE960HP is ideal for our measurements.

SE960HP barcode scanner engine has the general advantages of laser barcode scanner, and also has the advantages of the general CCD barcode scanner. This barcode scanner engine is the compact with dimension of 11.75mm Height x 21.6mm Width x 15.2mm Depth. It has a shock resistance of 2000G ±5%. The specular dead zone, which will be explained later, is ± 8°, and the scan repetition rate is 104 ±12 scans per seconds [13].

Table 1 Advantages and disadvantages between laser barcode scanner and CCD barcode scanner

Barcode Scanner Type	Advantages	Disadvantages
Laser	• Long Readable Distance • Wide readable area • Can read moving barcode	Generally larger than CCD barcode scanner type
CCD	• Compact • Firm	• Limited readable distance • Not suitable for moving object • Small readable label width

3.5 Scan Engine – SE960HP

Barcode scanner engine, Symbol SE960HP from Motorola, has a laser drive circuit controlling a 650nm laser diode. Scan element is driven by the circuit controlling a resonant single line scan element driver. Analog receiver with circuitry will identify the bar and space pulse duration from the received signal. The microcontroller provides control of the programmable features of the analog circuitry used for optimizing measurement. This engine will function as a laser diode emits a coherent beam of light focused to a diameter appropriate for the barcode densities to be read. The laser beam strikes the mirror of the scan element. This mirror oscillates about its vertical axis deflecting the beam, forming the outgoing scan line. As the laser spot sweeps across the barcode it is either reflected off the white spaces or absorbed by the black bars. A collection mirror tracks the location of the laser spot on the barcode, collects the reflected light, and focuses it onto the receiver photodiode. The photodiode is a transducer that converts optical energy to electrical current. This current feeds into the analog signal processing circuitry. The analog signal processing circuitry amplifies, filters, and edge enhances the signal returned from the barcode. These edges represent where the laser transitions between a bar and a space, and communicates the information contained in the barcode. The digitizer circuitry generates a digital waveform whose ones and zeros represent the width of the bars and spaces in the barcode. This waveform is called the Digital Bar Pattern (DBP) [13]. The DBP is sent to the host microprocessor to be analyzed. The scanning mirror oscillates with a frequency of 52Hz, resulting in 104 scans per second. A magnet assembly, cantilevered on a spring, drives mirror. This scanner engine has a selective scanning angle of 10^o, 35^o and 47^o. The scanning angle can be changed through Inter-Integrated Circuit (I2C) connection [5]. Scanner engine is connected to the microcontroller using a 10pin flex strip cable.

The basic block diagram of the hardware is shown in Figure 3.5 [13]. All the necessary hardware for producing the laser scan beam, detect the signal from the bar pattern, and output an undecoded digital signal is built into the tiny scan engine. The microcontroller provides control of the scan engine, processes the digital bar pattern signal to output the azimuth and elevation orientation of the cylindrical object. Additionally, the microcontroller can send control commands to the scan engine in order to change settings, such as, barcode scanning angle, start and stop the scanning, and also monitor the laser scanning frequency and the timing.

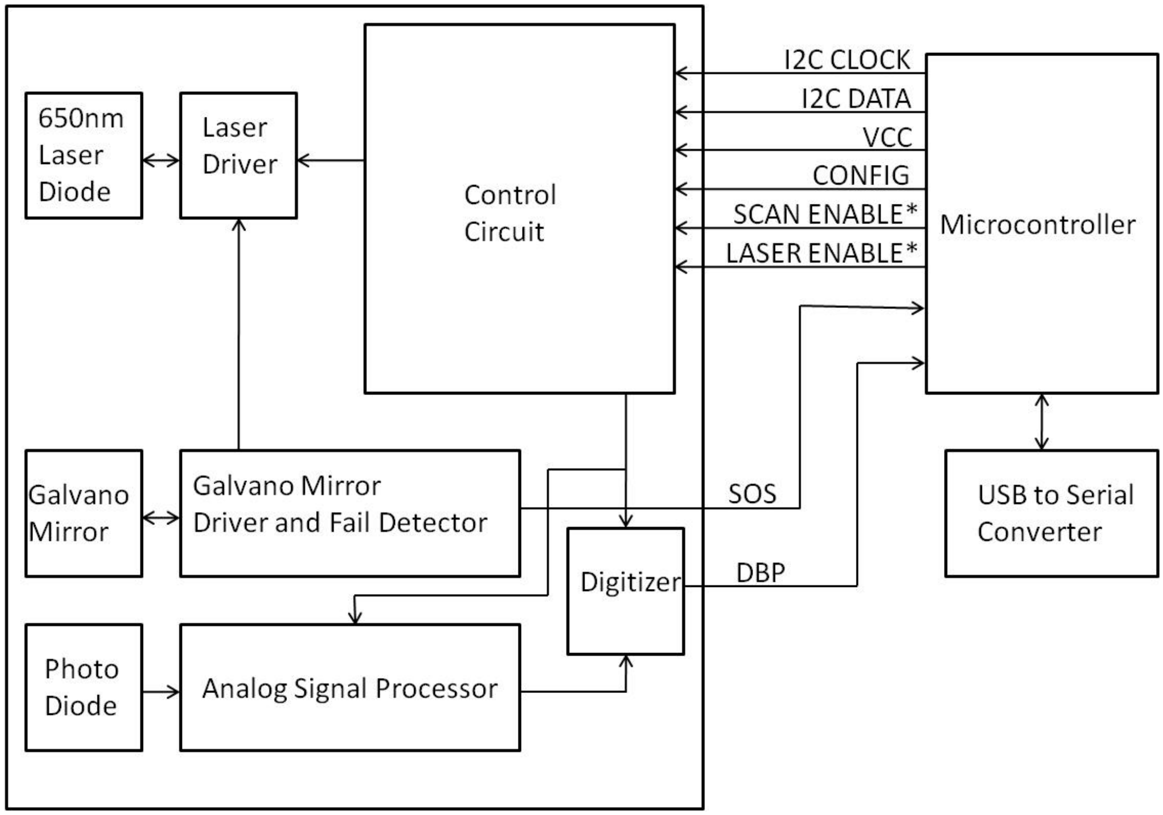


Figure 3.5 SE960HP Barcode scanner engine and microcontroller block diagram.

3.6 Host Microcontroller unit

Arduino Duemilanove microcontroller unit is used to monitor the barcode scanner engine, collect data, and calculate the pulse width between the scanned lines. Arduino is an open-source prototyping platform with microcontroller. This platform supports serial communications to send the collected data to computer through USB cable, and deliver the power to barcode scanner engine[2].

The 8-bit AVR microcontroller, ATmega328P from ATMEL is used as a host microcontroller. This microcontroller has 32K Bytes of Flash memory, 1K Bytes of EEPROM, and 2K Bytes of RAM, operates at 16MHz. ATmega328P supports Byte-oriented 2-wire Serial

Interface, which is compatible with Philips I2C to program the various command to the scanner engine [1].

The communication protocol between the host and scan engine is based on a two-layer model, which includes only a physical layer and data-link layer. The application layer sends and receives all messages in the form of packets.

I2C is a powerful and flexible communication interface, which requires only two bus lines, SDA (data) and SCL (clock). The scan engine is always the slave on the I2C bus (master operation is not supported). As a slave device, the scan engine supports data rates of up to 400 kHz (Fast Mode) [5]. The host has to have pull-up resistors on its SDA and SCL lines (the scan engine does not have pull-up resistors on these lines). The scan engine must be assigned a slave address. It defaults to the slave address: 0x50.

3.7 Remote Scanner Management

SE960HP can be managed from host interface, which can automate configuration, monitor and optimize scanner operation. Scanner engine can be remotely managed by supporting discovery, parameter configuration, and change settings electronically through the I2C host interface. Figure 3.6 illustrates the SE960HP scan engine and host interconnection for remote scanner management [13].

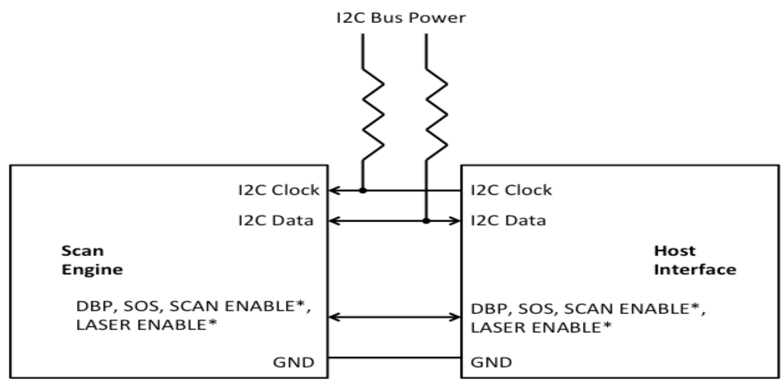


Figure 3.6 Remote Scanner Management via I2C interconnection

The scanner engine uses I2C interface to communicate and link between the un-decoded scan engine and a host [13]. This serial interface provides a bi-directional interface between the host (master) and the scan engine (slave). I2C connection will offer host control of scan engine features.

3.7.1 Attribute storage/retrieval

Attributes are the general properties of the device that include configuration parameters and diagnostic data. The SE960HP scan engine supports protocols that define a way to query/store these attributes over the I2C host interface. Tables 2 and 3 define the attributes assigned to the scanner engine used in this experiment [13]. The attribute numbers correspond to the command OpCodes used in the I2C protocol.

Table 2 Attribute number for receiving the motor information of SE960HP barcode scanner engine

Attribute number	Attribute name	User mode access	Size (bytes)	Data type	Description
0x71 01	Motor frequency	Read	1	Unsigned char	The motor frequency of the scan engine expressed in [Hz]
0x71 02	SOS Positive Duty Cycle	Read	1	Unsigned char	SOS duty cycle expressed in [%]

Table 3 Attribute number for configuring the various scanner mode for SE960HP barcode scanner engine

Attribute number	Attribute name	User mode access	Size (bytes)	Data type	Description
0xC0	Scan Engine Config0 Mode	Write	1	1	Configures the scan engine to support either Aim or Scanstand mode.
0xC2	Scan Angle Mode	Write	1	1	Configures the scan engine to start a scan session with a specific scan angle
0xC1	Adaptive Scanning Mode	Write	1	1	Configures the scan engine for maximum performance. It adaptive scanning mode is on, maximum performance is achieved by allowing the scan engine to automatically switch between wide and narrow scan angles

3.7.2 Engine control Commands

Table 4 lists the I2C OpCodes used in the Symbol SE960HP scan engine and shows the I2C partner allowed to send each message. Table 5 lists the I2C parameter used in the Symbol SE960HP scan engine for corresponding OpCodes in Table 4 [13]. The host transmits OpCodes designated by type **H**, and the scan engine transmits OpCodes designated by type **S**. I2C messages should not be sent to the scan engine while a scan session is in progress. The messages are separated into two categories:

• Commands that configure and control various scan engine features. These commands are available to all hosts. The OpCodes are in the range [0x80 - 0xCF].

• Commands that remotely monitor scan engine attributes. These commands are also available to all hosts. The OpCodes are in the range [0x60 - 0x7F].

Table 4 OpCode command for various configuration commands to send and acknowledge message receiving

Name	Type	OpCode	Description
PARAM_SET_SCAN_ENGINE_MODE	H	0xC0	Configures the scan engine to support either Aim or Scanstand mode.
PARAM_SET_ADAPT_MODE	H	0xC1	Controls the scan engine's adaptive scanning feature.
PARAM_SET_SCAN_ANGLE	H	0xC2	Configures the scan engine for a specific scan angle.
CMD_ACK	S	0x80	The scan engine uses this to acknowledge that the command it just received is supported and the message checksum is validated.
CMD_NACK	S	0x82	The scan engine uses this to inform the host that it just received an unsupported command opcode.
CMD_CSUM_ERR	S	0x84	The scan engine uses this to inform the host that it just received a message with an incorrect checksum. The host should resend the same command.

Table 5 Parameters of commands used in the experiment

Name	Parameters used in the experiment	Description of parameter
PARAM_SET_SCAN_ENGINE_MODE	0x00 (When positioning the barcode scanner to appropriate position)	Scan engine activates aim pattern when Config0 pin at interface is asserted low
	0x01 (After barcode scanner is located at appropriate position)	Scan engine operates in Scanstand mode when Config0 pin at interface is asserted low
PARAM_SET_ADAPT_MODE	0x01	Adaptive scanning is off
PARAM_SET_SCAN_ANGLE	0x00	Sets scan engine scan angle to narrow (10º) on subsequent scan sessions

The host microcontroller interface will send the code as follows;

First send the slave address, followed by desired OpCode, then parameters, and finally end with checksum. The barcode scanner engine will send the acknowledge OpCode 0x80 if command it just received is supported and the message checksum is validated.

3.7.3 Remote monitoring commands

The remote monitoring commands support the Remote Scanner Management (RSM) architecture. The host uses the commands defined in Table 6 to query the scan engine for important information, for example, the motor frequency, software revision, and serial number. Table 7 lists the parameters for corresponding OpCode in Table 6 [13]. The host also uses several of these commands to determine the status and overall health of several scan engine subsystems.

The OpCodes of the remote monitoring commands are in the range of [0x60 - 0x7F]. These commands are not generally acknowledged with the CMD_ACK, CMD_NACK, or CMD_CSUM_ERR OpCodes, instead the scan engine responds with the requested data byte(s). The exception is for commands that require a parameter (e.g., REQUEST_MOTOR_STATUS), where the scan engine responds with CMD_NACK if it receives an invalid parameter, or a CMD_CSUM_ERR if it receives an invalid checksum.

Table 6 Opcode to receive the scan engine motor status

Name	Type	OpCode	Description
REQUEST_MOTOR_STATUS	H	0x71	Requests the scan engine motor status.

Table 7 Parameters to change the scanning angle to narrow, medium, and wide scan angle, and parameter to request scan engine SOS frequency

Name	Parameters used in the experiment	Description of parameter	Response format
REQUEST_MOTOR_STATUS	0x00	Request scan angle the scan engine is currently using	0x00 = narrow scan angle 0x01 = medium scan angle 0x02 = wide scan angle
	0x01	Request scan engine SOS frequency	SOS_Frequency [Hz]

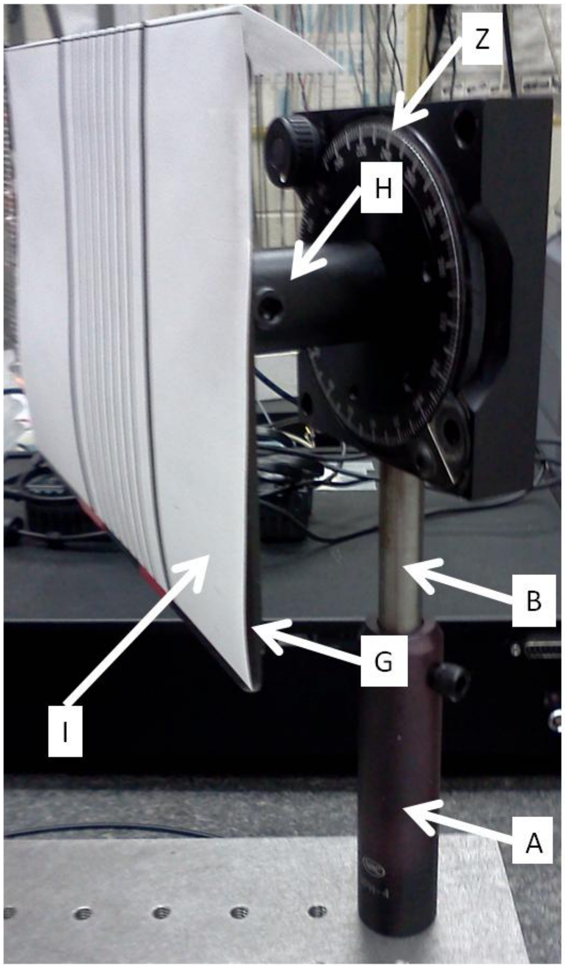
The host microcontroller interface will send the code as follows;

First send the slave address, followed by desired OpCode, then parameters, and finally end with checksum. The barcode scanner engine will send the response to the microcontroller due to the message sent from the microcontroller.

3.8 Observation target

Flat surface and cylinder are used as a target to calculate the rotation angle, and elevation and azimuth angle, respectively. In all cases, the barcode pattern is printed on paper and taped to the object surface facing the scan engine, located at a distance of 1 m.

For the flat surface rotation angle measurement, a plastic board with a size of 115mm width and 120mm height is placed at the rotating stage as shown in the figure 3.7. This stage has a resolution of 1° and rotates manually.



A: (Newport) Model:VPH-4
Vertical Post Holder 4 inch

B: (Newport) Model:9623
Stainless Steel Post, 4.0 in. Height, 0.5 in. Diameter

Z: (Newport) Model: RSX-2
Rotation Stage

G: Plastic board
(155mm x 120mm)

H: (Newport) Model: VPH-2
Standard Post Holder, 2 in. Height, 0.5 in. Diameter Post

I: Printed Barcode Pattern

Figure 3.7 Components used for flat surface rotation angle measurement

For the cylindrical object angle measurement, an acrylic tube with diameter of 115 mm and a height of 200 mm is used (see Figure 3.8) This tube is located on top of the 2 axes Gonio stage with a resolution of 0.1°.

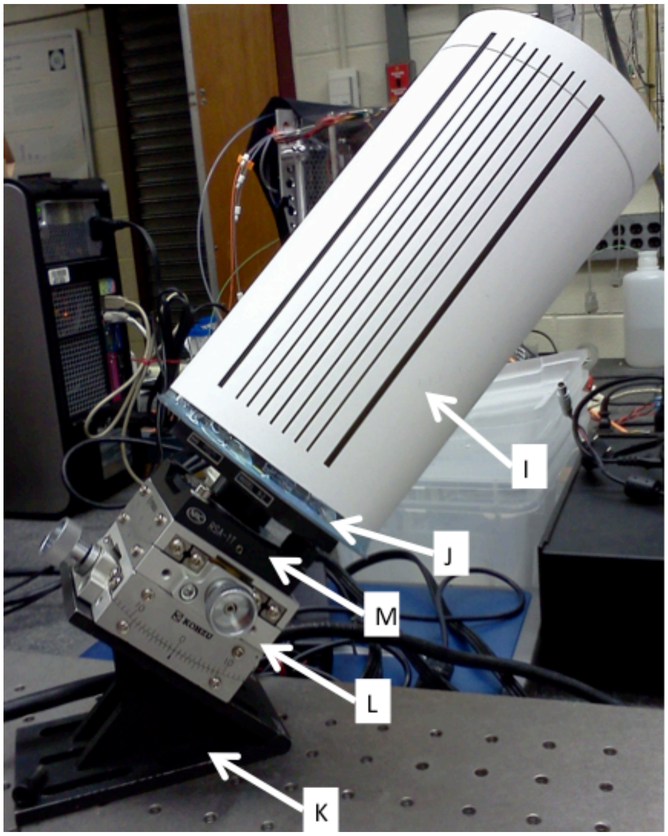


Figure 3.8 Components used for cylinderical object elevation & azimuth angle measurements

3.8.1 Print Contrast Signal (PCS)

The barcode scanner reads the barcode with the strength of diffused reflection of the scanned laser light. If the difference in strength is large, it is the barcode that it is easy to read. Conversely, if difference of strength is small, it is the barcode that is difficult to read. SE960HP barcode scanner engine requires minimum 25% absolute dark/light reflectance measured at 650nm.

The standard that gives the strength of this diffused reflection is called Print Contrast Signal (PCS) [6]. PCS can be determined from reflectance ratio of the space Rs, and the reflectance ratio of the line Rl, using the equation;

$$PCS = \left[\frac{Rs - Rl}{Rs}\right]$$

From this equation, if the space is completely white and the reflectance ratio is nearest to 100%, and if the line is completely black and the reflectance ratio is as nearest to 0%, PCS will be 1. As this explains, the barcode that has the PCS close to 1 is the barcode that is easy to read. Therefore, the scanner friendly barcode must to be printed on white paper and print the line as dense as possible and make PCS as high as possible. If the barcode pattern is printed to the white paper using ink jet printer, it might cause reading error as shown in Figure 3.9 [6].

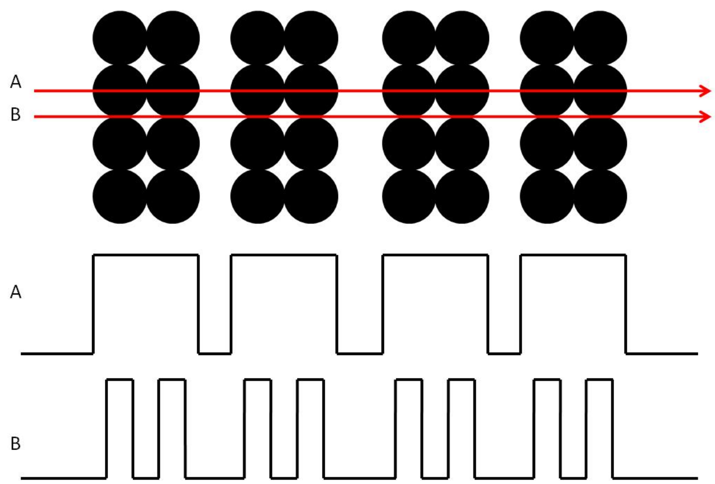


Figure 3.9 (A) is the appropriate signal from printed bar pattern and output signal. (B) is the different output signal caused by the dots by the inkjet printer

The laser printer, which has the ability to print high dense 1200 x 600 dpi resolution, is used to print the bar patterns with PCS values close to unity.

Another quantitative measure of bar detectablilityis defined by the the Mean Reflective Difference (MRD), which is given by,

$$MRD = MRRS - MRRL$$

where MRRS is the Mean Reflection Rate of Space, and MRRL is the Mean Reflection Rate of Line [6]. SE960HP barcode scanner engine can read a width of 20 mil at distances of up to 109.22cm when the MRD is higher than 80%.

3.8.2 Difference in bar reading with surface color

Visible laser diode with 650nm is used in the SE960HP barcode scanner engine. Figure 3.10 shows the reflectance of various spectal wavelength against various target color. For 650nm visible laser diode, purple, blue, or green has low reflectance, and yellow, orange, or red has higher reflectance. The lowest reflectance color is black and the highest reflectance color is white.

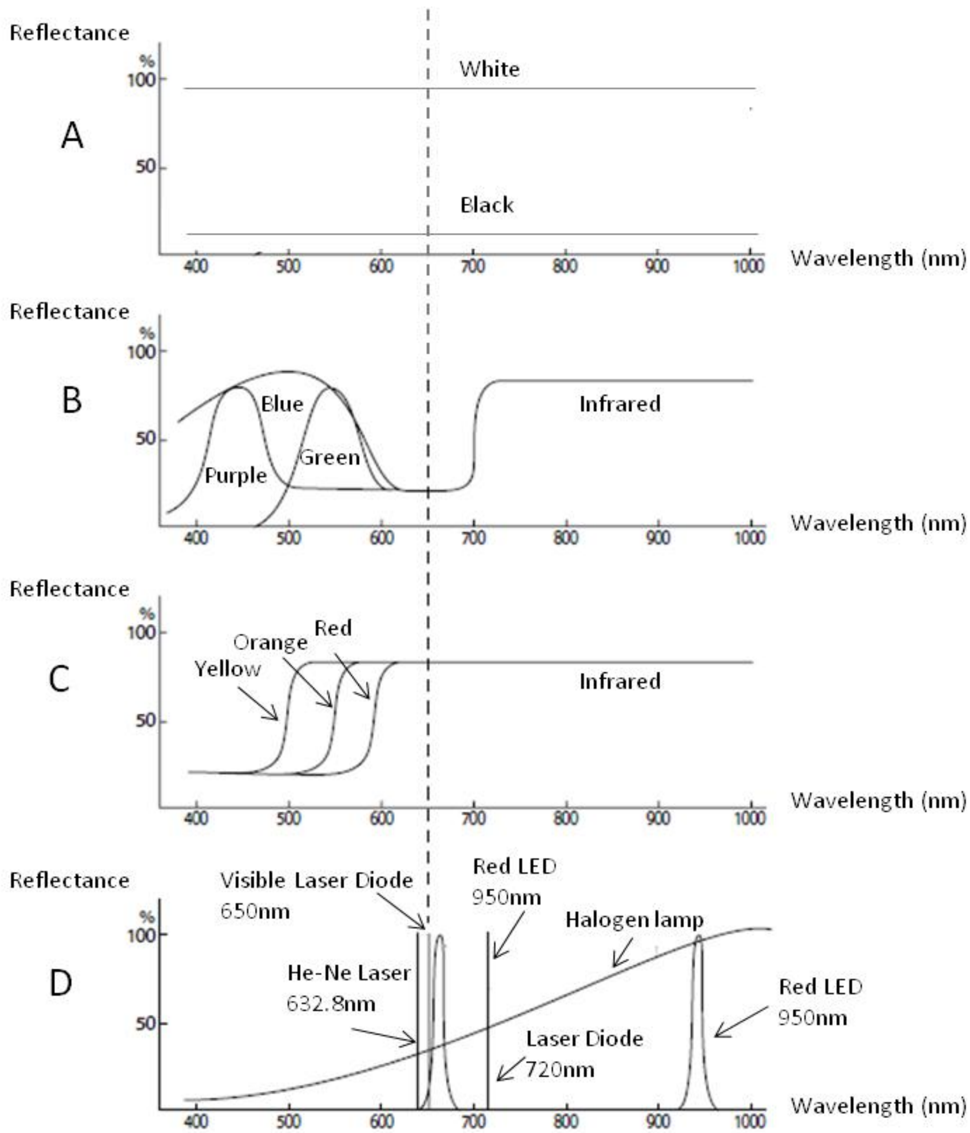


Figure 3.10 Reflectance Curve due to several target color versus each light source wavelength (D). For 650nm visible laser diode, (B) shows lower reflectance at purple, blue, or green surface color, and (C)shows high reflectance at yellow, orange, or red surface color. (A) shows white has high reflectance and black has low reflectance for any wavelength.

Also, Figure 3.10 shows that red, yellow, or orange color surface as high reflectance so it can be recognized as white (space), and blue, green, or purple has lower reflectance so it can be recognized as black (bar). Therefore, for example, barcode scanner can read the barcode with; blue bar with white surface, black bar with red surface, or purple bar with yellow surface, but it cannot read the barcode with; white surface with red bar, or black bar with blue surface.

3.9 Designing the Bar pattern

The precision, sensitivity and dynamic range of the angular orientation measurement is dependent on the shape of the printed pattern on the surface of the target, as well as, the various components of the laser scanning system. Within the scope of this thesis we have explored the effect of non-linear spacing and width of the bar pattern.

3.9.1 Bar pattern

This scanner engine has skew tolerance with ±40° within the condition of 20mil barcode at 10 inch. The skew angle is the angle due to perpendicular to the scanner, as shown in the figure 3.11.

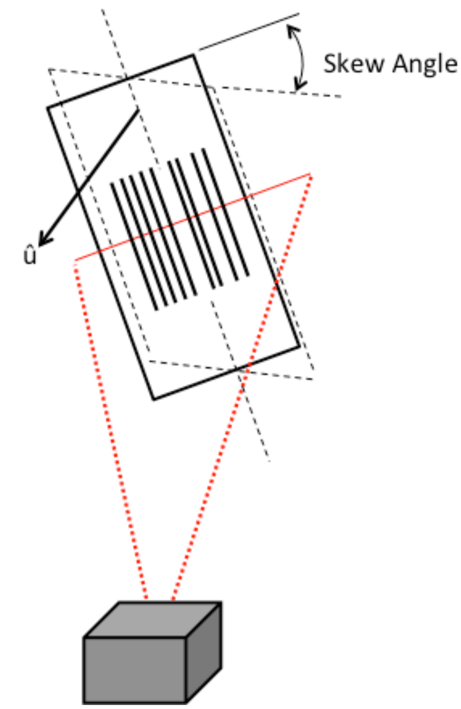


Figure 3.11 Skew angle torrelence. Skew angle is the angle from normal vector of the plane û

The skew angle places a constraint on the upper value of the scanning surface area for cylindrical objects. Figure 3.12 shows the available scanning surface for a cylindrical object surface with radius R. For the experiments reported in the thesis, the skew angle is in the range of $\pm 30^{\circ}$. The blank areas at the extremities of the bar pattern are used to define the quiet zones, corresponding the start/stop signal which is discussed later in this chapter.

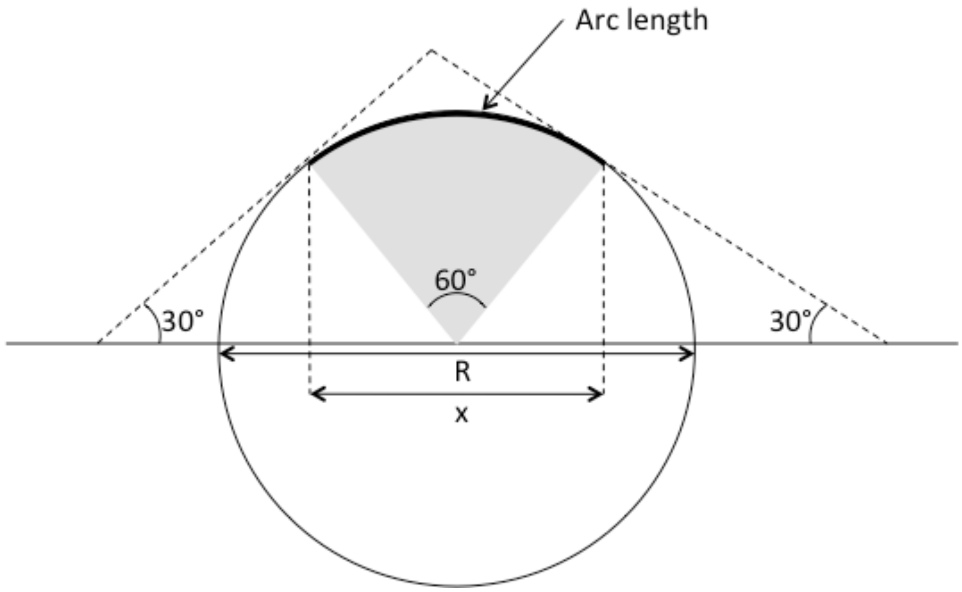


Figure 3.12 Arc length due to skew angle torrelence

Referring to Figure 3.12, the readable arc length S is given

$$S = R\left[\frac{2\pi * 2 * 30°}{360°}\right]$$

and the projected length on diameter X is

$$X = 2\sqrt{R^2 - (R\sin(50°))^2}$$

For a cylinder of diameter 115 mm, the above conditions require that the bar pattern be printed over a width smaller than 60.2 mm.

3.9.2 Start/Stop, main pattern, and quiet zone

The barcode pattern consists of three parts, start/stop signal, main pattern, and quiet zone. Start/stop bars identify the beginning and end of the bar pattern and are used by the microcontroller algorithm to compute the orientation angle. The microcontroller is programmed to compare the temporal signals at two orientations to compute the change. The optoelectronic system is fairly insensitive to ambient light conditions. Quiet zone is the margin where the microcontroller can detect start/stop signal, and has to be more than 10 times wider than the line between start/stop signals. Figure 3.13 shows the various zones of the bar pattern.

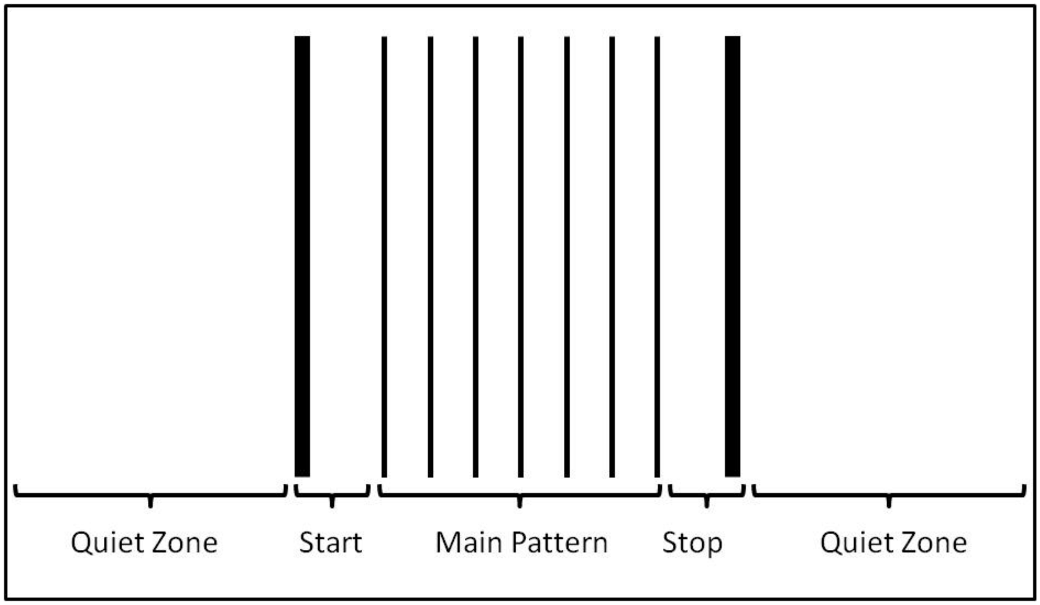


Figure 3.13 Bar pattern components

3.9.3 Bar line and space width

A typical bar pattern used the experiments is given in sketched Figure 3.14. The start line (B_{start}) and end line (B_{end}) are both 3 mm, start space (S_{start}) end space (S_{end}) are both 7 mm. Main pattern consists of 7 bars (B_1 to B_7) and 8 spaces (S_1 to S_8), with 1mm width line and 5mm spacing. 1mm line is the minimum readable line width. 5mm spacing will produce about 100us of signal when the pattern is read from the distance of 1m, which is the minimum computable time which microcontroller can calculate the each line pulse width before barcode scanner starts to read the next line due to the limitation by the microcontroller master clock. In general, the bars and spaces can have different widths.

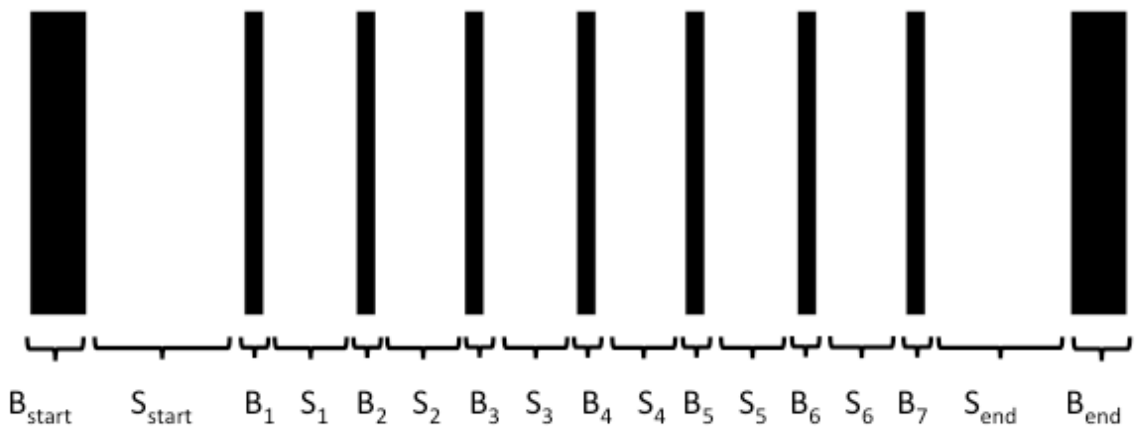


Figure 3.14 Bar and space widths of the bar pattern used in the experiment. B_{start} and B_{end} are 3mm, Send and Sstart are 7mm. Each bar in main pattern is 1mm and each space in main pattern is 5mm. Bar and space width are determined that microcontroller can detect and calculate the pulse duration before scanning next line.

3.9.4 Positioning the Barcode Scanner

The scan engine emits the laser in a slanted direction against barcode label and absorbs its diffused reflection light to read the barcode. Usually, as shown in the Figure 3.15A, the scan plane is tilted at an angle of 8° to the target surface normal.

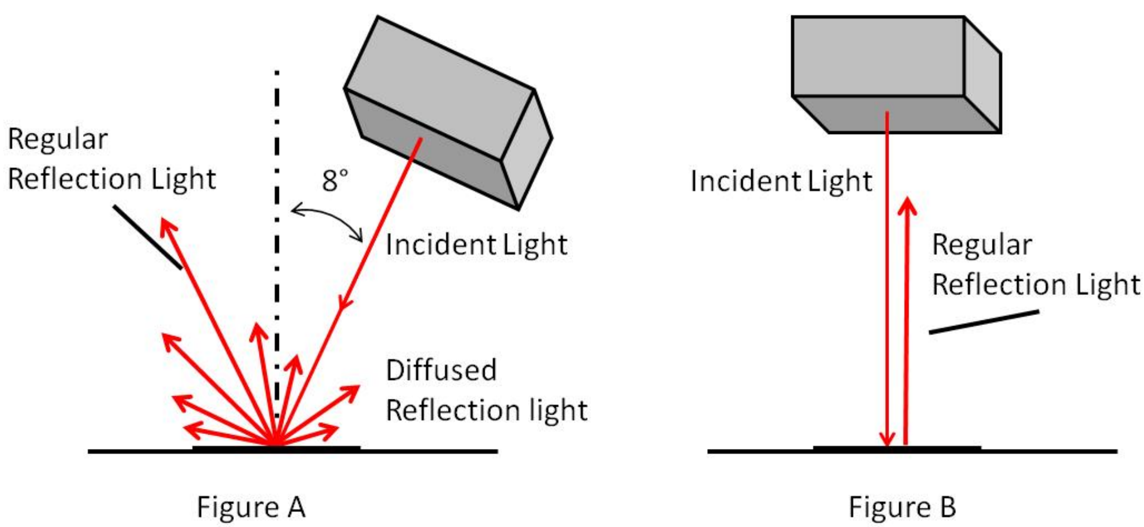


Figure 3.15 (A) is appropriate angle, more than 8°, to receive diffused reflection light from the surface. (B) is unappropriate position where scanner receives incident light and could not scan the bar pattern appropriately

If the barcode scanner is placed perpendicular to the barcode label as shown in the Figure 3.15B, there will be strong specular reflection from the center of the barcode label, resulting in non-uniform signal strength. If the barcode scanner is placed in an angle, all of the reflection light will be diffused so that the analog signal is correctly converted to digital signal. This angle is called the specular dead zone, which for the SE960HP scan engine is $\pm 8^{\circ}$. Figure 3.16 shows the resulting signals at the output of the analog receiver for the two scan positions discussed. Incorrect position of the scan engine produces an erroneous analog signal. This problem is exacerbated for bars printed on highly reflecting surfaces.

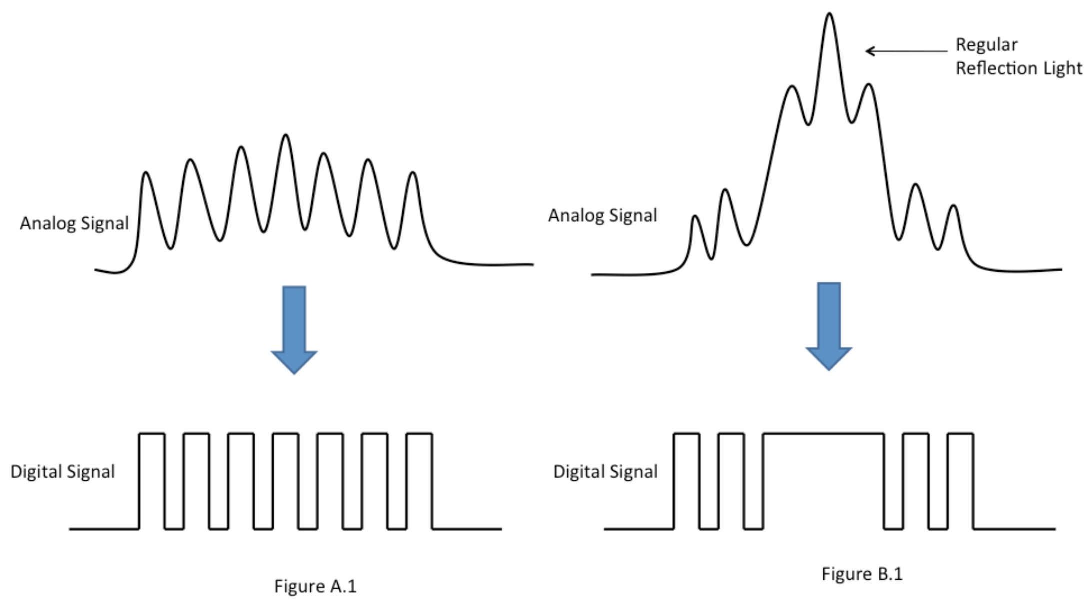
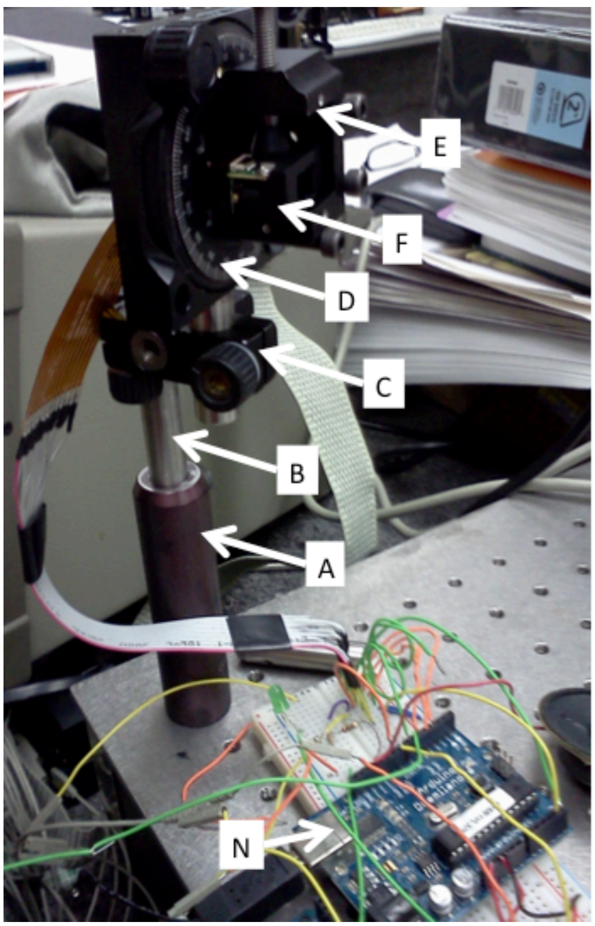


Figure 3.16 (A.1) is the Received analog signal and converted digital signal from previous figure in (A). (B.1) is the received analog signal and converted digital signal from previous figure in (B)

Laser barcode scanner cannot read the barcode if there is no barcode located at the scanned laser. Barcode scanner has to be located at the position where it can detect all the barcode printed on the target in a certain angle, and has to be where it can detect the diffused reflected light.

The angle calculation method used in this experiment requires at two different orientations and thus measures the change in angle. However, if the first reading is a zero° then the measure reading will correspond to the absolute angle.

Figure 3.17 shows how does the SE960HP barcode scanner engine is positioned. It is attached to the rotating stage to adjust the initial rotating angle, clamp to adjust the angle of specular dead zone, and steel post to adjust the height. Scanner engine is powered and controlled from microcontroller unit.



A: (Newport) Model:VPH-4
Vertical Post Holder 4 inch

B: (Newport) Model:9623
Stainless Steel Post, 4.0 in. Height, 0.5 in. Diameter

C: (Newport) Model: CA-1
Right-Angle Post Clamp, 0.5 in. Posts x2

D: (Newport) Model: RSA-1
Rotation Stage With Aperture

E: cramp

F: (Motorola) Model: SE960HP
Miniature High Performance 1D Scan Engine

N: Microcontroller unit(ATMEL)
ATmega328P microcotroller with power supply and USB to Serial interface

Figure 3.17 Components used to positioning the SE960HP scan engine. Scan engine is powered and controlled by microcontroller unit

4.0 Software Setup

The standalone microcontroller angular orientation measurement system was developed using a logic analyzer, Hewlett Packard (HP) #1662A. During the development phase, the logic analyzer records are essential as all timing events can be recorded, permitting a detailed analysis of various edges resulting from the scan. Barcode scanner engine SE960HP will toggle output DBP pin between HIGH and LOW states. The time duration of the HIGH and LOW states corresponds to the width of bar (black) and space (white), respectively. The SOS pin is asserted HIGH when the scanner is scanning from left to right, and LOW when the scan is from right to left.

Figure 4.1 shows a typical image captured by the logic analyzer. DBP pin is connected to this logic analyzer probe 0, and SOS pin is connected to probe 1, labeled “lab0” and “lab1” on the top of the screen.

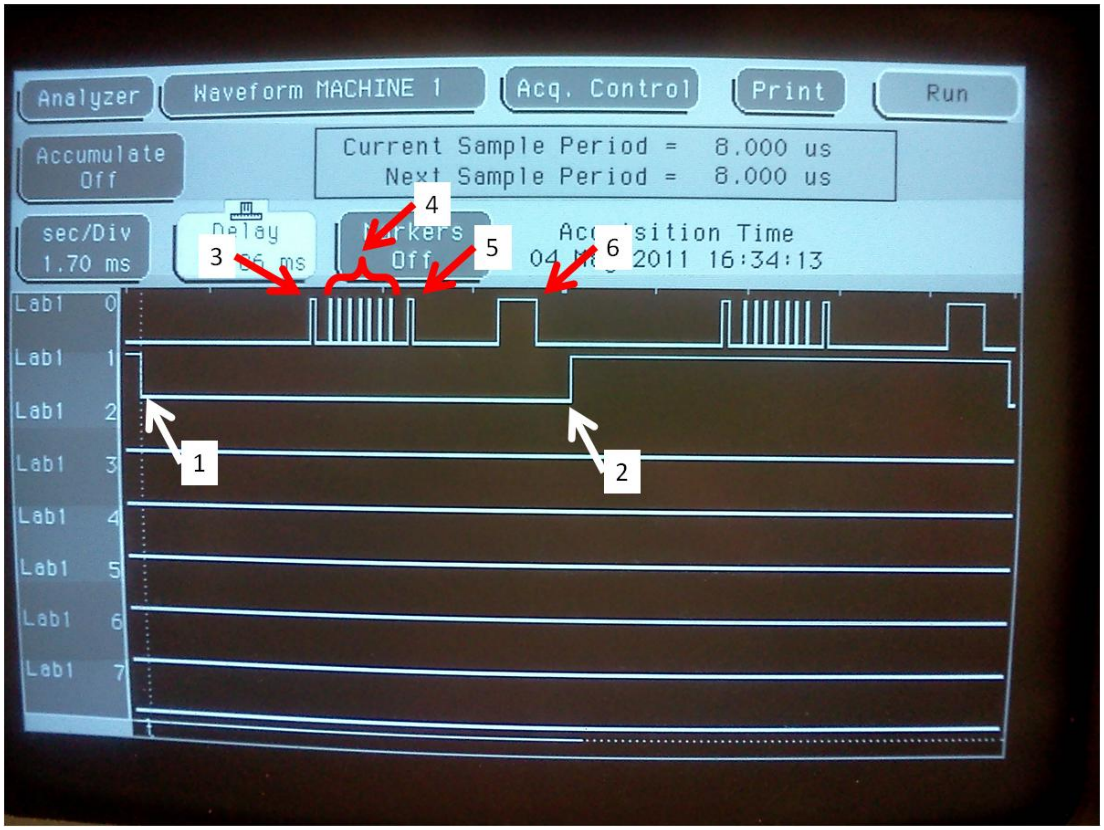


Figure 4.1 Captured image of HP 1662A LOGIC ANALYZER of output signal from scanner when scanner is scanning barpattern. (1) and (2) is SOS signal, (1) represents scanner started scanning left to right, and vice versa for (2). (3) is start signal to start reading the bar pattern in main pattern. (4) is the main pattern of the bar pattern. (5) is stop sinal to stop scanning bar pattern and let microcontroller start calculating the time of barpattern in (4). (6) is the noise from outer environment.

In Figure 4.1, the labels have following associations: (1) represents when the scanner started to scan from left to right; (2) indicates when the scanner has finished scanning from left to right, and has begun to start scanning right to left; (3) is the starting line (4) is the main pattern with seven black lines; (5) is the stop line; and (6) represents an error pulse which is outside the valid bar signal and is ignored by the software.

4.1 Microcontroller Programming Flow chart

Figure 4.2 shows a flow chart of the software program developed for the microcontroller. Measurement is triggered when SOS pin is asserted LOW, however recording of timing events is initiated by detection of the start line signal. Upon detection of the start line, timing stamp of the seven bar pattern is saved. End of the one scan measurement is activated by the detection of the stop bar signal. If all seven data is collected, and able to detect stop line signal successfully, finish taking data and wait until SOS pin becomes high. Begin next measurement when SOS pin becomes low again.

Invalid scans can be identified and discarded if seven bars are not detected between valid start and stop events. The precision of the measurement, particularly in a noisy background, can be significantly improved by averaging over multiple scans. Before one begins calculations, the microcontroller has to determine the range of pulse duration for start/stop bar, and each of the seven bars. This process is required to configure the microcontroller to read which pulse duration is appropriate signal for start/stop bar and each of the seven bars, to eliminate all noise signals.

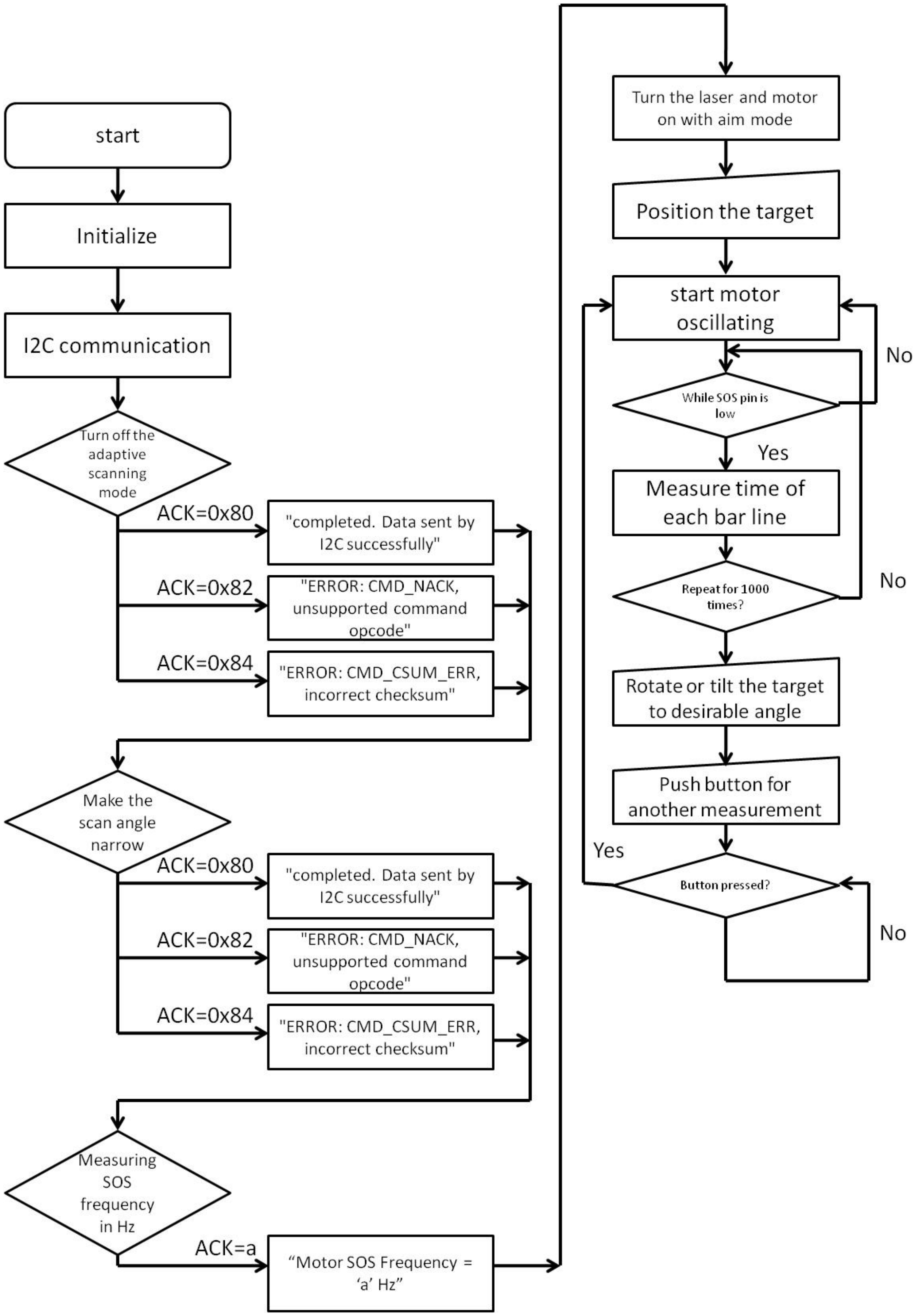


Figure 4.2 Flow chart of the microcontroller

5.0 Data analysis

Flat surface rotation angle measurement is done to make sure the cylindrical object elevation and azimuth angle measurement could be done correctly.

5.1 Real time correction factor

The system has two independent clocks that need to be matched, there is an internal clock inside the microcontroller that can measure time intervals from 10 μs to 180 s and a second clock defined by the scan angle. The time width of the bars is measured relative to the scan time. We can determine the time correction factor by measuring the physical width of a printed bar using the scanning system and comparing it with the real printed size. Figure 5.1 shows the set up with a single 1 mm dark bar. Measurements were performed at two different scan distances to confirm that the time correction factor is independent of scan distance.

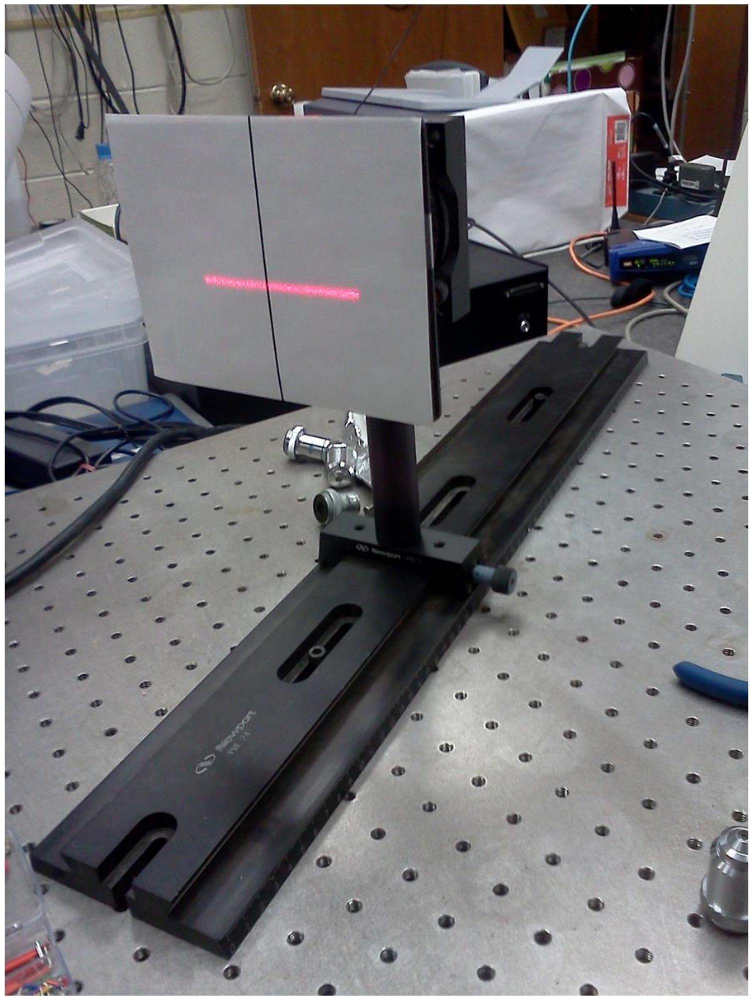


Figure 5.1 Testing setup to calculate correction factor

A full scan angle of 10° or 0.1759 radians is obtained when the scanner is set to narrow scanning mode, this was confirmed by an independent measurement. The corresponding scan time was measured with the logic analyzer to be 8.25 ms. The resulting angular speed is 21.3 rad/s. Table 8 shows the measured bar width with microcontroller at two scan distances. In both cases a time correction factor of 0.616 is obtained. This factor is applied to timing data measured with the microcontroller.

Other source of timing error include, the jitter associated with the galvano-mirror scanner and the master clock inside the microcontroller. The former is specified at ±10%.

Table 8 Calculations for determining correction factor

Pulse duration (us)	Distance between scanner and target (cm)	Actual line width (mm)	Measured line width (mm)
36.44	80	1	0.6167
38.85	75	1	0.6164

5.2 Experimental procedure –flat surface

The barcode pattern with quiet zone, start/stop line, and main seven line pattern as previously presented is printed on the white paper using laser printer and used in the system as shown in Figure 5.2. The paper is taped on the surface of the plastic board and rotated by using the rotating stage with 1° angle resolution. The test is done at scan distance of 1m.

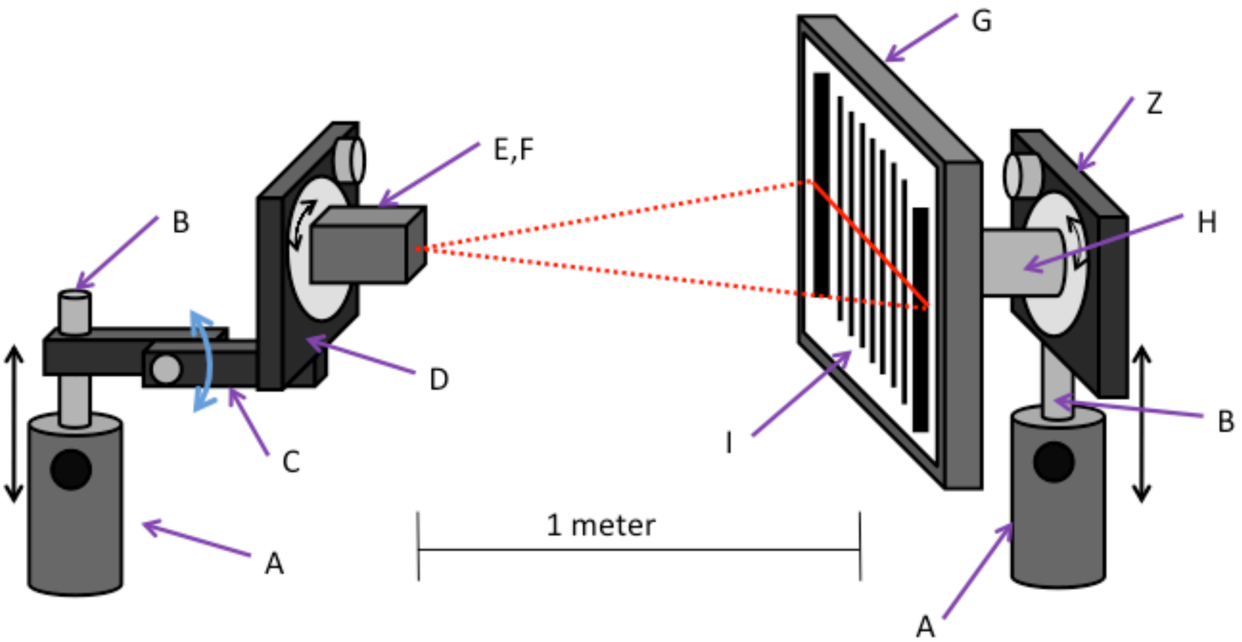


Figure 5.2 Illustration for the experiment setup for flat surface rotation angle measurement. (Component labels in this figure corresponds to Figure 3.7 and Figure 3.17)

A time stamp of the full scan is recorded at 0°, the resulting time event history, T0_1, T0_2,…T0_7, is stored for 1000 scans.

After collecting the initial data, the bar pattern is rotated by 10° in a clockwise direction and 1000 scans of the time stamp T10_1, T10_2,…,T10_7 are stored. Further data in the range of 10^{o} to 20^{o} is recorded in 1^{o} intervals. Figure 5.3 shows a plot of the measured and expected rotation angle.

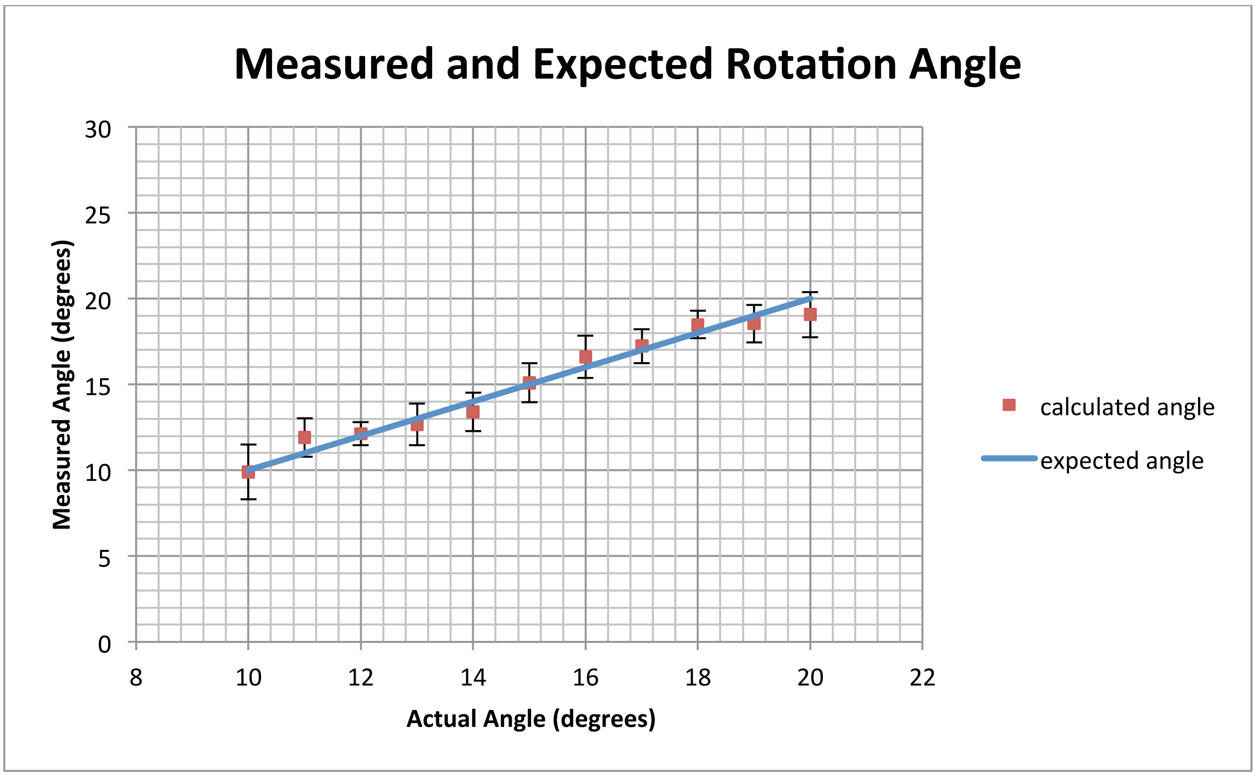


Figure 5.3 Flat surface rotaiton angle measurement graph between actual angle and measured angle with a standard deviation error bar

5.3 Cylindrical Surface

The barcode pattern of Figure 5.4 is placed on the surface of the cylinder with a diameter of 115 mm and a height of 200 mm.

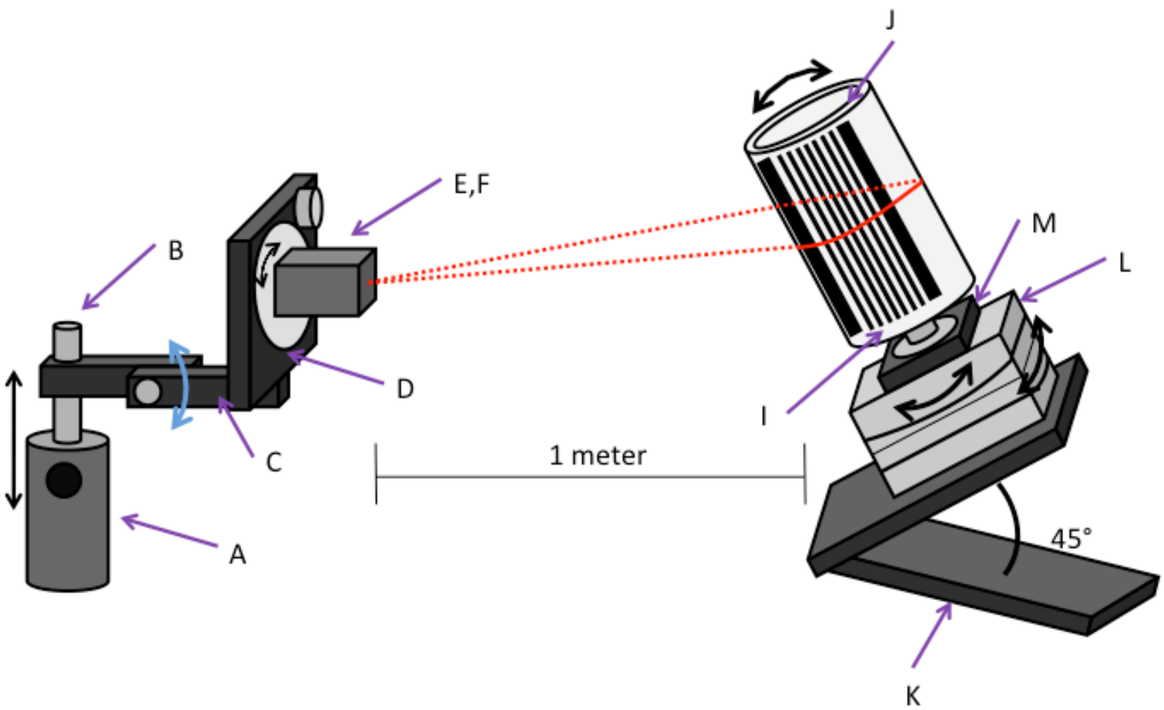


Figure 5.4 Experiment setup illustration for measuring elevation and azimuth angle of cylinderical object. (Component labels in this figure corresponds to Figure 3.8 and Figure 3.17)

The cylinder is located on the 2 axes goniometer, and set to a 45° initial elevation and 0° azimuth angle, respectively. Goniometer is controlled manually causing tilt in both elevation angle and azimuth angle to cylinder. Scanner, at the horizontal position, will scan the surface of the tilted cylinder from side view of cylinder and from backside of cylinder for azimuth angle measurement were done from a 1m distance to confirm that the system can measure both elevation angle and azimuth angle of cylindrical target.

5.3.1 Setup and result analysis for elevation angle measurement

First locate the scanner at a 1m distance. Using remote control command, adjust the scanning angle to "narrow" scanning mode, which determines the strength signal. Locate the cylinder on the goniometer, and set the cylinder angle to 35°. Rotate and adjust the barcode scanner in which the scanning laser beam will be perpendicular to the printed barcode and collect the initial data by taking 1000 measurements and take the average T0. Tilt the stage up to 45°, and then start taking measuring by elevating the stage by 0.1°. Repeat collecting the data until the cylinder elevation angle is 55°. The collected data will give angular information from 45° to 55°. Figure 5.5 shows a plot of the measured elevation angle. We note that the measurement accuracy is better than 1^o over a range of $\pm 5^\circ$ and drops to $\pm 2^\circ$ over the range of $\pm 5^\circ$ measured here.

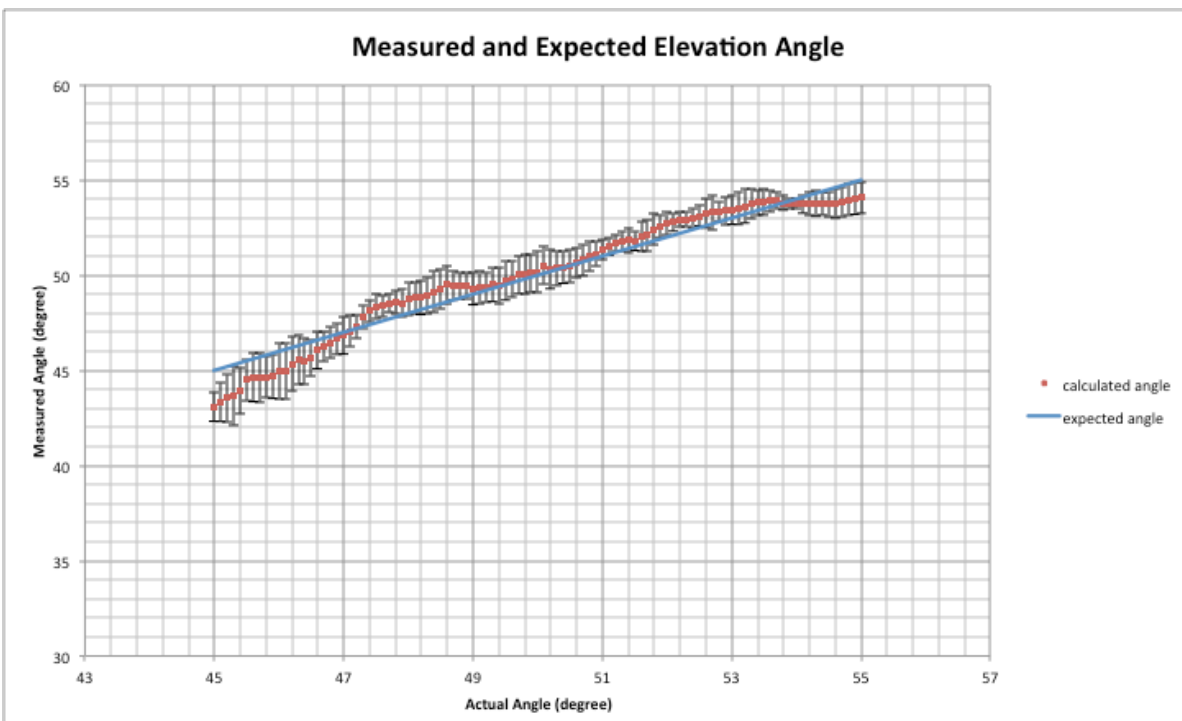


Figure 5.5 Cylinder elevation angle measurement graph between actual angle and measured angle with a standard deviation error bar

5.3.2 Setup and result analysis for azimuth angle measurement

The azimuth angle measurements were performed in the same manner discussed above. Azimuth angular ranges of $\pm 5^{\circ}$ were done at an elevation angle of 55^{o}. Figure 5.6 shows a summary of the azimuth measurements. The azimuth angle measurements have a slightly higher error.

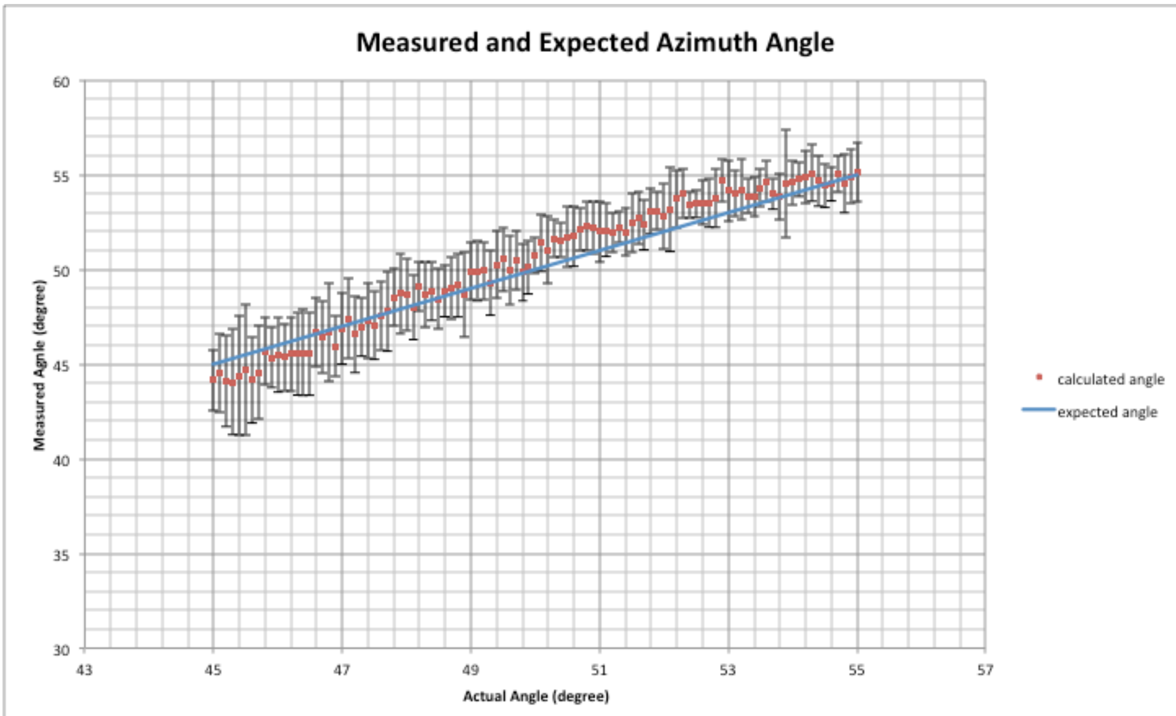


Figure 5.6 Cylinder azimuth angle measurement graph between actual angle and measured angle with a standard deviation error bar

6.0 Conclusion

The primary goal of this thesis was to fabricate a remote angular orientation measurement system for cylindrical targets. This has been successfully achieved with the development of a compact microcontroller based system, using a commercial laser scan engine. We have devised a differential time stamp measurement technique that does not require calibration due scan velocity variation over the surface of a cylinder. Angle measurement can be obtained in a few seconds.

The 7-bar pattern devised here resulted highly repeatable measurements. Averaging over a thousand scans improves the signal to noise ratio of the measurement. The current system has an angular accuracy better than 1^o for elevation measurements and about 2^o for azimuth measurements.

The scan angle range is primarily determined by diameter of the cylindrical target, the width of the bar, and the scan distance to the target. Target dimensions are determined by the applications. The minimum bar width is a trade-off between scan distance and scanner sensitivity.

Improvements in the range and accuracy may be possible by exploring other types of printed patterns, they need not be confined to bar patterns. Additionally, low jitter timers and galvano-scanners will certainly be needed.

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