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JUDUL: ALTITUDE MEASUREMENT AND CALIBRATION ON MILLING OPERATION.

SESI PENGAJIAN: 2012/2013

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ALTITUDE MEASUREMENT AND CALIBRATION ON MILLING OPERATION

NOR HANIS BINTI AHMAD NAZRI

Thesis submitted in fulfilment of the requirements
for the award of the degree of
Bachelor of Mechatronics Engineering

Faculty of Manufacturing Engineering
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I certify that the project entitled “Altitude Measurement and Calibration on Milling Operation” is written by Nor Hanis binti Ahmad Nazri. I have examined the final copy of this thesis and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Mechatronics Engineering. I herewith recommend that it be accepted in fulfilment of the requirements for the degree of Bachelor of Mechatronics Engineering.

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I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged. The thesis has not been accepted for my degree and is not concurrently submitted for award of other degree.

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A special dedication of this Grateful feeling to my parents, for giving me full supports. It is very meaningful for me in order to finish my degree. Not forgetting my siblings and my beloved ones and last but not least to my lecturers and friends.

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ABSTRACT

ADXL335 accelerometer is an electronic sensor which is used in detecting the acceleration of a moving object in x, y and z axis. In this project the function of the accelerometer had been applied on a platform which can be move in z-axis. This project is all about developing a device where distance can be obtained by manipulating the acceleration from accelerometer. Performing this task will contribute to certain problems that need to be focus in order to get an accurate distance value, such as unknown initial positions of the device on the platform and also the vibration on the accelerometer. There are objectives that had been achieved in this project which includes the implementation of the accelerometer application on shaker, development of a device for accurate distance calculation using accelerometer, and comparison between calculated distance values with the actual value of distance on shaker. First stage of this project is where the accelerometer had been programmed by using a microcontroller board, Arduino Uno. In this Arduino program, the analog reading from accelerometer that had been recorded will be directly converted into acceleration in unit of m/s^2. Simple circuit had been etched before being attached in the device box. During the collection of data, actual distance is being recorded too, to be compared with the calculated distance through double integration method. The device is placed on top of the platform and the original position is being set up before the platform is moved upward and the time is started to be recorded. By using this kind of method, the acceleration and time will be recorded and as the output from this procedure, double integration is being performed and the distance value calculated is being recorded. The result from the calculated distance error will be compared to the actual data where here the percentage error and standard deviation is being analysed. This project had been done very well where all the objectives are a success with the results of average error of 0.27%.

ABSTRAK

ADXL335 pecutan adalah sensor elektronik yang digunakan dalam mengesan pecutan objek yang bergerak dalam paksi x, y dan z. Dalam projek ini fungsi pecutan itu telah digunakan di atas pelantar yang boleh bergerak dalam paksi z. Projek ini adalah tentang pembangunan peranti di mana jarak boleh diperolehi dengan menggunakan pecutan daripada bacaan pecutan. Dalam melaksanakan tugas ini akan menyumbang kepada masalah-masalah tertentu yang perlu menjadi tumpuan untuk mendapatkan nilai jarak yang tepat, seperti kedudukan awal yang tidak diketahui peranti pelantar dan juga getaran pada meter pecutan. Terdapat objektif yang telah dicapai dalam projek ini termasuk pelaksanaan permohonan pecutan pada penggetar, pembangunan alat untuk pengiraan jarak tepat menggunakan pecutan, dan perbandingan antara nilai jarak yang dikira dengan nilai jarak yang sebenar pada jarak penggetar. Peringkat pertama projek ini adalah di mana pecutan yang telah diprogramkan dengan menggunakan papan mikropengawal, Arduino Uno. Dalam program Arduino ini, bacaan analog dari pecutan yang telah dirakam secara langsung ditukar kepada pecutan dalam unit m/s^2. Litar yang ringkas telah terukir sebelum dilekatkan di dalam kotak peranti. Semasa pengumpulan data, jarak sebenar direkodkan untuk dibandingkan dengan jarak yang dikira melalui kaedah integrasi berganda. Peranti ini diletakkan di atas pelantar dan kedudukan asal yang ditetapkan sebelum pelantar akan digerakkan ke atas dan masa akan mula direkodkan. Dengan menggunakan ini kaedah ini, pecutan dan masa akan direkodkan dan sebagai keluaran daripada prosedur ini, integrasi berganda yang dilakukan dan nilai jarak yang dikira akan direkodkan. Hasil dari kesilapan jarak yang dikira akan dibandingkan dengan data yang sebenar di mana kesilapan peratusan dan sisihan piawai akan dianalisis. Projek ini telah dijalankan dengan jayanya di mana semua matlamat tercapai dengan hasil purata kesilapan 0.27%.

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a	Acceleration
v	Velocity
g	Gravitational force
d	Distance
m	Meter
sec	Second
f	Frequency
Hz	Hertz
t	Time taken

LIST OF ABBREVIATIONS

COM	Computer output on microfilm
LCD	Liquid crystal display
VCC	Voltage
GND	Ground
PCB	Printed circuit board
SPI	Serial peripheral interface
DC	Direct current
I/O	Input output
USB	Universal Serial Bus
PWM	Pulse Width Modulation
ICSP	In Circuit Serial Programming
CNC	Computer Numerical Control
RLS	Recursive-least Squares
MEMS	Microelectromechanical Systems
RMS	Root Mean Square

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The current practice of measuring accurate distance travelled for an object often use techniques with limitation, where it is very difficult to be used on variety purpose. There is another way of measuring distance, laser displacement gauge which can accurately measure small displacement, but then, the device is too expensive. Therefore, there techniques in measuring distance, which is accelerometer. Accelerometer is a device used to measure acceleration of a motion structure. From the acceleration, a formula had been generated to obtain distance. Theoretically if one wanted to measure vibration, either position, velocity or acceleration, it can be generate using integration and differentiation.

Accelerometer is useful in measuring the amount of dynamic acceleration to analyse the way the device is moving where, from the acceleration obtained it will convert into velocity and the distance itself. Accelerometer used in this project is triple axis accelerometer breakout ADXL335. The breakout board for the 3-axis ADXL335 from Analog Devices is a low noise and power consumption accelerometer. The sensor range is within +/- 3g. The interface of the accelerometer is 3V with an output of analog voltage for each three outputs.

There is another advantage in using the accelerometer for measurements, where the size very small and can be easily attached to a body. It is also has wide frequency and dynamic ranges. Accelerometer is measurement equipment because of its ability to pick up high frequency content with high sensitivity.

The accelerometer will be program by using Arduino Uno which is a microcontroller board that is based on the ATmega328. This type of arduino has 14 digital input/output pins of which 6 can be used as PWM outputs, six analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. This board contains everything which will be needed to support the microcontroller. It is simple to use by simply connect it to the computer with a USB cable and control the input/output by program using its own compiler. The operating voltage is 5V while the DC current per I/O Pin is 40 mA.

Milling Machine is the equipment for machining process of using a rotary cutter in removing the material from a work piece. In advance, it can cut in a direction at an angle with the axis of the tool. This equipment can be move in three positions including x, y, and z axes. There are many types of Milling Machine exists, and one of it is CNC Milling Machines. CNC Machines can exist in virtually any of the forms of manual machinery like horizontal mills. Measurement and calibration of the altitude using accelerometer on Milling Machine can be done with the results of acceleration of the Milling Machine. The present of the accelerometer in the Milling Machine can be used for inertial measurement of velocity and position, vibration and shock measurement, and also measurement of gravity to determine the orientation of the Milling Machine. In this project the main function of the accelerometer used on Milling Machine is inertial measurement of velocity and position.

1.2 PROJECT SYNOPSIS

Accelerometer is main equipment which will be used along this project. Therefore, in order to organize the schedule every detail works need to be done and it includes few steps until final part. First of all, research on accelerometer is done before further investigation on others, such as, distance calculation and application on Milling Machine. The research includes its functions, how the accelerometer works, condition of the accelerometer, specification of the accelerometer, and simple application of the accelerometer. Accelerometer has a potential technique to measure acceleration, which can then be converted to distance.

Accurate distance calculation of the Milling Machine motion is needed in order to get the exact position. Accelerometer attached to the Milling Machine will help us in recording the acceleration of the Milling Machine up and down. From the acceleration, programming which had been structured will lead us in getting the exact distance of the

Milling Machine motion. Accelerometer functions in inertial measurement of velocity and position where acceleration is single integrated for velocity and acceleration is double integrated for position. Inertial measurements are non-contact method to measure acceleration, velocity and distance travelled. Velocity is the integral of acceleration while the distance is the integral of velocity which is also the double integral of acceleration.

The projects continue with the research on Milling Machine. The research includes the operation of the Milling Machine, and how the accelerometer being connected to the Milling Machine. The Milling Machine operates in multiaxis motion. Therefore, from the movement up and down of the Milling Machine, accelerometer is attached to get the distance travel between the z-axis motions of the Milling Machine.

Measurements of distance is an advantage in manipulating the acceleration from the accelerometer, it is physically small and can be easily attached to the Milling Machine. In motion, acceleration is one of the measurements required because of its ability to pick up high frequency and sensitivity, yet it is cheap and available in the market. In order to gain the value of the distance, c-program for distance calculation need to be build and run before combine the program with accelerometer to get the acceleration.

Simulation of accelerometer is to be done after the research and build the c-program of the distance and the acceleration. The simulation will be tested on actual accelerometer in order to manipulate the acceleration value. If there is mistake after the test, modification is needed before build the device. The test needs to be done many times to make sure the consistency of the distance reading before test the device on Milling Machine. Calibration of the distance data is done after completed the test on Milling Machine, and followed by analysis of data.

1.3 PROBLEM STATEMENT

This project is all about developing a device which distance data can be found from acceleration data through double integration. The focus is developing the device in order to measure accurate distance calculation using accelerometer. Using integration method errors exists, so from that minimization of the errors is needed so the distance calculation is very close to the actual distance value. This device is attached to the

Milling Machine to get the reading of the acceleration from the motion of the machine. Performing this task is easy, but there are certain problems that need to be focus in order to get an accurate distance value. Firstly, there is the problem of unknown initial positions of the device on the shaker and also the problem of vibration on the accelerometer.

1. 4 PROJECT OBJECTIVES

There are three objectives had been identify in this study, there are:

1. To develop a device for accurate distance calculation using accelerometer.
2. To implement the accelerometer application on milling operation.
3. To compare the calculated distance value with the actual value on Milling Machine.

1.5 PROJECT SCOPES

In order to finish this project, precise scope of work and proper plan needed to be followed before it would achieve the objectives that had been structured. The scopes of this study are:

1. Study on the application of accelerometer on Milling Machine.
2. Research on the development of the Milling Machine.
3. Design a device for accurate distance calculation using accelerometer.
4. Construct a program to convert the acceleration reading from analog to digital, and voltage.
5. Perform conversion of the acceleration reading into distance using double integration method.
6. Comparison between calculated distances with the actual distance on Milling Machine.

1.6 PROJECT ORGANIZATION

In this thesis, there are five chapters presented. An overview of the following chapters is as follows:

Chapter 1 is about the introduction of the calibration and accurate distance calculation using accelerometer. In this chapter, the problem statement, objective and scope will be identified.

Chapter 2 will discuss about the review of the literature that related to the title. It reviews the application of accelerometer in various kind of device done by others researcher.

Chapter 3 will discuss about the materials and methods that will be using in the project. This chapter is all about the framework and approach of the project. It explains about software and also the hardware that had been used to develop the project.

Chapter 4 will discuss about the result and discussion of the project. The result included the project limitation, and result analysis.

Chapter 5 will discuss about the conclusion and future work of the project. This chapter will briefly summarize the overall developed project.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter summarize the stages which are related to the study from various literatures review studied. The first section discusses the distance calculation using accelerometer. Then it will followed by the calibrations of readings obtained from accelerometer and the Milling Machine. All of the research in literature review will be used as a guideline in calibration and accurate distance calculation using accelerometer.

2.2 DISTANCE CALCULATION

2.2.1 Double Integration Methods

Accelerometer is a small, thin, low power, complete 3-axis accelerometer with a signal conditioned voltage outputs. Accelerometer measures acceleration with a minimum full-scale range of ±3 g. Accelerometer also can measure the static acceleration of gravity in tilt-sensing applications, as well as dynamic acceleration which results from motion, shock, and vibration.

In this project, the requirement is to get the accurate distance calculation using accelerometer. Therefore there are a few calculations involve in obtaining the distance or position from the acceleration readings of the accelerometer. Double integration is used for calculation as follows:

Position versus time of an object, x(t), the velocity, v(t), can be derive from the first derivative, where :

$$v(t) = \frac{dx}{dt} \tag{2.1}$$

From the first derivative, the second derivative is applied to get the acceleration, a (t).

$$a(t) = \frac{d^2x}{dt^2} = \frac{dv}{dt} \tag{2.2}$$

The reverse of derivation is integration, from integration, double integration of the acceleration, a(t), the initial position and initial velocity must be known. To get the initial velocity, first integration should be applied.

$$v(t) = v(t_0) + \int_{t_0}^{t} a(\tau)d\tau \tag{2.3}$$

From the equation above, t_0, the initial time while the $v(t_0)$, is the initial value of the velocity where t = 0. To get the distance or position of the movement of the Milling Machine itself the next formula is needed:

$$x(t) = x(t_0) + \int_{t_0}^{t} v(\tau)d\tau \tag{2.4}$$

As a conclusion, in order to get the value of distance or exact position, double integration of the acceleration need to be performed with the presents of the two conditions, initial position and velocity [1].

In order to get a distance, the accelerometer must undergo a movement or motion which will help it to sense the movement and give out acceleration reading. Vibration is one of the example can used for the test. Vibration is a mechanical oscillation. Mechanical oscillation is the motion around a reference point of equilibrium. From the movement of the accelerometer, data on displacement or distance through acceleration and velocity was obtained [2]. Single integration of acceleration will give us velocity, while double integration will give us displacement or distance as stated above [1]. Therefore the conversion process will be applied in analog integrators hardware and software for double integration operation.

$$d_c(t) = d_0 + v_0 t + \int_{t_0}^{t} dt \int_{t_0}^{t} a(\tau) d\tau \tag{2.5}$$

Where:

d_0 : initial displacement, $t = 0$

v_0 : initial velocity, $t = 0$

d_c : calculated displacement, t

2.2.2 Trapezoidal Methods

Equation (2.5) is being used for analog functions, functions which are continuous. There are other numerical integration methods which can be used to obtain displacements. Trapezoidal method is one of the methods. Figure 2.1 shows the trapezoidal method of numerical integration. The region under the signal is approximate by the sum of a series of rectangles. Δt depends on the frequency of digitalized analog signal.

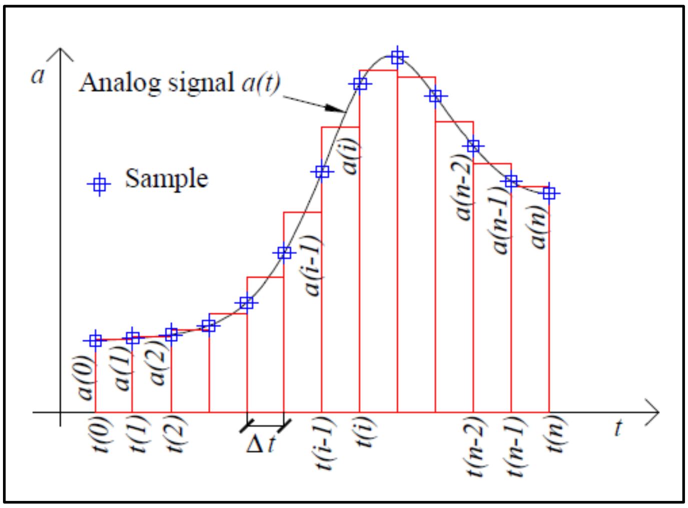


Figure 2.1: Trapezoidal method of numerical integration [2].

Numerical integration calculation of the discrete signal in the time domain:

$$\int_{t(0)}^{t(n)} a(t)dt \cong \sum_{i=1}^{n} \left(\frac{a(i-1)+a(i)}{2} \right) \Delta t \tag{2.6}$$

Where:

$a(t)$: Continuous time domain waveform

$a(i)$: i^{th} sample of the time waveform

Δt : Time increment between samples *(t(i)-t(i-1))*

n : number of samples of the digital record

From the above equations, we can calculate the displacements. Computation of the velocity from acceleration is needed before followed by displacement computation.

$$v_c(i) = v_c(i-1) + \frac{a(i-1)+a(i)}{2} \Delta t \tag{2.7}$$

$$d_c(i) = d_c(i-1) + \frac{v(i-1)+v(i)}{2} \Delta t \tag{2.8}$$

Where:

$a(i)$: i^{th} sample of the acceleration waveform

$v_c(i)$: i^{th} sample of the calculated velocity

$d_c(i)$: i^{th} sample of the calculated displacement

Example of numerical integration which shows the double integration effects on the waveform.

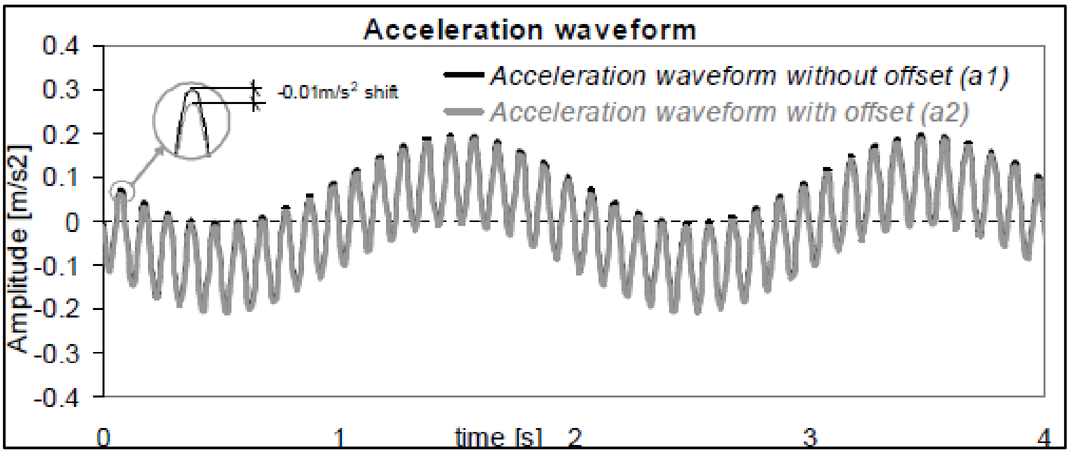


Figure 2.2: Time histories of two periodic acceleration waveforms [2].

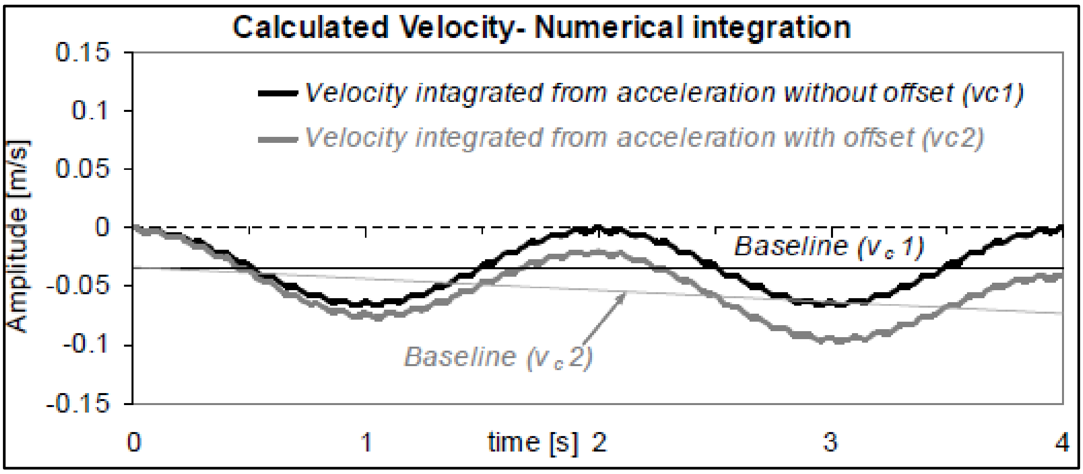


Figure 2.3: Two traces correspond to the numerical integration calculation [2].

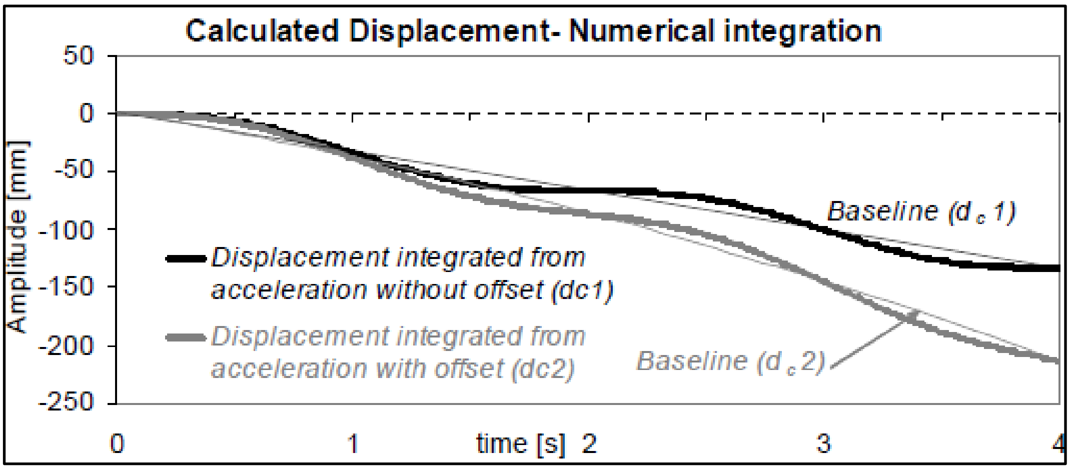


Figure 2.4: The difference in the baseline which reveals the influence of the added offset presents a linear drift [2].

Research is done by the attachment of accelerometers on a moving plate to gain the results. From the experiments displacements obtained by double integration can be seen from Figure 2.5.

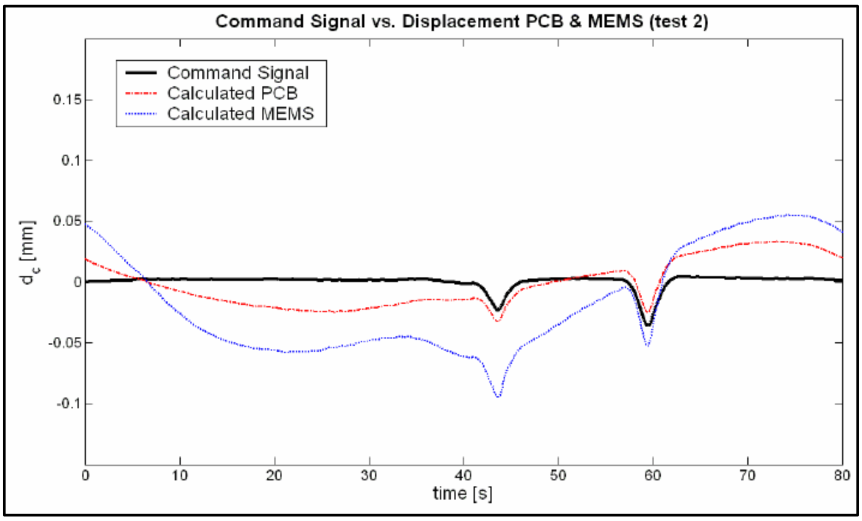


Figure 2.5: Displacements obtained by double integration [2].

The accelerometer is suitable to measure low frequency signals with high resolution. It is shown that the conversion of acceleration into displacement using numerical double integration can be done successfully [2]. Double integration in time domain can be achieved by scaling the discrete Fourier transform of the measured acceleration signal in frequency domain [3].

2.3 CALIBRATION OF DISTANCE USING ACCELEROMETER

The correlation of displacement is much easier rather than correlating the accelerometer in studying a large structure. Measured displacement is proportional to the stresses in elastic structure and can be used directly in determining the accumulated damage. Displacement is more difficult to be measured than accelerations as the devices used to measured are non-inertial and we need a fixed reference to work properly, but by using accelerometer the measurement of displacement can be done easily using double integration technique. Unfortunately there are many problems that will cause errors in the results [4]. Therefore, calibration is needed to fix the errors.

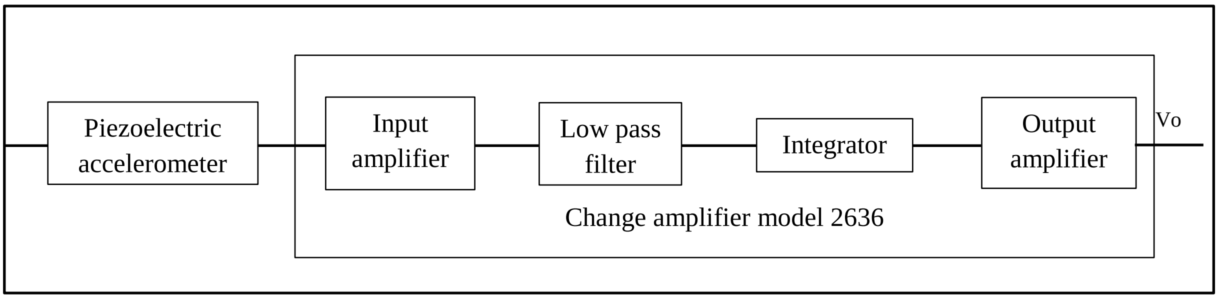


Figure 2.6: System utilized to obtain displacement from piezoelectric accelerometer [4].

A modelled consists of piezoelectric accelerometer and amplifier charge system which provide analog double integration is used to measure displacements. Figure 2.6 shows how the system works in obtaining the displacements. The integrator stage is where is where the user can choose the quantity to be measured.

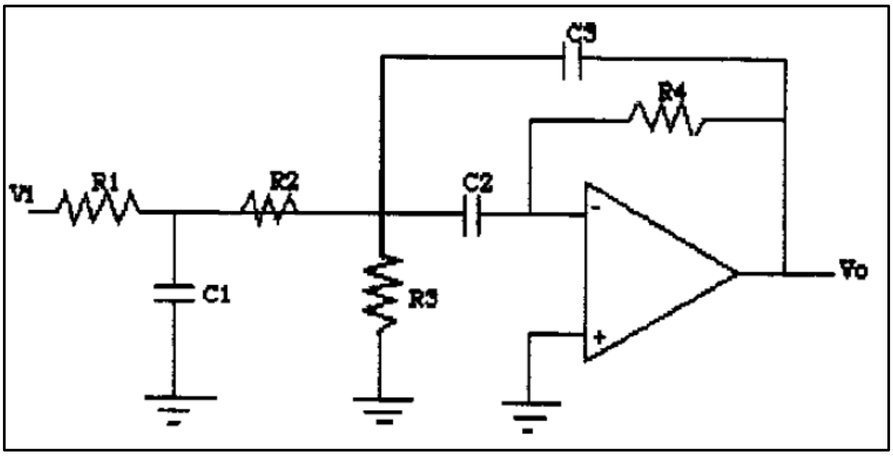


Figure 2.7: Double integrator amplifier [4].

Figure 2.7 shows the double integrator amplifier which will be used in obtaining the displacement from acceleration. Figure 2.8 shows that from double integrator oscillation cannot be accepted due to external forces exert on it.

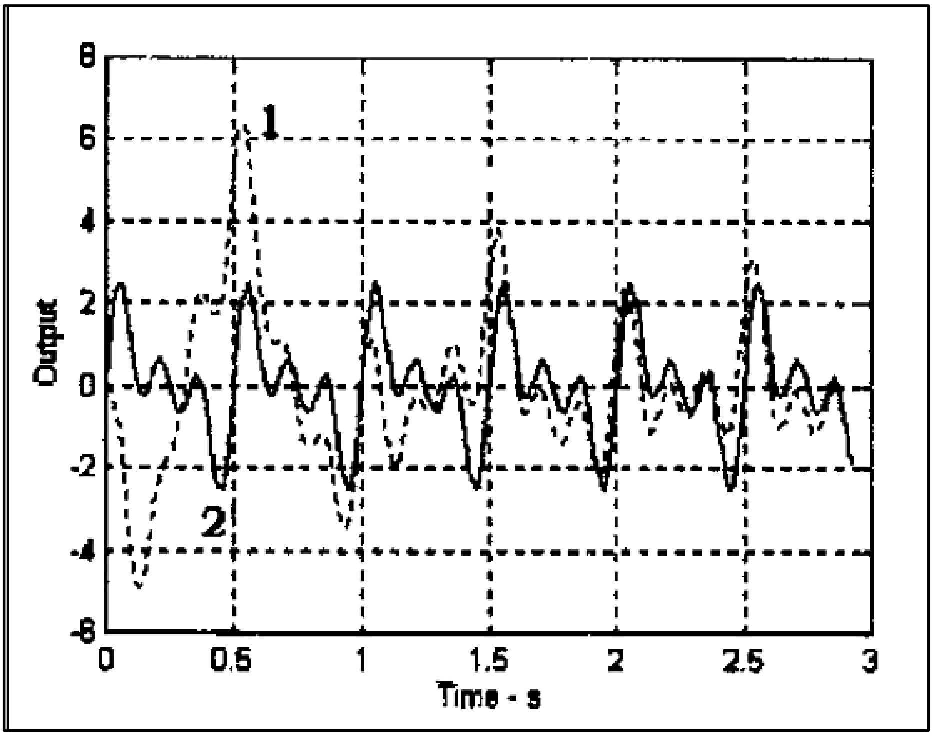


Figure 2.8: Response from the output integrator and the actual displacement [4].

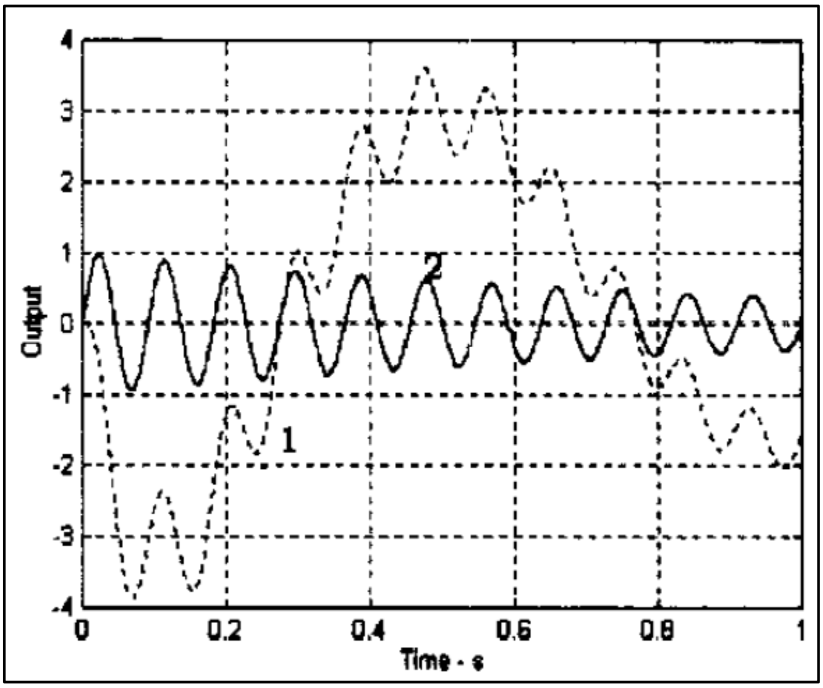


Figure 2.9: Simulation of the response of the integrator to a damped sinusoid from an accelerometer [4].

Verification of the modelled is done by undergo an experiment to compare the results. Therefore it can be conclude that the analog double integrator can only be used to measure sinusoidal steady state displacements.

Other than the above method, there is other research had been done in improving the response of accelerometer by using optimal filtering [5]. The elimination of noise by using conventional methods is very difficult due to signals corrupted by additive noise or interference. An efficient method of signal conditioning and processing is very important in measurements of physical magnitude.

Accelerometers functioned in sensing the motion of vibration and measurement method based on acceleration acting on spring mass system which involves damping [6]. Measurement of acceleration is reduced to a measurement of spring extension under the steady-state accelerations.

$$a = \frac{k}{m}\Delta x \tag{2.9}$$

The important thing to be concerned in using the transient response is the friction.

$$f_{osc} = f_N\sqrt{1-2\zeta^2} \tag{2.10}$$

$$f_N = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{2.11}$$

Usually people used filter in correcting the corrupted signal by additive noise. Active filters such as Notch filters, Sallen-Key filters and other filters is not recommended to use because the noise reduction should be treated as an unknown signal estimation problem [7]. An adaptive noise cancellation is used to subtract noise from a received signal [8]. Figure 2.10 shows the method which used primary signal contains the corrupted signal; combine with the noise reference source which contains the noise correlated in certain way.

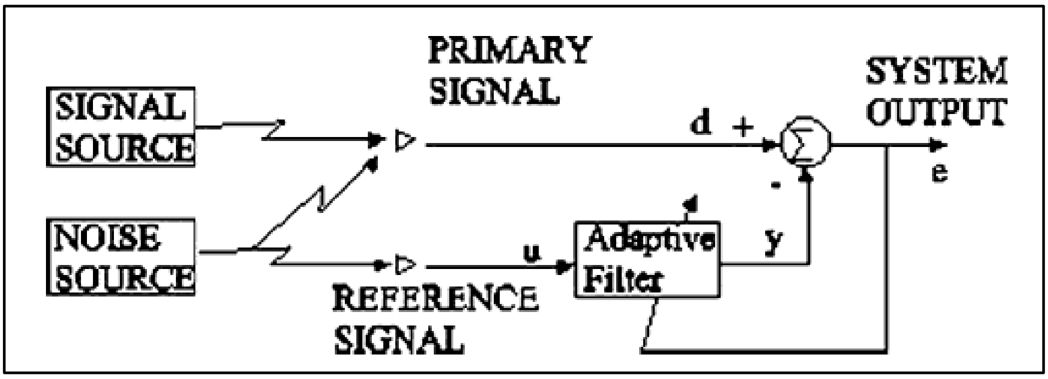


Figure 2.10: Adaptive noise cancellation [8].

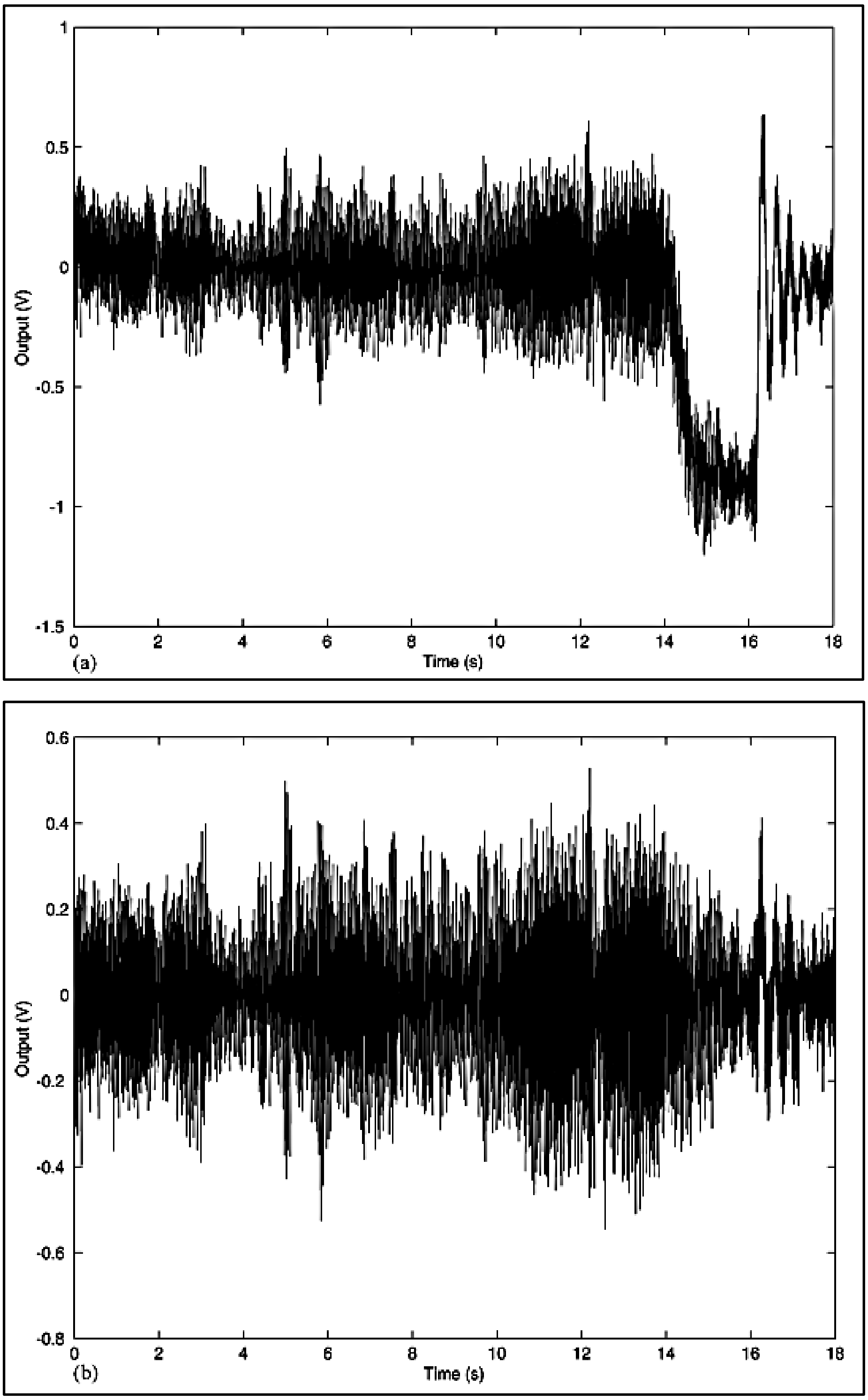


Figure 2.11: Output from accelerometer (upper) with the noise signal (lower) [5].

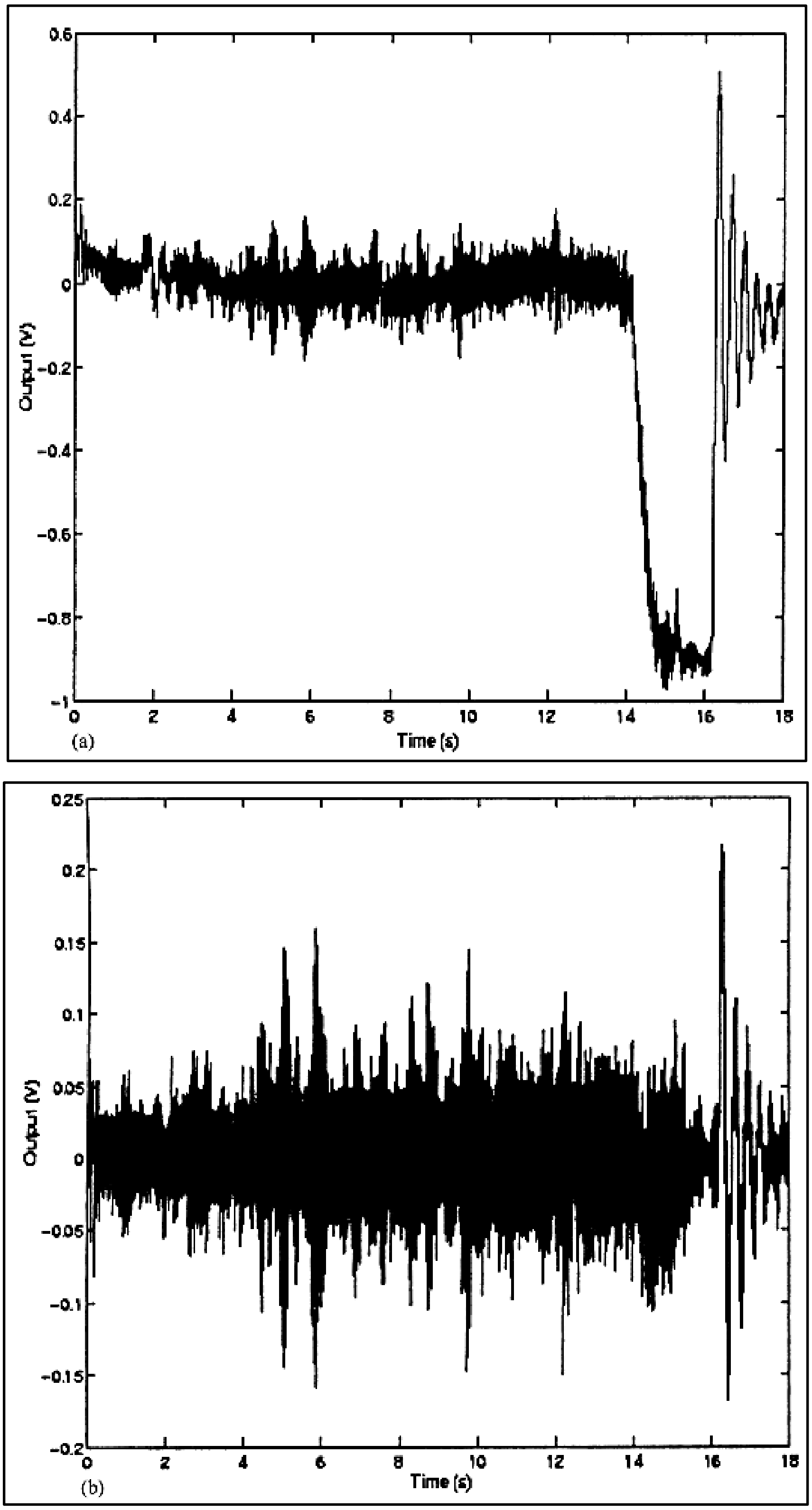


Figure 2.12: Time response of the adaptive filter with the noise of the signal after filtering [5].

The Recursive-least Squares (RLS) method is used to cancel the noise in the signal (Wilmar Hernandez, 2001). RLS will remove the noise in measuring a corrupted signal. We can see the difference before and after applying the filter to the signal from Figure 2.11 and figure 2.12.

More than one accelerometer had been used to estimate position by using double integration of acceleration (Y.K. Thong, 2004). Development of the method in calibrating the positional errors cause by noise already had been done [9]. The positions are estimated from accelerometer measurements using numerical double integration. Numerical integration will lead to errors because it only approximating the continuous signal. Other than that, the errors also occur because of the output of root mean square value that increasing with integration time even without motion from the accelerometer.

Zoran Djurić had done the study of mechanism of noise sources in microelectromechanical systems (MEMS), which conclude that the noise can be modelled [10]. It is very important for us to do the experimental calibration procedure because it will give a measurement of the expected maximum error in estimated position due to noise. There is a practical method in describing the calibration of accelerometer in terms of error in estimated position [11]. To separate out contributions to root mean square errors from noise from numerical integration, measurements are taken from stationary rather than moving accelerometer. From this research, the experiment is set up into M blocks of N samples. Within the blocks, double integration is applied using trapezoidal rule. From the research, the measurements were taken using two different accelerometers.

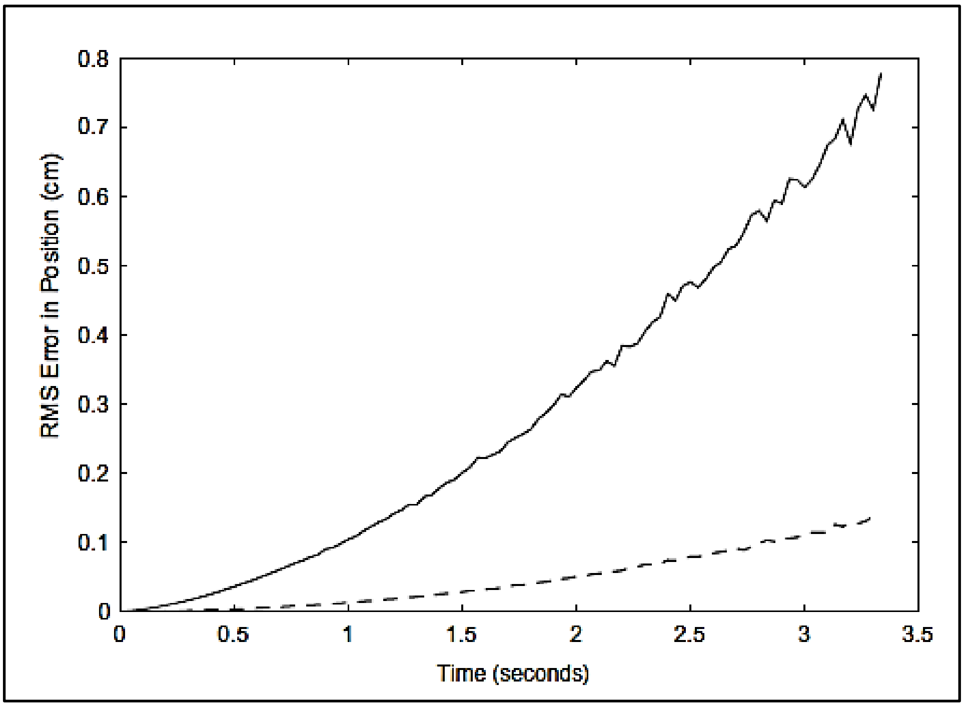


Figure 2.13: Root Mean Square errors in position as a function of integration time [9].

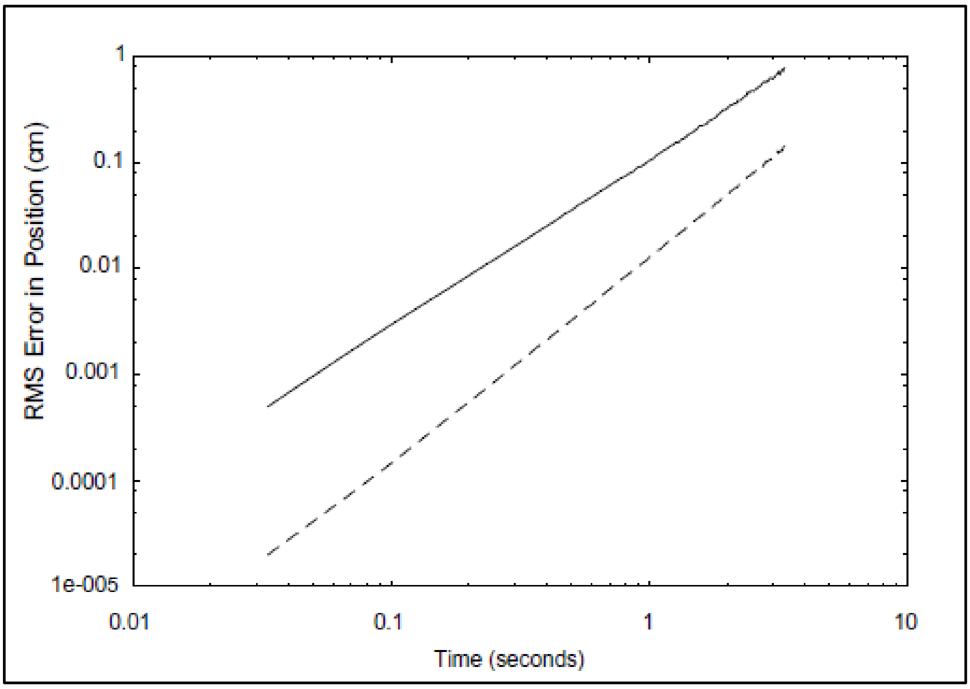


Figure 2.14: The experimental Root Mean Square errors in position as function of integration time for accelerometers [9].

$$RMS(s(T)) \propto T^{\alpha} \quad (2.12)$$

Eq. (12) is the equation on approximation variation of RMS errors in estimated position with integration time. The contribution of the research is on the practical method in calibrating the positional errors determined by double integration of accelerometer data.

2.4 MILLING OPERATION

CNC Milling Machines is a computer controlled mills with the ability to move the spindle of the machine vertically along the Z-axis. The most advance machine is the multiaxis CNC Milling Machines. Milling machines basically classified as being horizontal or vertical to indicate the axis of the milling machine spindle [12]. This milling machine is typically obtained by attaching a rotary work table to an existing 3-axis machine to guide the cutter following the CL points generated by the CAM software; the commands in the CNC controller translate the work-piece coordinates to machine coordinates [13]. Types of milling machines are:

- Knee-type Milling Machines: it can be characterized as vertical adjustable worktable resting on saddle which is supported by knee.
- Ram-type Milling Machines: it can be characterized by a spindle mounted to a movable housing on the column, permitting positioning the milling cutter forward or rearward in a horizontal plane.

Figure 2.15 shows the plain Milling Machine Knee-type. This type of Milling Machine is a massive casting that rides vertically on the machine and it can be clamped to the column in desired position where here, the milling head and machine spindle is adjusted in vertical position for the operation of the machine.

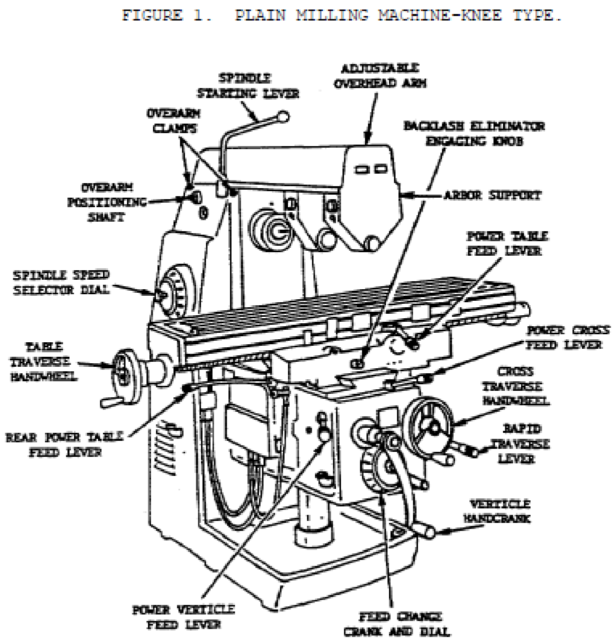


Figure 2.15: Plain Milling Machine Knee-type [12].

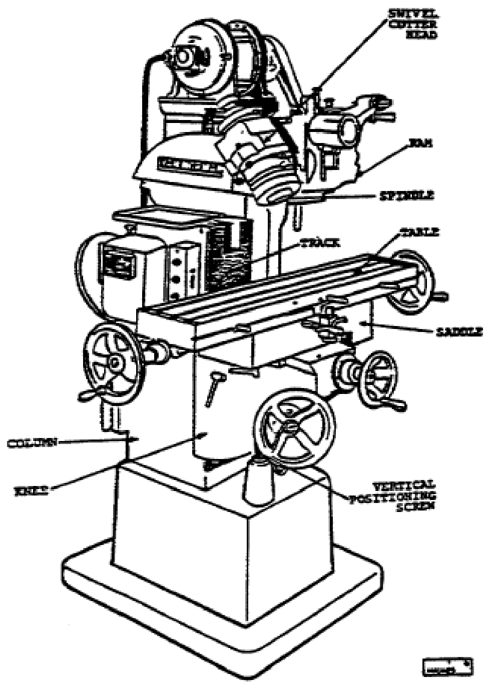


Figure 2.16: Swivel cutter head Ram-type Milling machine [12].

Figure 2.16 shows that the Swivel cutter head Ram-type Milling Machine. This type of machine contains the spindle attached directly to the ram. The cutter head can be swivelled from a vertical to a horizontal spindle position and it also can be fixed at desired angular position.

Milling Machine had been applied in many experiments to gain data on certain measurements. Additionally, advanced machining operations utilizing multi-axis or multitasking machine tool requires much more time and effort of machining operators [14].

In general, other than applying the basic function of the Milling machine, it also can be used as a platform to obtain certain parameters needed in an experiment.

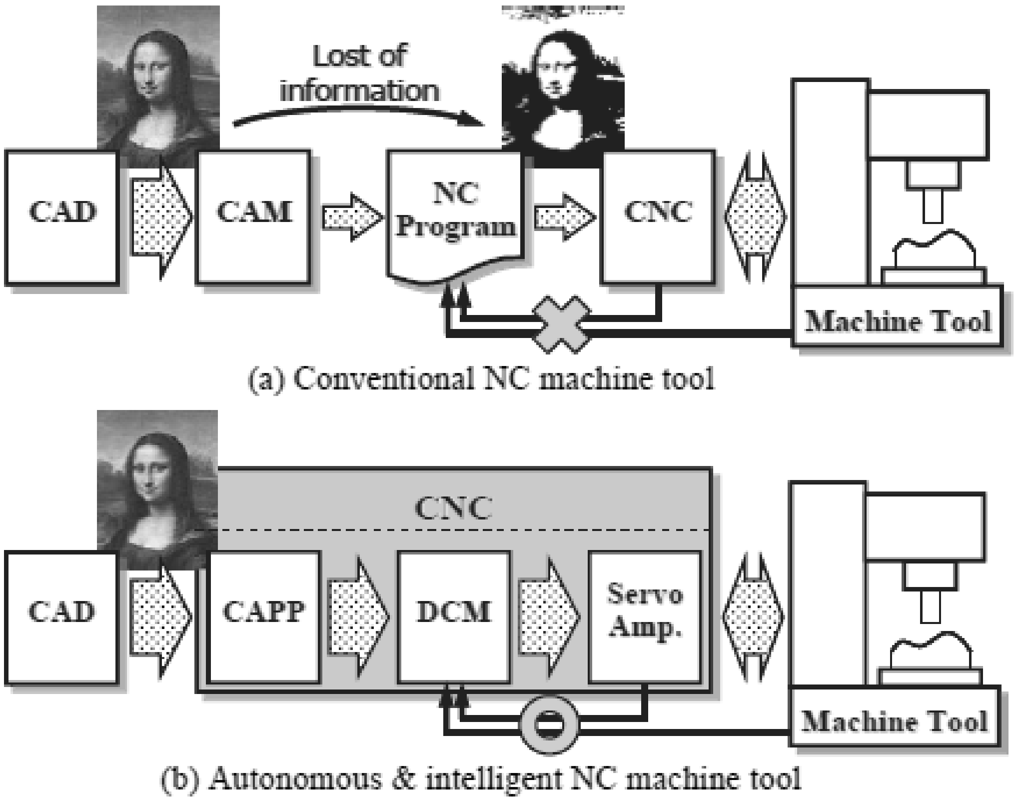


Figure 2.17: The concept of achieving and autonomous and intelligent NC machine tool [13].

An autonomous and intelligent machine tool, which can realize easy operations for both CAM and machining operators, is needed in order to satisfy the requirements.

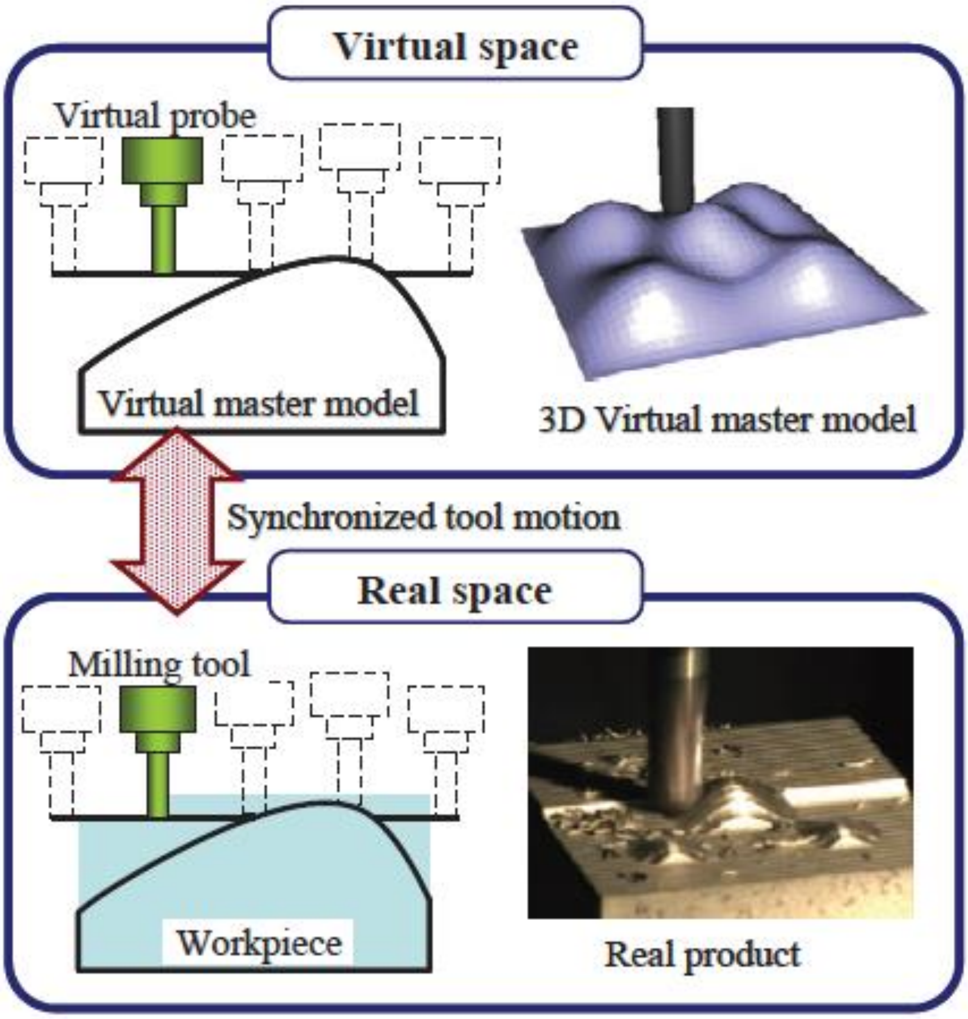


Figure 2.18: Milling operation performed by DCM [13].

Figure 2.19: MAKINO KE55 CNC Milling Machine [14].

CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

In this chapter, research methodology which had been adapted to this study is discussed. In this study, device used to calculate accurate distance calculation using accelerometer is modelled. In addition, this application can be used in comparing the experimental distance value obtains from accelerometer and the actual distance of the platform. The development of this device is involving the software, hardware and mathematical modelling. The software involves on the way to convert the acceleration value from accelerometer to distance value. While, the hardware will involves the placement of the software which will be attached to the Milling Machine to gain the results from accelerometer.

3.2 OPERATIONAL FLOW CHART

Figure 3.1 shows the operational flowchart that being develop in completing the process of the successful project.

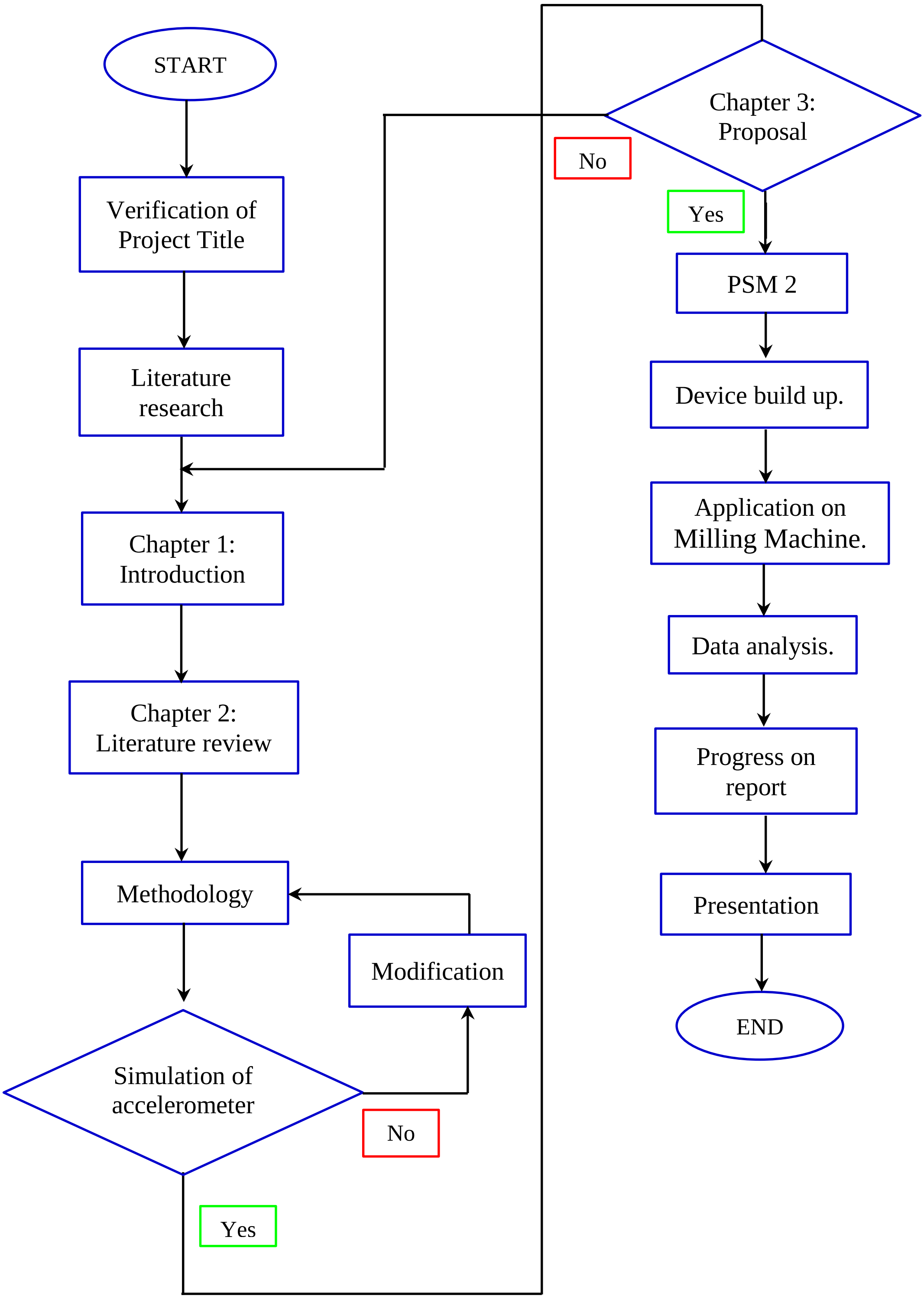


Figure 3.1: Operational Flow chart.

3.3 SOFTWARE

The term software represents computer instructions or data where anything can be stored electronically. It is in contrast to storage devices which are called as hardware. Software can be categories into two parts, which are, system software and applications software.

3.3.1 Proteus Virtual System Modelling (VSM)

Proteus Software is a software tool suite used primarily for microprocessor simulation. It is used mainly to design and simulate circuit design. The system components include ISIS Schematic capture, tool for entering designs. It is capable in schematic capture for both simulation and PCB Design. The important part of this software is co-simulation of microcontroller software. The ability to simulate the interaction between software running on microcontroller and any analog digital electronics connected to it.

This software combines mixed mode SPICE circuit simulation, animated components and microprocessor models to facilitate co-simulation of complete microcontroller based designs. LCD displays is an example of indicator which can be used to interact the software with the design, with the existence of actuators such as switches. An extensive debugging facility which includes breakpoints, single stepping and variable display is also being provided in this software.

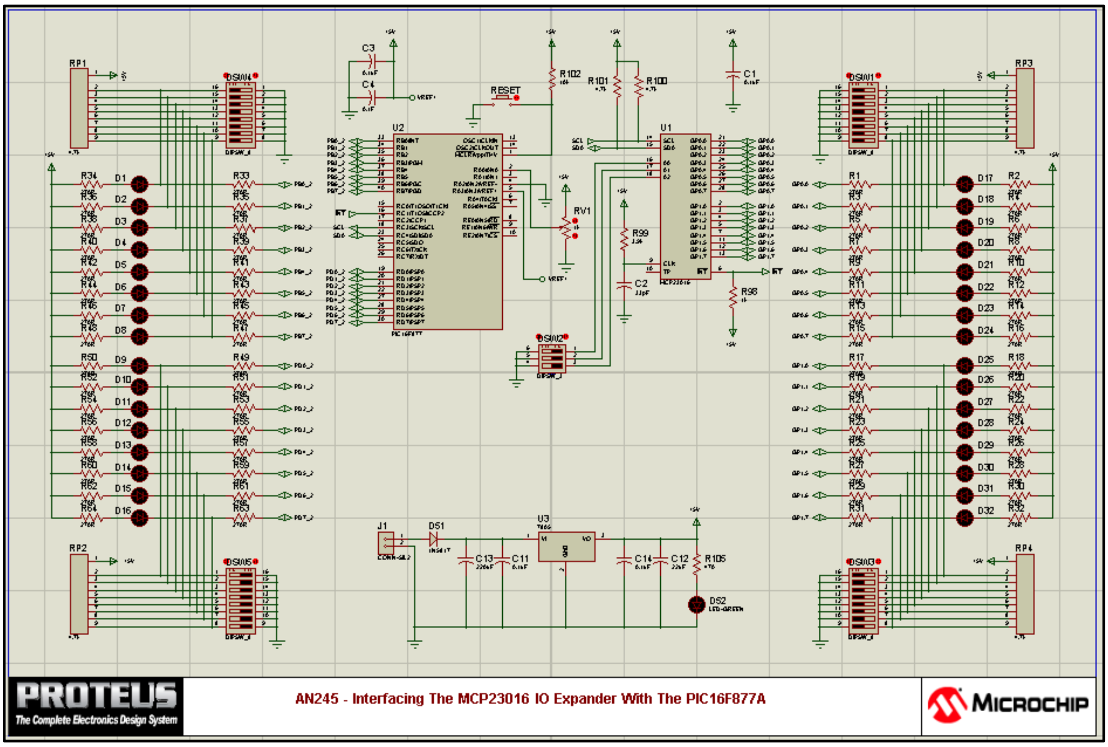


Figure 3.2: The screenshot of Proteus Software [17].

Proteus Software is used for simulation of the circuit, for this simulation the configuration of the circuit consists of:

- LCD I/O Peripheral.
- Arduino Uno.
- Microcontroller (ATMEGA328).
- Accelerometer.

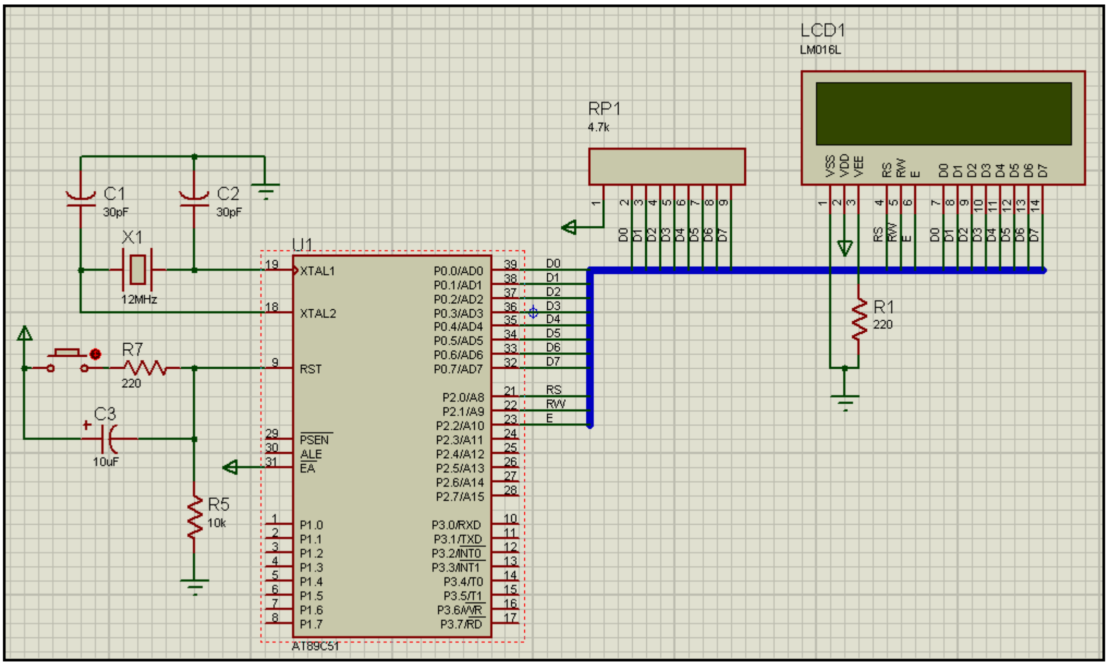


Figure 3.3: LCD I/O Peripheral [17].

Figure 3.3 shows the circuit of LCD I/O Peripheral design by using Proteus Software. This circuit had been design to be connected with the accelerometer and the Arduino. It will function as the display of the reading from the experiments. Step by step experiments will be done in order to make sure all the circuits function as needed.

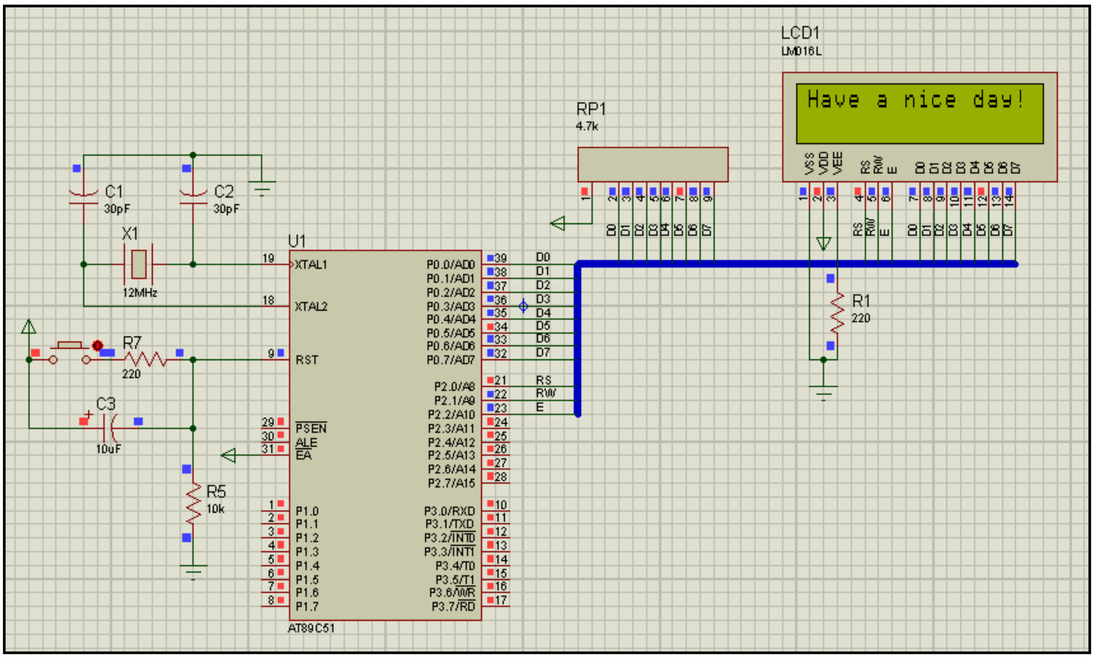


Figure 3.4: Simulation of the LCD I/O Peripheral.

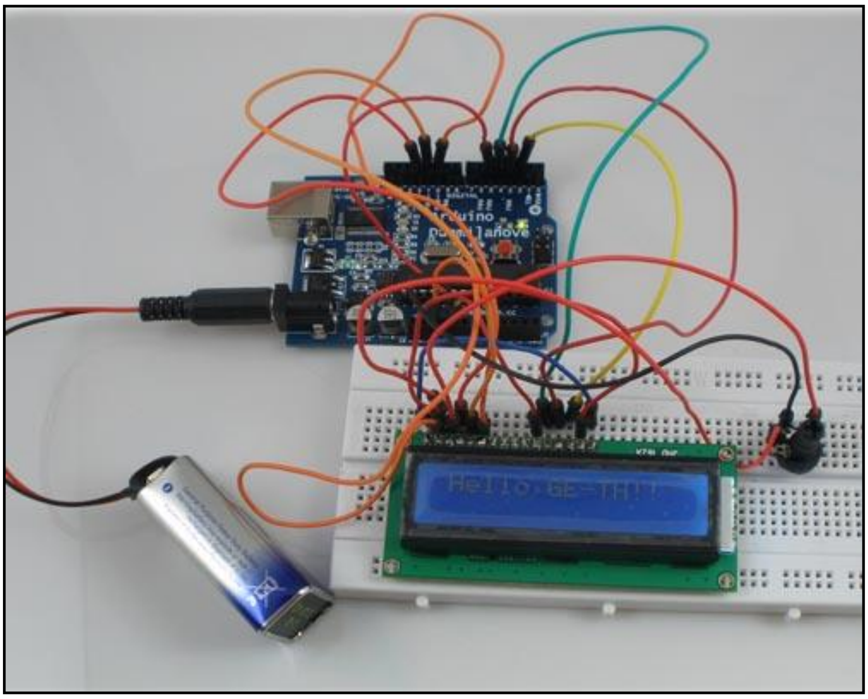


Figure 3.5: Circuit connection on breadboard between Arduino Uno with LCD.

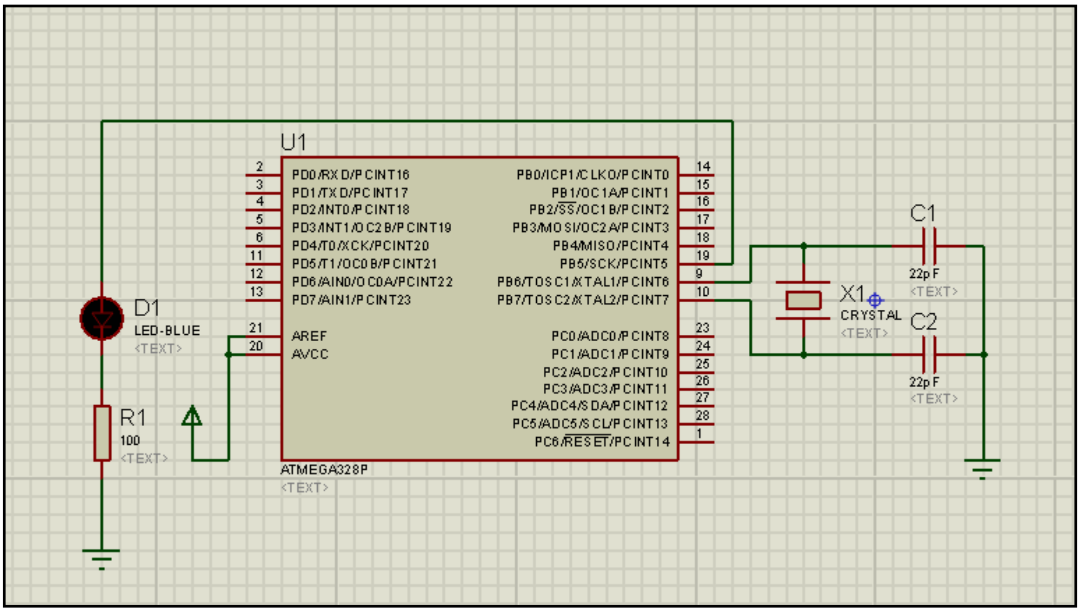


Figure 3.6: ATMEGA328P simulation circuit in Proteus Software.

3.3.2 Arduino Software

Arduino software is open software which is easy to use in writing code and uploads to the I/O board. It runs on Windows, Mac OS X, and Linux. The Arduino software consists of a development environment (IDE) and the core libraries. The IDE is written in Java and based on Processing, avr-gcc, and other open source software. The core libraries are written in C and C++ and compiled using avr-gcc and AVR Libc. The source code for Arduino is now hosted on GitHub. Arduino programs can be divided in three main parts:

- Structure
- Values(variables and constants)
- Functions

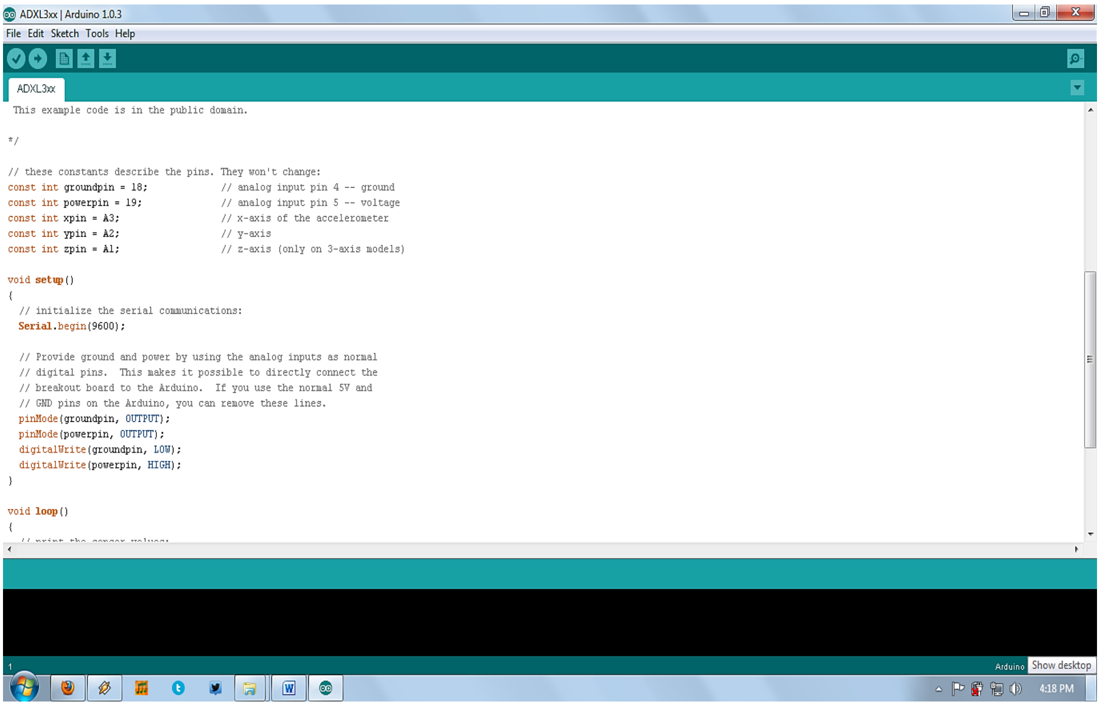


Figure 3.7: Screenshot of the Arduino software.

Regarding the title of "Altitude Measurement and Calibration on Milling Operation" there will need to be a program to be built in order to operate the device before being place on the Milling Machine for test. Figure 3.8 shows the flowchart for software development of the device.

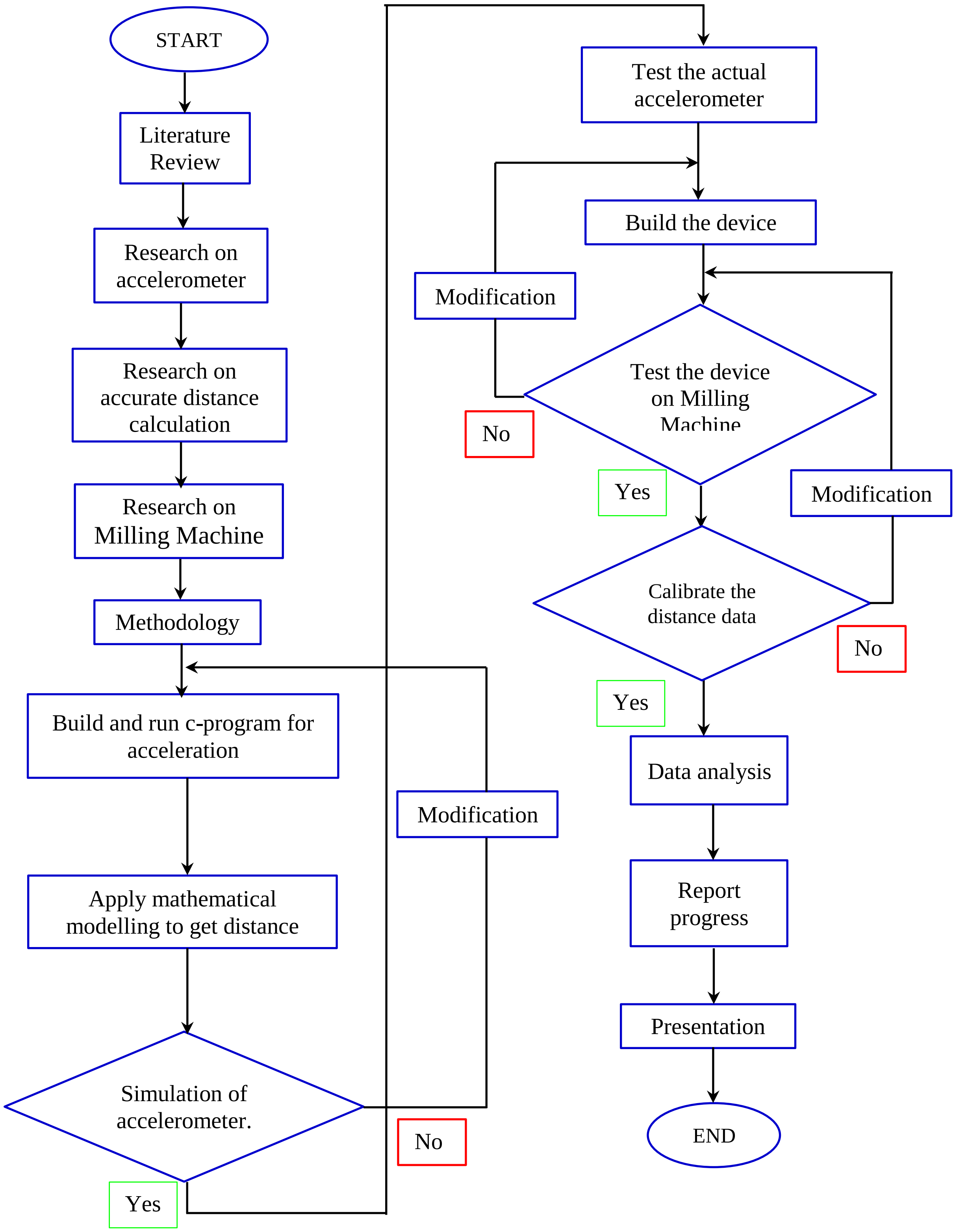


Figure 3.8: Flowchart of software development.

Through programming, a program of getting the reading of acceleration is being constructed. Part of software programming includes:

- Program for acceleration in analog from accelerometer.
- Program for acceleration in digital from accelerometer.
- Program for acceleration in voltage from accelerometer.
- Program for acceleration in Gs from accelerometer.
- Program for acceleration in m/s^2 from accelerometer.

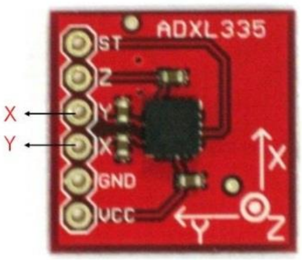
3.4 HARDWARE

The term hardware refers to objects which can be touch such as keyboards, printers, disk drives and disks. In other words, it is touchable while the software is untouchable.

3.4.1 Electronic Components

Electronic components are a basic device which will be used in an electronics system. It is usually available in singular form. Basic electronics components usually packaged discretely, as arrays or for networks of like components or integrated inside packages.

Table 3.1: List of electronic components.

No.	Components	Part Number	Specifications
1	**Triple Axis Accelerometer Breakout.**  **Figure 3.9**: Accelerometer ADXL355 [18].	SN-ADXL335	• Weight: 0.037 kg • 5V powered 2 x 16 characters. • SPI communication. • 3 Pins interface to microcontroller. • Compatible with all types of microcontrollers. • Back light and contrast control available.
2	**Arduino Uno Rev3-Main Board.**  **Figure 3.10**: Main-board of Arduino Uno [18].	Arduino-Uno Rev 3	• Weight: 0.040 kg • Microcontroller: ATmega328 • Operating voltage: 5V • Input voltage (recommended): 7 – 12V • Input voltage (limits): 6 – 20V • Digital I/O Pins: 14 (6 provides PWM output) • Analog input pins: 6 • DC Current per I/O Pin: 40mA • DC Current for 3.3V Pin: 50mA • Flash memory: 32KB (ATmega328) of which 0.5 KB used by bootloader • SRAM: 2KB (ATmega328) • EEPROM: 1KB (ATmega328) • Clock speed: 16MHz

3	**Serial LCD (2x16)**  **Figure 3.11**: LCD 16 x 2 Alphanumeric display [18].	DS-LCD-SRL 162	• Weight: 0.037 kg • 5V powered 2 x 16 characters. • SPI communication. • 3 Pins interface to microcontroller. • Compatible with all types of microcontrollers. • Back light and contrast control available.
4	**UV PCB Board**  **Figure 3.12:** UV PCB [19].	GS1015	• Fibre-glass - 1.6mm. • Single sided 1oz copper. • Positive presensitised PCB. • Dimension: 100 x 150 x 1.6mm.
5	**Potentiometer**  **Figure 3.13:** Potentiometer [20].	10k Ohm	• An adjustable potentiometer can open up many interesting user interfaces. • Turn the pot and the resistance changes. • Connect VCC to an outer pin, GND to the other, and the center pin will have a voltage that varies from 0 to VCC depending on the rotation of the pot.

3.4.2 Milling Machine as a platform for experiments

Milling Machine is being used as a platform to measure distance. In this study, the acceleration, time and actual distance measured during the motion of the machine will be included during the experiment. The device will be place on top of the platform of the Milling Machine as shown in Figure 3.14.

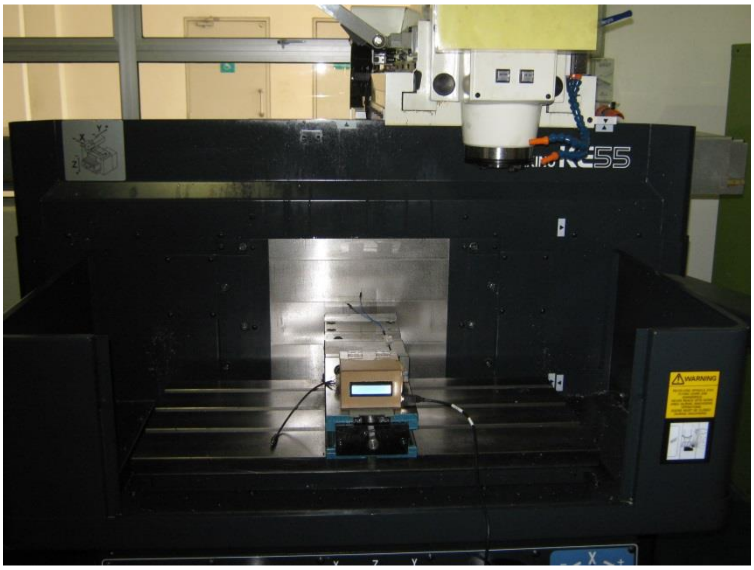


Figure 3.14: The attachments of accelerometer on top of the platform of the Milling Machine.

3.4.3 CATIA Software for device casing

Device casing will be design by using CATIA Software. Inside the casing we will place all the circuits and the LCD will be attached to the wall of one part of the casing as shown in Figure 3.15.

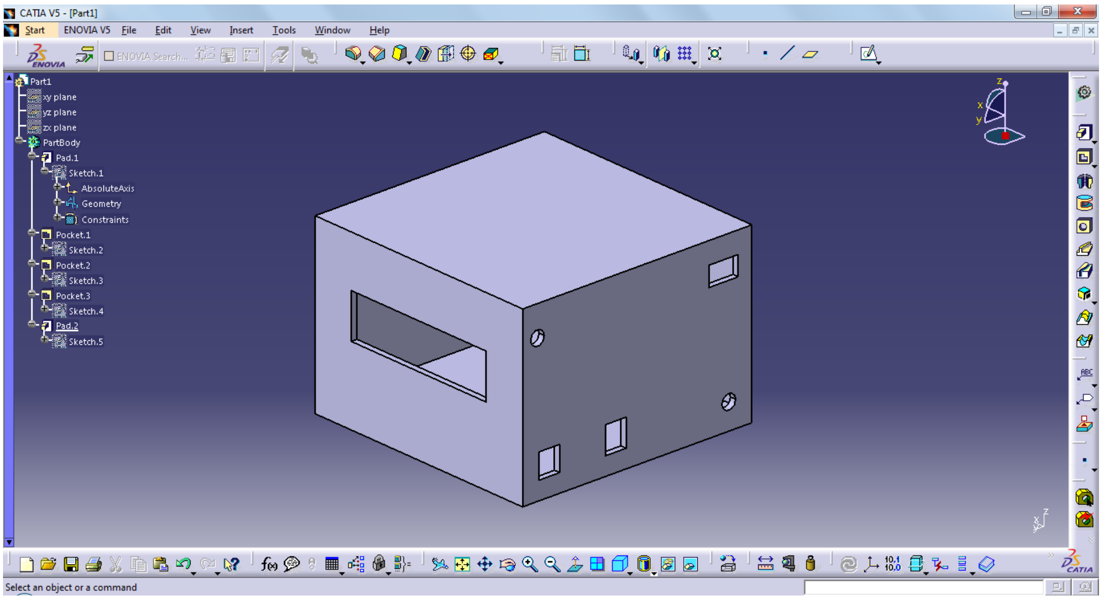


Figure 3.15: 3D view of the device casing to be place on top of the Milling Machine.

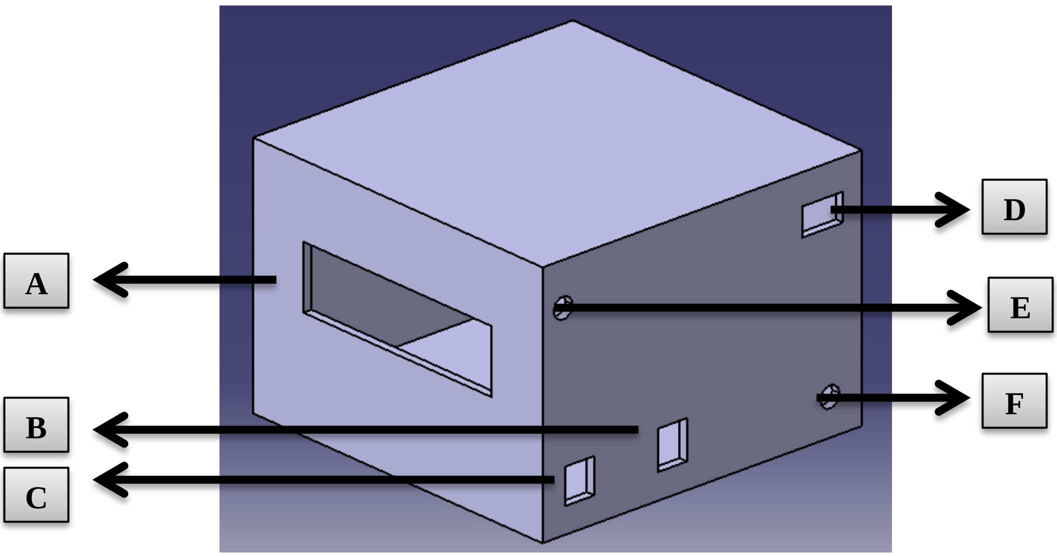


Figure 3.16: Labelled part for components placement.

A – LCD Placement.

B – Arduino Uno adapter placement.

C – Arduino Uno USB placement.

D – Switch placement.

E – Potentiometer placement.

F – Wiring out.

3.5 MATHEMATICAL MODELLING

Mathematical modelling is a method of a system by using mathematics concept. It includes dynamical systems, statistical models, differential equations and integration.

3.5.1 Double integration method

To measure acceleration from accelerometer, conversion of acceleration is needed. The first reading from the accelerometer is analog reading; therefore few conversions are needed before performing double integration to gain distance. Unfortunately, the reading that will get from the accelerometer is not constant due to vibration from surroundings. Filtering is needed to be done before integrating because the output could become unbounded over time.

To perform the double integration method, initial conditions is needed. Therefore, for proper integration initial velocity and initial position must be known from direct measurement. The equations that relate in conversion of acceleration to distance are:

Equation 1: Formula for acceleration.

$$a(t) = A \sin 2\pi ft \tag{3.1}$$

Equation 2: Formula integration of acceleration to get velocity.

$$v(t) = \int a(t) = -\frac{A}{2\pi f} \cos 2\pi ft \tag{3.2}$$

Equation 3: Formula double integration of acceleration to get distance.

$$x(t) = \int v(t) = \iint a(t) = -\frac{A}{(2\pi f)^2} \sin 2\pi ft \qquad (3.3)$$

Where,

A = Acceleration value from device, m/s^2

f = frequency, Hz

t = time taken, s

π = 3.142 radian

a(t) = acceleration

v(t) = velocity

x(t) = distance

Data which is needed for double integration includes the initial and final time during the Milling Machine move from minimum height to maximum height which is 35cm. Other than that, is the acceleration value that we get from the device with the unit of m/s^2. The distance will be calculated within difference height and difference voltage given to the Milling Machine to move it upward until maximum position. After the data had been tabulated, analysis will be done to compare the experimental value of distance with the actual distance on the Milling Machine. Results and discussion will be discussed in the next chapter.

3.5.2 Percentage error formula, % Error

The percentage error is a formula which helps in identifying how much error that we get from the experiments. In some data, the difference in continuous data that we gain will exist, this is due to some factors which sometimes undetermined. Therefore, by using this formula it will helps in identifying how accurate the data. The formula that represents the percentage error is:

$$\%Error, e = \left| \frac{TheoreticalValue - ExperimentalValue}{TheoreticalValue} \right| \times 100 \tag{3.4}$$

Where,

Theoretical Value = Actual value which is known.

Experimental Value = Results from experiments.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter will be devoted for the project output, analysis, and discussion. Milling machine was chosen as the platforms. The implementation of the device had been successfully being done in getting distance reading. Data of the analog, digital, voltage and real acceleration was collected during the experiments. After all the parameters needed was collected, comparison between calculated distance value and the actual distance had been done and being analysed in graphical method.

4.2 VERIFICATION OF HARDWARE AND SOFTWARE

Verification on Arduino board, ADXL335 accelerometer sensor and software related had been carried out. The COM port was wished to be detected on the user computer and the function of the sensor at graphical software was tested well. All the results were discussed in the following section.

4.2.1 Experimental Setup

This project started with the setup of the device on the platforms. During test run, zero reading of the sensor was recorded to be included in the software part. The motion chose is only on z-axis in order to measure and calibrate the altitude of the milling machine operation.

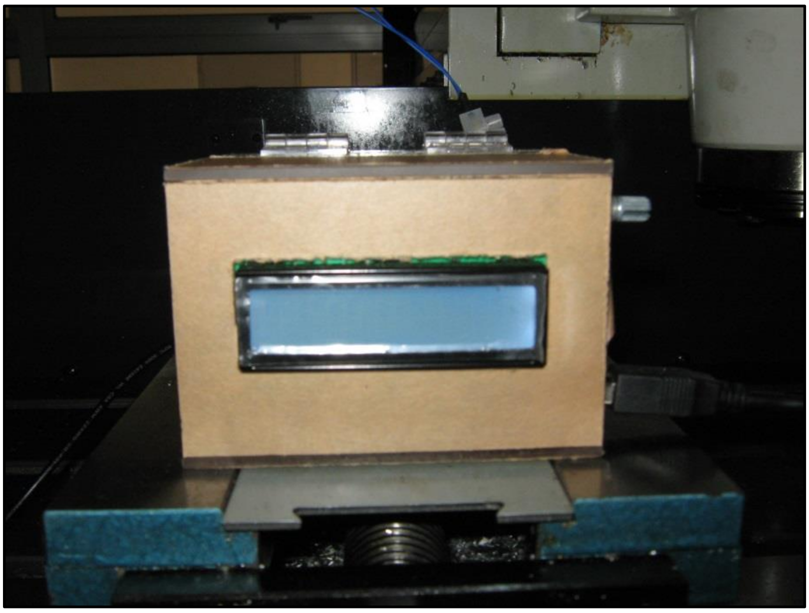


Figure 4.1: Test run of the device on Milling Machine.

Firstly, Arduino program is uploaded onto the device and setup on the platform. Before moving up the platform, the device is set at minimum position. Data was collected while the Milling machine is moving upward into desired height. The overall distance of z-axis position of the Milling machine is 0.35m. The distance was divided into seven sections with 0.05m for each increment. The acceleration data will be used to calculate distance value using double integration method.

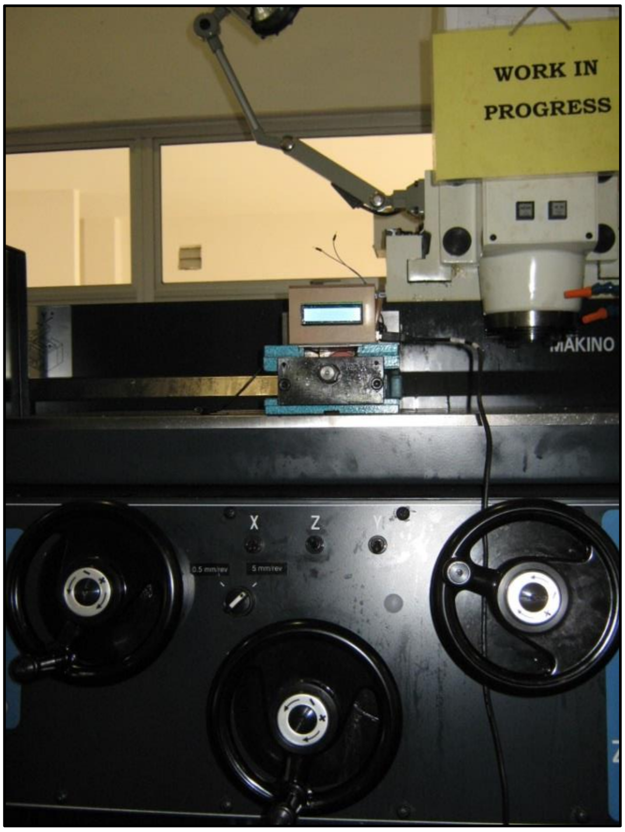


Figure 4.2: Device is being run on platform (Milling Machine) for z-axis direction at maximum height.

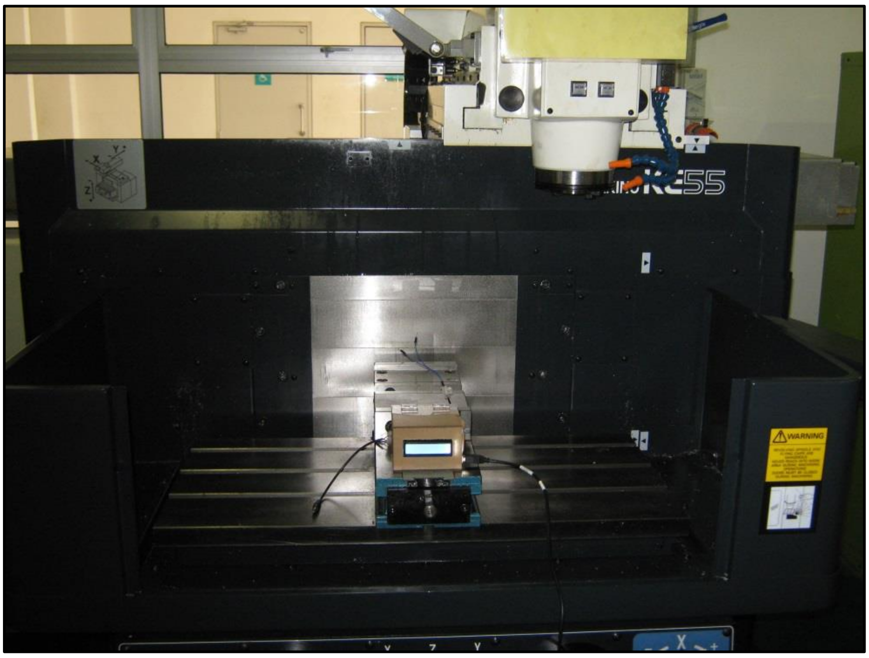


Figure 4.3: Device is being run on platform (Milling Machine) for z-axis direction at minimum height.

4.3 RESULT ANALYSIS AND DISCUSSION

This section is the analysis of the results from the implementation of the accelerometer on Milling Machine by running the program in gaining the analog value of acceleration and converting the reading into unit of m/s^2. Accelerometer will give an output of analog reading which contains noise in analog signal. Low pass filter was applied on the device to reduce the noise.

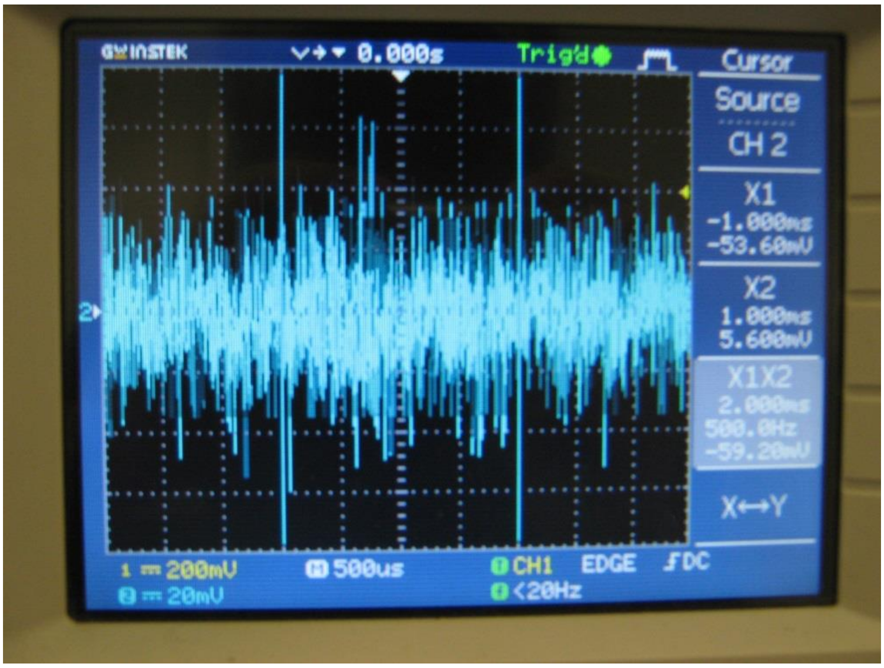


Figure 4.4: Graph of z-axis analog signal acceleration from accelerometer before applied low pass filter.

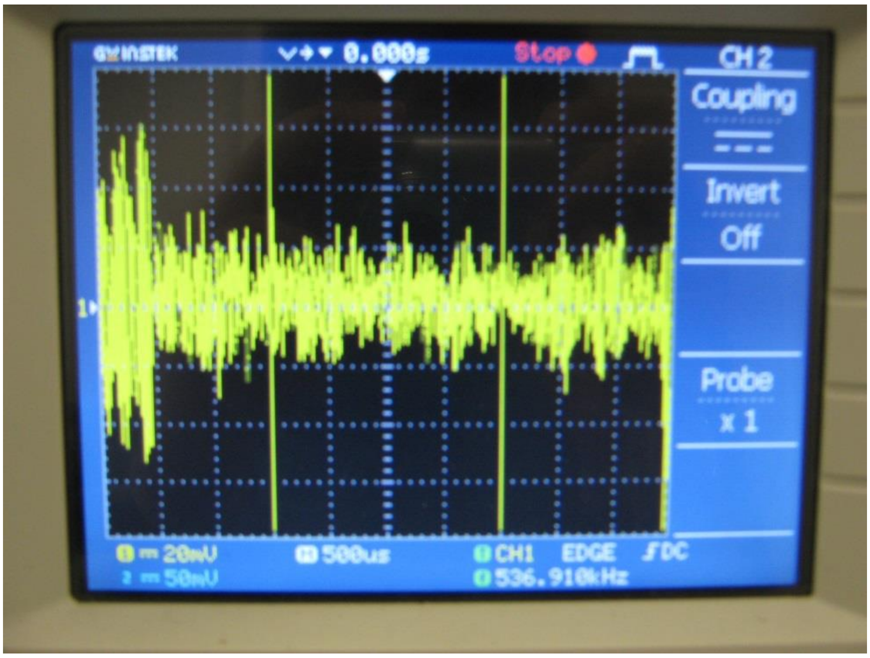


Figure 4.5: Graph of z-axis analog signal acceleration from accelerometer after applied low pass filter.

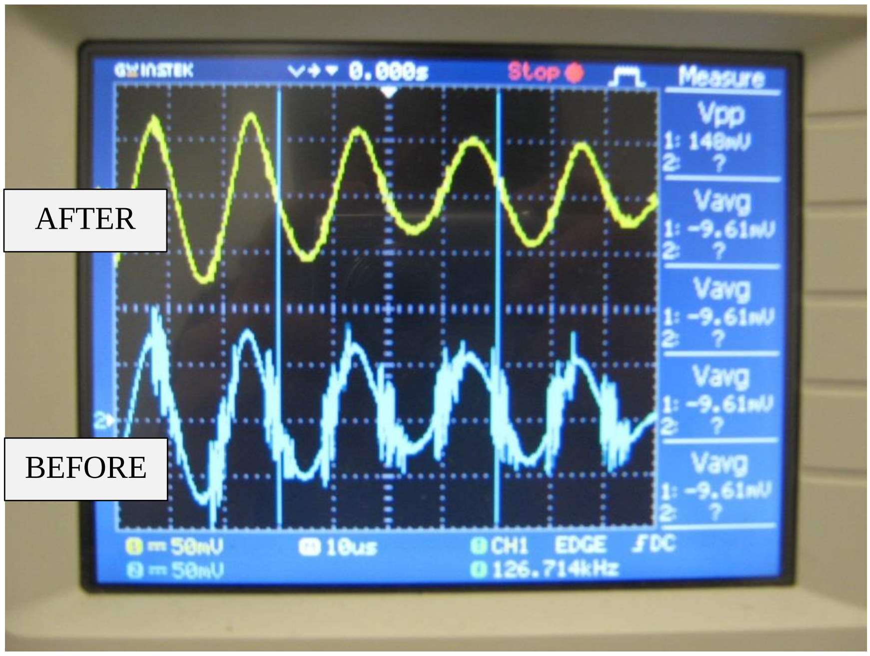


Figure 4.6: Analog signal acceleration from accelerometer before and after applying low pass filter.

According to Figure 4.6, there are noises produce which will affect the accuracy of the reading of acceleration from the accelerometer. After applying the filter, the accuracy of the calculated distance value which obtained from double integration method is improved.

Table 4.1: Tabulation of collected data.

No.	Average acceleration, Δa (m/s2)	Average time, Δt (s)	Frequency, f (Hz)	Actual Distance, d (m)	Calculated Distance, d (m)	% Error, e
1	9.84	3.33	1.00	0.05	0.09	0.80
2	9.86	4.67	1.00	0.10	0.12	0.20
3	9.84	8.33	1.00	0.15	0.19	0.27
4	9.86	10.67	1.00	0.20	0.23	0.15
5	9.86	13.00	1.00	0.25	0.24	0.04
6	9.86	16.00	1.00	0.30	0.25	0.17
7	9.85	18.67	1.00	0.35	0.26	0.26

4.3.1 Calculation of distance

In order to obtain the value of the calculated distance, double integration method will be applied. Therefore, calculation using equation (3.3) was applied for each reading of the acceleration according to Table 4.2.

$$\iint a(t) = -\frac{A}{(2\pi f)^2}\sin 2\pi f t$$

Where,

$A = acceleration\ value\ from\ the\ device, m/s^2$

$f = frequency, Hz$

$t = time\ taken\ for\ the\ device\ to\ move\ into\ the\ desired\ distance, sec$

$\pi = 3.142\ rad$

Table 4.2: Calculation of acceleration using double integration method.

Acceleration, m/s^2	**Time, s**	**Distance, m**
9.84	3.33	0.09
9.86	4.67	0.12
9.84	8.33	0.19
9.86	10.67	0.23
9.86	13.00	0.24
9.86	16.00	0.25
9.85	18.67	0.26

4.3.2 Calculation of percentage error, e (%e)

Percentage error is calculated in order to analyse the difference between calculated distances with the actual distance values. According to the comparison between the values analysis was made. This error exists due to some limitations that need to be improved for future works. Table 4.3 shows the calculation of each error produce for each reading of acceleration by referring equation (3.4) in Chapter 3.

$$\%\, Error, e = \left|\frac{Theoretical\, Value - Experimental\, Value}{Theoretical\, Value}\right| \times 100$$

Table 4.3: Calculation of percentage error, % e.

Acceleration, m/s^2	**%e**
9.84	0.80
9.86	0.20
9.84	0.27
9.86	0.15
9.86	0.04
9.86	0.17
9.85	0.26

Figure 4.7: Distance against Iteration for actual and calculated distance.

After calibration had been done to obtain the most accurate readings referring the actual readings the graph between calculated distance and actual distance was plotted in Figure 4.7. From Figure 4.7 above at sixth and seventh iteration, the reading of distances slightly difference from the actual distance which produce an error of 0.17% and 0.26% respectively. These may results from some factors that affects the accuracy of the readings.

There are factors which caused the error in the readings. According to the datasheet of the accelerometer, ADXL335, this type of accelerometer can measure dynamic acceleration resulting from motion, shock and vibration. Therefore, the first factor is vibration exert on the sensor. Sensitivity of the sensor played an important role in sensing because the more sensitivity the better. That means, for a given change in acceleration there will be a larger change in signal, since the larger change in signal will make it easy to measure and increase the accuracy of the sensor readings.

Another factor is ADXL335 is a single structure sensor to sense x, y, and z axes. The three axes sense directions are highly orthogonal and have a little cross-axis sensitivity. It is caused from the mechanical misalignment of the sensor because it is focussing on z-axis motion only.

Last but not least is the position of the sensor itself. Where, the sensor must be mounted directly to the machine surface to correctly measure the distance. Instead of attaching the accelerometer, ADXL335 together with the device, the sensor can be jumped alone and attached on top of the platforms that will probably give accurate readings.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

In this thesis, the work was successfully completed until the process of applying double integration on the acceleration data from the device was developed and tested. The experiment was evaluated using Milling Machine which involved z-axis movement of the machine. The developed device will read acceleration reading from accelerometer in analog and convert it into real acceleration with the unit of m/s^2.

During the experiment, parameters that were collected are acceleration, actual distance and time taken for the device to move upward in z-axis direction. By using all the parameters collected, calculation of double integration had been done in order to get the calculated distance value. Through this method, the difference between the actual and calculated distance were analysed and tabulated.

Calculation of percentage of error were calculated and discussed. From the results conclusion and recommendation was made to improve the development of the project in terms of software and hardware. As a conclusion, this project had achieved the objectives where the device for accurate distance calculation using accelerometer is successfully developed and the implementation of the accelerometer application on Milling Machine had achieved the target with allowable error between calculated and actual distance.

5.2 RECOMMENDATION

For future work will concentrate on the amount of collected acceleration data and refining data analysis in order to establish more definitive statistical information regarding the accuracy reading of the distance calculated. In this project, it is also suggested that the experimental test should be run on variety of platforms. This is because vehicles will produce better reading of acceleration compare to other platforms. All parameters involved in the test must take into consideration so that the data obtained is accurate.

Besides that, in this project a few factors of acceleration performances on the device are not considered because of some limitations and constrains. Therefore, for further work it is recommended that this research can be extent with the consideration of the x, y and z-axis of the accelerometer, platforms for experimental test, software development and mathematical modelling to generate distance reading. Other than that, it is recommended that the accelerometer is attached directly to the platforms that will probably give accurate readings.

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APPENDIX A
GANTT CHART

SEMESTER 7: Final Year Project 1

ALTITUDE MEASUREMENT AND CALIBRATION ON MILLING OPERATION															
PSM 1															
No.	Project Activities	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
1	Verify poject title.														
2	Research on accelerometer.														
3	Research on Milling Operation.														
4	Verify project objectives, problem statement, and project scopes.														
5	Chapter 1: Introduction (compilation).														
6	Chapter 2: Literature Review (compilation).														
	6.1 Accurate distance calculation.														
	6.2 Application of accelerometer.														
	6.3 Application of accelerometer on Milling Machine.														
7	Build c-program for accurate distance calculation and accelerometer.														
8	Design simulation.														
9	Implement the program to the actual accelerometer.														
10	Build up the device.														
11	Implement the device on shaker.														
12	Collect distance data on accelerometer through LCD, and calibrate the value of distance recorder with the actual value.														
13	Writing progress report.														

<u>SEMESTER 8: Final Year Project 2</u>

ALTITUDE MEASUREMENT AND CALIBRATION ON MILLING OPERATION																		
PSM 2																		
No.	Project Activities	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16	W17
1	Gather requirements for software development.																	
2	Software development stage 1: Analog to digital conversion.																	
3	Software development stage 2: Acceleration to distance conversion.																	
4	Software development stage 3: Applying low pass filter.																	
5	Software development stage 4: Compile software.																	
6	Build up the casing.																	
7	Device and system testing.																	
8	Data Analysis.																	
9	Discussion of of the experimental results.																	
10	Compilation of thesis report.																	
11	PSM fair (poster and booth).																	
12	Virtual Presentation.																	
13	Report submission.																	

APPENDIX B
ARDUINO PROGRAM

```
// NOR HANIS BINTI AHMAD NAZRI
// UNIVERSITI MALAYSIA PAHANG 2012/2013
// FACULTY OF MANUFACTURING ENGINEERING
// BACHELOR OF MECHATRONICS ENGINEERING
// PSM : Calibration and accurate distance calculation
   using accelerometer.

// Include the library code:
#include <LiquidCrystal.h>

// Initialize the library with the numbers of the interface
pins:
LiquidCrystal lcd(12, 11, 5, 4, 3, 2);

// these constants describe the pins. They won't change:
const int xpin = A1;     // x-axis of the accelerometer
const int ypin = A2;     // y-axis
const int zpin = A3;     // z-axis (only on 3-axis models)

int sampleDelay = 300;   //number of milliseconds between
readings

void setup()
{
  // initialize the serial communications:
  Serial.begin(9600);

  // Make sure the analog-to-digital converter takes its
  reference voltage from
  // the AREF pin
  analogReference(EXTERNAL);

  // Setup the LCD's number of columns and row:
  lcd.begin(16, 2);

  pinMode(xpin, INPUT);
  pinMode(ypin, INPUT);
  pinMode(zpin, INPUT);
}

void loop()
{
  int x = analogRead(xpin);

  //add a small delay between pin readings.  I read that
  you should
  //do this but haven't tested the importance
  //delay(1);

  int y = analogRead(ypin);
```

```
//add a small delay between pin readings.  I read that
you should
//do this but haven't tested the importance
//delay(1);

int z = analogRead(zpin);

//zero_G is the reading we expect from the sensor when it
detects
//no acceleration.  Subtract this value from the sensor
reading to
//get a shifted sensor reading.
float zero_G = 512.0;

//scale is the number of units we expect the sensor
reading to
//change when the acceleration along an axis changes by
1G.
//Divide the shifted sensor reading by scale to get
acceleration in Gs.
float scale = 102.3;

// Simple calibration of accelerometers:
float x_origin = 1.97;
float y_origin = 1.63;
float z_origin = 1.65;

// Convert voltage reading of x, y, z to acceleration
[m/s2]:
float acc_x = ((analogRead(xpin) / 1023.0 ) * (3.3 -
x_origin));
// Convert Gs unit value into m/s2:
float X = acc_x * 9.80665;
float acc_y = ((analogRead(ypin) / 1023.0 ) * (3.3 -
y_origin));
// Convert Gs unit value into m/s2:
float Y = acc_y * 9.80665;
float acc_z = ((analogRead(zpin) / 1023.0 ) * (3.3 -
z_origin));
// Convert Gs unit value into m/s2:
float Z = acc_z * 9.80665;

// Print reading on serial monitor:
// Display value of acceleration in ANALOG reading:
Serial.print("Acceleration of x in analog x = ");
Serial.print( analogRead(xpin));
// delay before next reading:
delay(sampleDelay);
Serial.print);
```

```
//add a small delay between pin readings.  I read that
you should
//do this but haven't tested the importance
//delay(10);

Serial.print("Acceleration of y in analog y = ");
Serial.print( analogRead(ypin));
// delay before next reading:
delay(sampleDelay);
Serial.print("\n");

//add a small delay between pin readings.  I read that
you should
//do this but haven't tested the importance
//delay(10);

Serial.print("Acceleration of z in analog z = ");
Serial.print( analogRead(zpin));
// delay before next reading:
delay(sampleDelay);
Serial.print("\n");
Serial.print("\n");

// Display value of acceleration in Gs reading:
Serial.print("Acceleration of x in Gs x = ");
Serial.print(((float)x - zero_G)/scale);
// delay before next reading:
delay(sampleDelay);
Serial.print("\n");

//add a small delay between pin readings.  I read that
you should
//do this but haven't tested the importance
//delay(10);

Serial.print("Acceleration of y in Gs y = ");
Serial.print(((float)y - zero_G)/scale);
// delay before next reading:
delay(sampleDelay);
Serial.print("\n");

//add a small delay between pin readings.  I read that
you should
//do this but haven't tested the importance
//delay(10);

Serial.print("Acceleration of z in Gs z = ");
Serial.print(((float)z - zero_G)/scale);
// delay before next reading:
```

```
  delay(sampleDelay);
  Serial.print("\n");
  Serial.print("\n");

  // Display value of acceleration in m/s2:
  Serial.print("Acceleration of x in m/s2 x = ");
  Serial.print(X);
  // delay before next reading:
  delay(sampleDelay);
  Serial.print("\n");

  Serial.print("Acceleration of y in m/s2 y = ");
  Serial.print(Y);
  // delay before next reading:
  delay(sampleDelay);
  Serial.print("\n");

  Serial.print("Acceleration of z in m/s2 z = ");
  Serial.print(Z);
  // delay before next reading:
  delay(sampleDelay);
  Serial.print("\n");
  Serial.print("\n");

  // Print values on LCD:
  lcd.print("Acc of X = ");
  lcd.print(X);
  lcd.print("y = ");
  lcd.print(Y);
  lcd.print("Acc of z = ");
  lcd.print(Z);
  delay(sampleDelay);
  lcd.clear();

}
```

APPENDIX C
DATA COLLECTION

Actual Distance = 0.05m

No.	Acceleration, a (m/s^2)		
	Reading 1	**Reading 2**	**Reading 3**
1	9.85	9.87	9.87
2	9.79	9.85	9.85
3	9.82	9.90	9.78

Actual Distance = 0.10m

No.	Acceleration, a (m/s^2)		
	Reading 1	**Reading 2**	**Reading 3**
1	9.87	9.87	9.85
2	9.90	9.93	9.82
3	9.89	9.78	9.81

Actual Distance = 0.15m

No.	Acceleration, a (m/s^2)		
	Reading 1	**Reading 2**	**Reading 3**
1	9.81	9.85	9.85
2	9.90	9.81	9.84
3	9.82	9.87	9.93
4	9.79	9.90	9.81
5	9.85	9.90	9.79
6	9.82	9.81	9.79

Actual Distance = 0.20m

No.	Acceleration, a (m/s^2)		
	Reading 1	**Reading 2**	**Reading 3**
1	9.85	9.85	9.85
2	9.82	9.90	9.89
3	9.84	9.90	9.87
4	9.82	9.92	9.81
5	9.90	9.85	9.82
6	9.81	9.92	9.78
7	9.84	9.89	9.84
8	9.90	9.84	9.85

Actual Distance = 0.25m

No.	Acceleration, a (m/s^2)		
	Reading 1	Reading 2	Reading 3
1	9.85	9.87	9.85
2	9.82	9.87	9.89
3	9.79	9.84	9.87
4	9.92	9.89	9.81
5	9.82	9.92	9.82
6	9.90	9.81	9.78
7	9.92	9.90	9.84
8	9.92	9.78	9.85
9	9.84	9.92	9.78
10	9.84	9.90	9.92

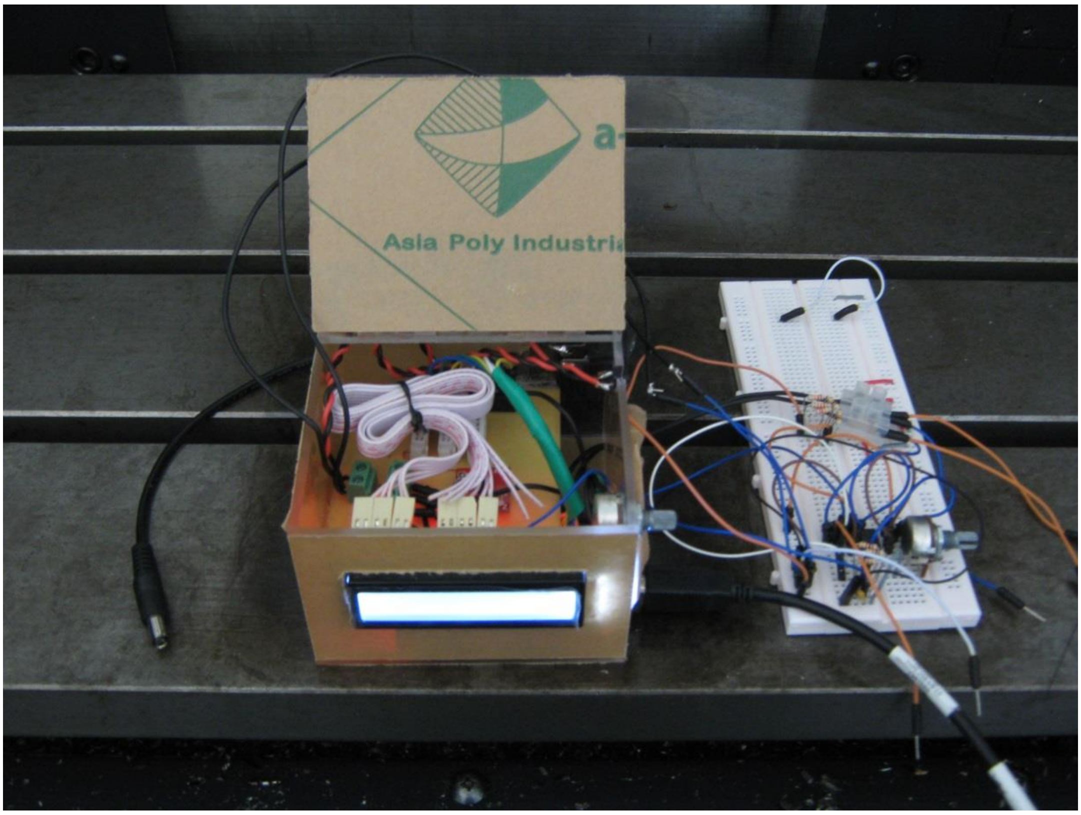
Actual Distance = 0.30m

No.	Acceleration, a (m/s^2)		
	Reading 1	Reading 2	Reading 3
1	9.85	9.85	9.85
2	9.81	9.89	9.89
3	9.82	9.85	9.85
4	9.92	9.82	9.76
5	9.82	9.89	9.89
6	9.92	9.90	9.82
7	9.79	9.92	9.89
8	9.87	9.81	9.82
9	9.84	9.84	9.92
10	9.81	9.92	9.90
11	9.79	9.87	9.85
12	9.92	9.89	9.89
13	9.82	9.79	9.89

Actual Distance = 0.35m

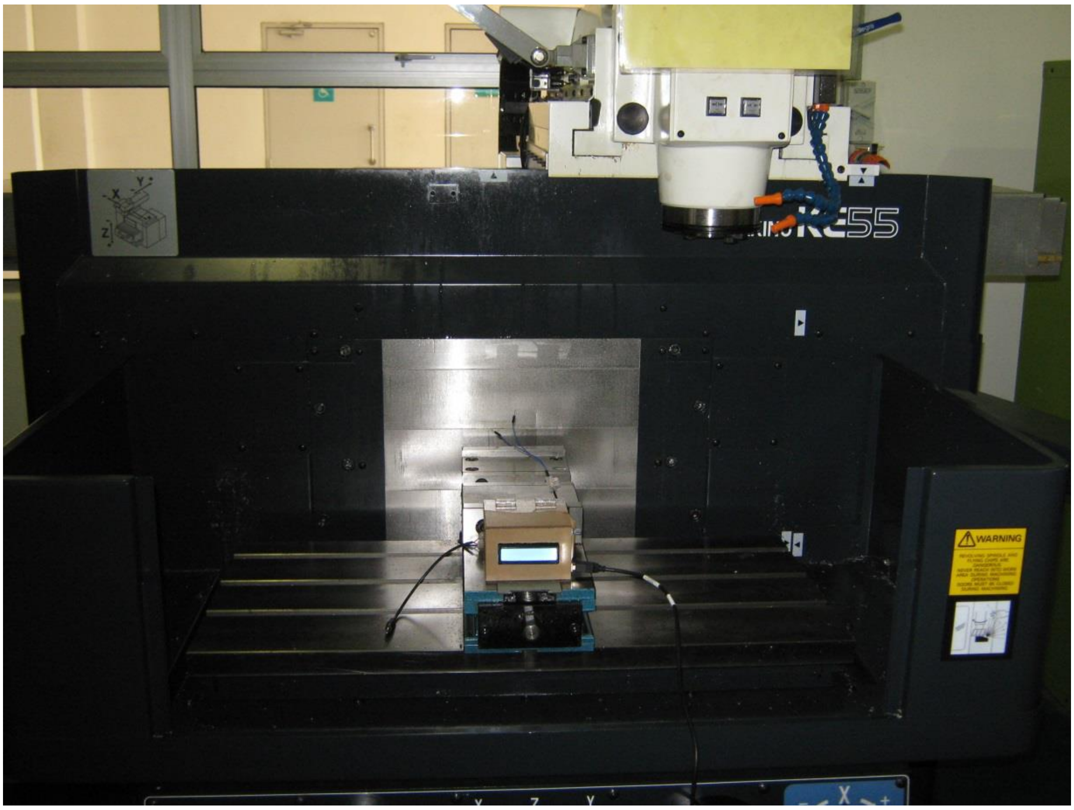
No.	Acceleration, a (m/s^2)		
	Reading 1	**Reading 2**	**Reading 3**
1	9.85	9.85	9.85
2	9.81	9.81	9.87
3	9.81	9.81	9.87
4	9.90	9.92	9.84
5	9.79	9.82	9.92
6	9.78	9.79	9.84
7	9.81	9.90	9.92
8	9.82	9.90	9.92
9	9.84	9.87	9.87
10	9.82	9.82	9.87
11	9.87	9.90	9.92
12	9.89	9.84	9.81
13	9.78	9.82	9.79
14	9.81	9.87	9.85
15	9.89	9.85	9.92
16	9.85	9.87	9.89

APPENDIX D
EXPERIMENTAL PICTURES

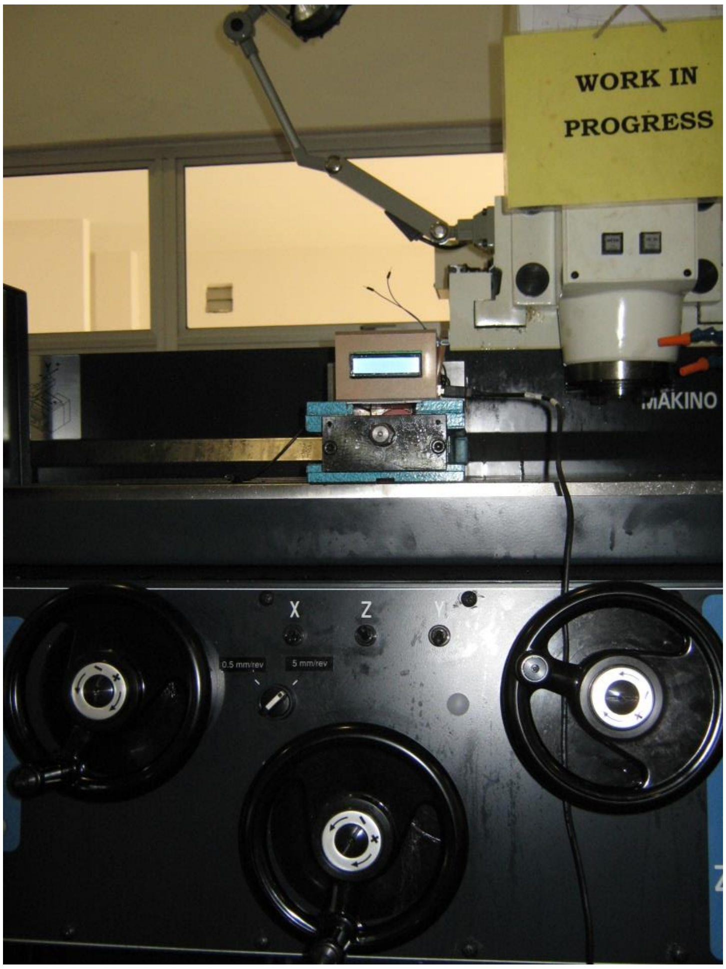

Asia Poly Industria

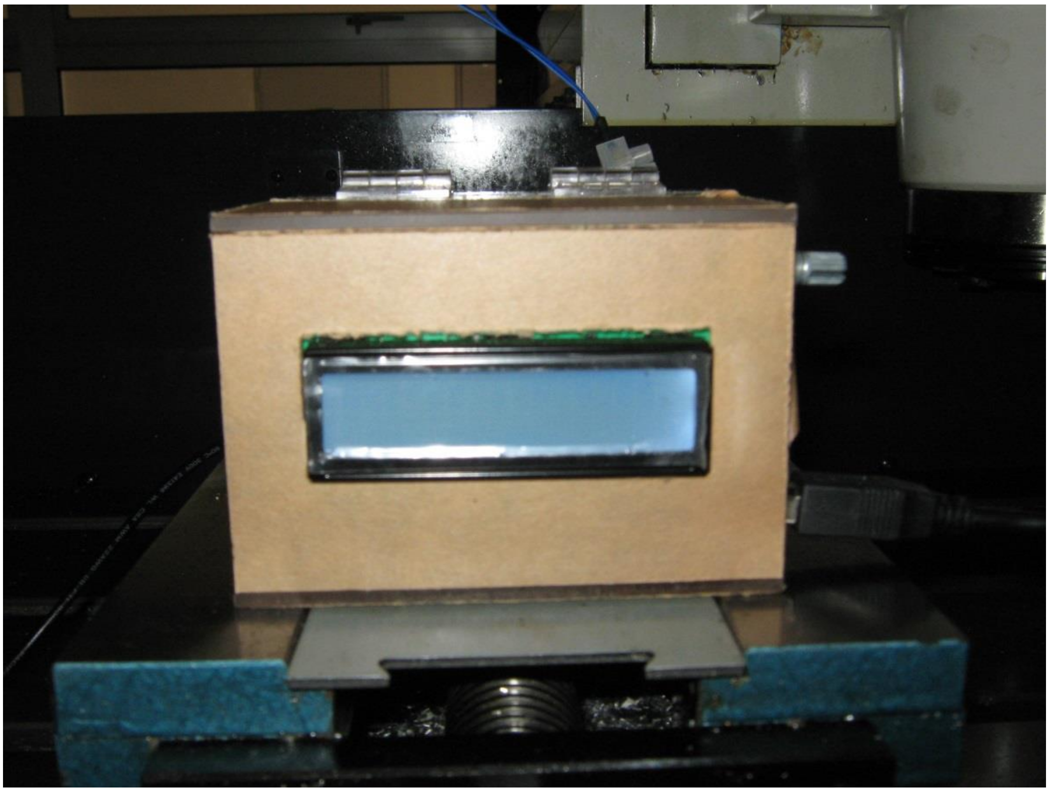

KE55
X
Z
Y

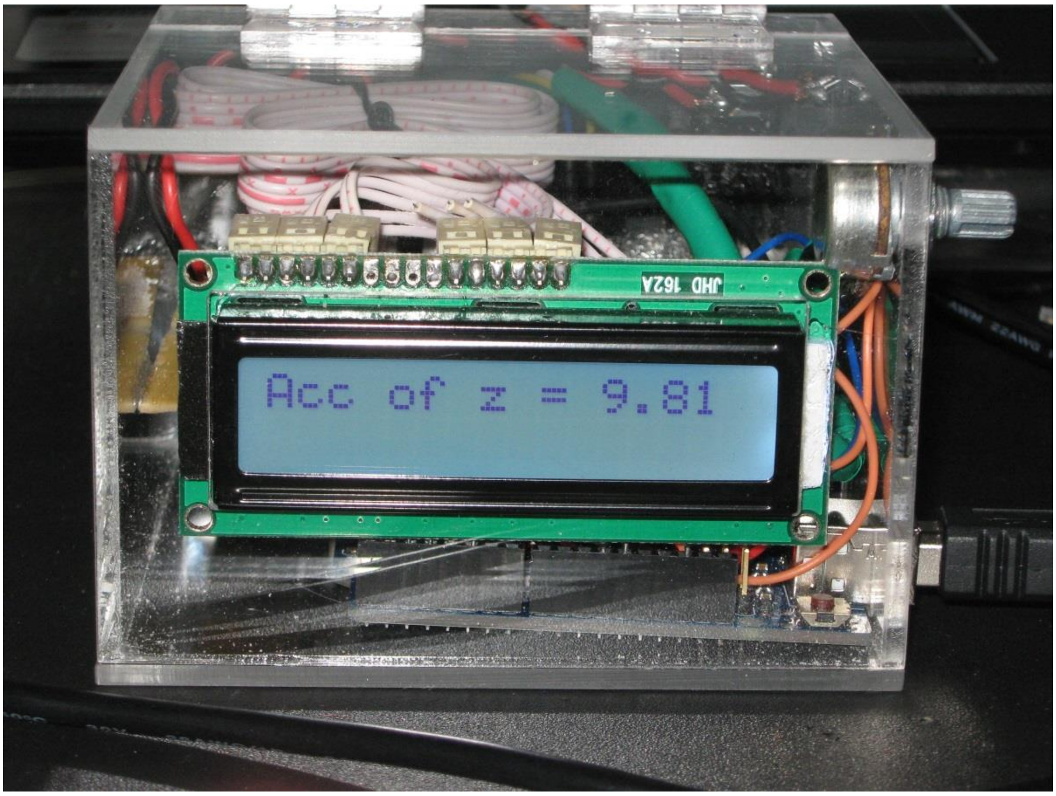

KE55
X
Z
Y
0.5 mm/rev
5 mm/rev
X
Y


KE55
WARNING


Canon
lenovo


WORK IN
PROGRESS
MAKINO
X
Z
Y
0.5 mm/rev
5 mm/rev




JHD 162A
Acc of z = 9.81