

**COMPARATIVE STUDY OF CONSTANT HEIGHT MODE AND
CONSTANT DETECTION MODE IN ATOMIC FORCE MICROSCOPY
(AFM) IMAGING**

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**A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Bachelor of Engineering (Hons) Electronic Engineering**

**Faculty of Engineering and Green Technology
Universiti Tunku Abdul Rahman**

April 2016

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **“COMPARATIVE STUDY OF CONSTANT HEIGHT MODE AND CONSTANT DEFLECTION MODE IN ATOMIC FORCE MICROSCOPY (AFM) IMAGING”** was prepared by **LAU SAI YEE** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons) Electronic Engineering at Universiti Tunku Abdul Rahman.

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**COMPARATIVE STUDY OF CONSTANT HEIGHT MODE AND
CONSTANT DEFLECTION MODE IN ATOMIC FORCE MICROSCOPY
(AFM) IMAGING**

ABSTRACT

Atomic Force Microscopy (AFM) is a kind of Scanning Probe Microscopes (SPM) which is designed to measure local properties of materials, such as height, area, friction and magnetism, using a probe that operates at high resolution. AFM demonstrates scanning resolution on the order of fractions of a nanometer and thus it is widely used in Nano technology. The development of AFM is important as it helps to overcome the basic weakness of optical microscope, which is limited by optical diffraction limit in scanning, and also the weakness of Scanning Tunnel Microscopy (STM), which can only produce images on conducting and non-conducting surface. Increasing use of AFM has been found in diverse field of technology, such as physical and biological sciences and it was predicted that this trend will continue. In view of this, the purpose of this project is to develop a functional software prototype AFM scanning mechanism through LABVIEW platform and features will be further discussed in the report. The work here focuses on the comparative study of Constant Height mode and Constant Deflection mode in AFM imaging. Basic framework of system was constructed in the early phase so that further integration and improvement can be achieved progressively. In the last phase of prototyping development, there will be a software prototype which works as AFM scanning mechanism, in LABVIEW. Involvement of NI ELVIS board is mainly for future integration with real-case AFM machine.

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LIST OF SYMBOLS / ABBREVIATIONS

K_p	proportional gain
K_i	integral gain
K_d	derivative gain
$e(t)$	difference between setpoint and process variable
ΔP	displacement change of Piezoelectric Ceramic Buzzer
ΔL	change of laser position
AFM	Atomic Force Microscopy
2D / 3D	2-Dimensional / 3- Dimensional
PCB	Printed Circuit Board
LABVIEW	Laboratory Virtual Instrument Engineering Workbench
NI ELVIS board	National Instruments Educational Laboratory Virtual Instrumentation Suite
DAQ	Data Acquisition
FYP	Final Year Project
PID	Proportional-Integral-Derivative

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CHAPTER 1

INTRODUCTION

1.1 Background

Atomic Force Microscopy (AFM) is a development of Scanning Tunnelling Microscopy (STM), which intends to extend all of the possibilities of STM to imaging samples. STM was developed by Gerd Binnig and Heinrich Rohrer in the early 1980s in IBM Research and this great invention earned them the Nobel Prize for Physics in 1986. This definitely adds credits to the importance of STM in the Physics field and thus AFM was then developed to replace the electron tunnelling from a fine wire of STM with the cantilever approach of AFM (Eaton and West, 2010). Commercial instruments were introduced since 1988 and this resulted in the aggressive development and advanced operation of modes devised for AFM.

When the first AFM was introduced, it operated in contact mode, as shown in Figure 1.1. In contact mode, the end of a flexible cantilever is mounted with a tip to implement raster scan on the sample surface. The tip-surface interaction causes the deflection of cantilever which helps in surface topography. Unfortunately, contact mode of AFM performs badly in biological samples which are generally weakly bounded to surface and may be damaged easily. In view of this, this drove the development of non-contact mode in 1987. Non-contact mode enables the cantilever to oscillate within its resonant frequency to give small scale of moving above samples' surface, without any contact with samples. Amplitude, frequency and phase of cantilever are maintained at constant separation distance from sample and changed based on the strength of induction of long-range attractive forces. Eventually it gives

sample image without any damage. Further improvement on operation mode of AFM was done continuously and in 1993, tapping mode, which enables cantilever to have gentle tap on sample while scanning, was launched. Tapping mode further reduces damage on lateral parts and performs stably in air. Therefore, tapping mode is currently more commonly used in most AFM applications. In 1996, smaller cantilever was invented to allow higher resolution and smaller scanning times. It was believed that the widely use of AFM scanning in many fields like Engineering, Materials Science and Biology will motivate further development of AFM scanning system.

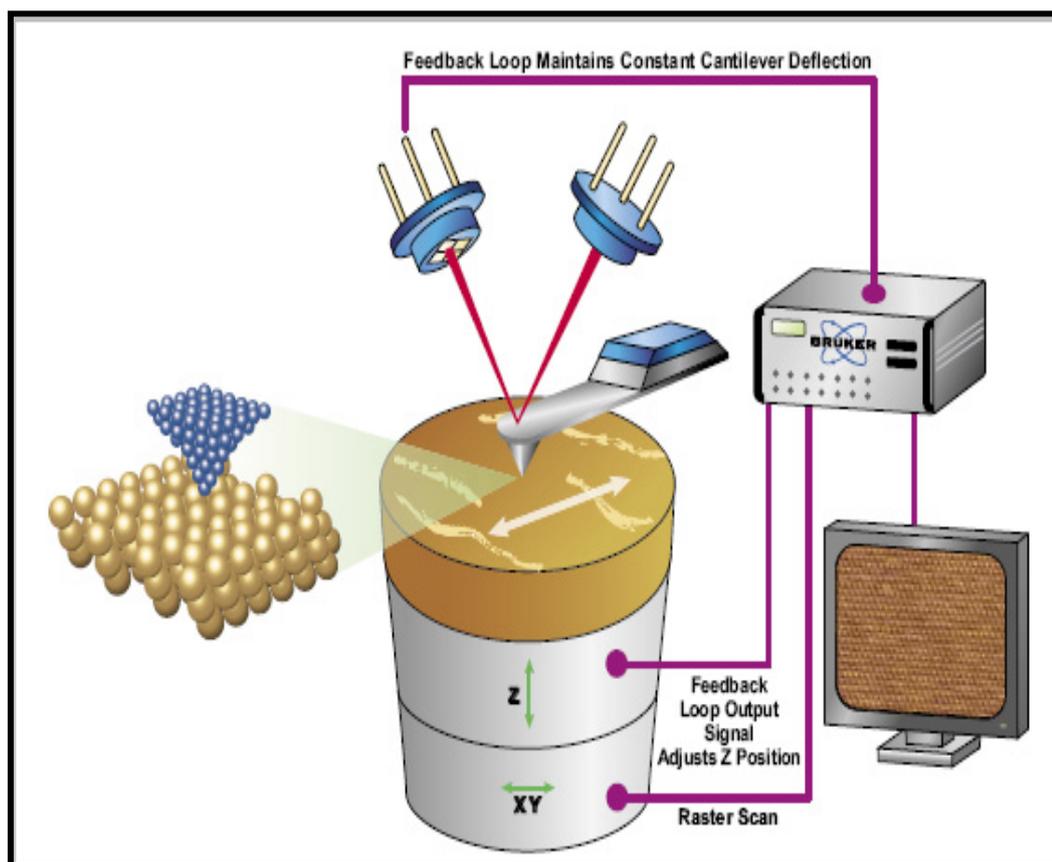


Figure 1.1 Contact Mode of AFM Scanning (Bruker AFM Probes Announcements, 2011)

1.2 Problem Statements

The technology of AFM has been developed since early 1980s until now. Different modes of scanning methods have been investigated in order to improve the accuracy of scanning and quality of results. However, the market price of AFM scanning machine is still considered high and unaffordable for some budget projects.

Therefore, AFM imaging machine is investigated in this project, in term of software and hardware, to produce an AFM scanning software prototype which has lower development costs with high quality of scanning outcomes. Also, different scanning modes have different imaging accuracy and thus Constant Height and Constant Deflection scanning mode are studied and applied in the AFM imaging process of the project.

1.3 Aims and Objectives

The objectives of the thesis are shown as follows:

- i) To study and understand the working principles of an Atomic Force Microscopy (AFM).
- ii) To carry out a comparative study on Constant Height mode and Constant Deflection mode in AFM imaging.
- iii) To integrate and develop a working software prototype that can perform two different imaging modes, Constant Height mode and Constant Deflection mode, in AFM imaging.
- iv) To analyse and evaluate the performance of the system based on the two imaging modes.

1.4 Project Scope

In this project, AFM scanning machine is formed by three parts: XY Direction Controller Unit, Z Direction Controller Unit and Data Collection Unit. Three units have been developed by seniors in their Final Year Project. Therefore, integration of these three controller units will be carried out, in term of software, in order to develop a well-working AFM scanning mechanism which can perform in two different AFM scanning modes: Constant Height and Constant Deflection. Also, further enhancement and improvement on the AFM algorithms will be implemented to increase the system accuracy. Software LABVIEW is chosen as development platform as it provides highly productive development environment which helps for creating customized applications interacting with real-world data or signals. Furthermore, NI ELVIS board acts as a prototyping platform to offer the flexibility of virtual instruction from LABVIEW and the ability of customizing application (Ni.com, 2013).

CHAPTER 2

LITERATURE REVIEW

2.1 Basic Working Principle of Atomic Force Microscopy (AFM)

The scanning and imaging processes of a sample using Atomic Force Microscopy (AFM) involve several critical components, such as photodiode detector, laser, cantilever with a tiny probe, XYZ scanner and data processor. The basic setup of AFM is shown in Figure 2.1. The position of the laser, photodiode detector and cantilever are set up in a fixed position such that the light beam emitted from the laser is reflected to the origin position of detector, after falling on cantilever surface. When the sample on the stage is oriented to pass through the probe, the cantilever will deflect differently, regarding to the shape of the sample. The deflection of cantilever results in the reflected light beam no longer stays at the origin. Based on the new position of reflected light beam on quadrant photodiode, the shape of sample will be figured out by data processor (Solid.unito.it, n.d.).

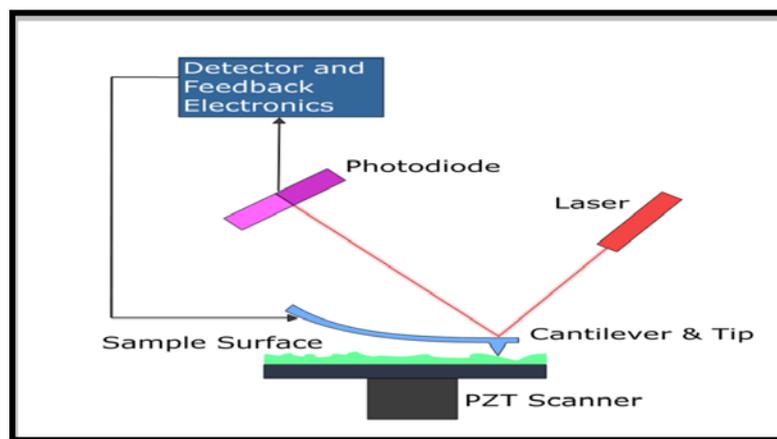


Figure 2.1 Basic AFM Setup (Solid.unito.it, n.d.)

The AFM instruments can be operated in two different scanning modes: Constant Height and Constant Deflection mode. In Constant Height mode, every new position of pixels on quadrant photodiode will be collected and processed by data processor in order to acquire surface image. On the other hand, in Constant Deflection mode, electronic feedback loop is employed in the sample scanning. This feedback loop has the cantilever deflection as input and its output monitors the height of XYZ scanner. Height variations in the sample will change deflection of the cantilever and the feedback will be applied to adjust stage height so that deflection of the cantilever will be restored to a user-defined value (setpoint). Therefore, the total displacement change of stage during every pixel scanning will help to obtain surface image of sample. Both imaging modes require software to process the data and thus LABVIEW Software and Instrument is chosen as it provides both hardware and software interface, which can achieve the work effectively and efficiently. Table 2.1 tells the summary of operation process for both imaging modes.

Table 2.1 Summary of Operation Process for Constant Height and Constant Deflection AFM Scanning Mode

<i>Modes</i>	<i>To be kept constant</i>	<i>To be changed</i>	<i>Way to know sample shape</i>
Constant Height	Stage height	Position of reflected laser beam on photodiode	New position of reflected laser beam on quadrant photodiode
Constant Deflection	Position of reflected light beam on photodiode	Stage height with feedback loop	Total displacement change of stage

2.2 General Parts of a Customized Atomic Force Microscopy (AFM) Scanning System

Atomic Force Microscopy (AFM) scanning system uses the force existing between the probe and the sample to construct an image of object. A typical configuration of AFM scanning system consists of cantilever, Quadrant Photodiode Detector, laser source, XYZ scanner body and data processor. In a customized AFM scanner, additional features like Photodiode Light Detector Circuit and LM741 Operational Amplifier also involve in the imaging process.

2.2.1 Cantilever

Cantilever consists of a long curved layer which is made of silicon or silicon nitride. An extremely small and tiny microscopic probe (curvature radius: 10~50 nm) is attached to the end of the cantilever spring, as shown in Figure 2.2 (Online-Redaktion, 2015). The underlying principle of AFM is explained by the detection of bending of the cantilever spring due to external forces. When the probe is in touch with the surface of the sample, the protruded part of the sample will cause the cantilever, which has the characteristic of spring, to deflect. Probes with smaller scale are significant for Nano technology measurement.

As the small-scale cantilever is very costly, the cantilever is replaced with a highly flexible ruler attached with a small needle in this project. A cantilever is ready to be used when the software and hardware of the AFM system are well-developed and can run stably.

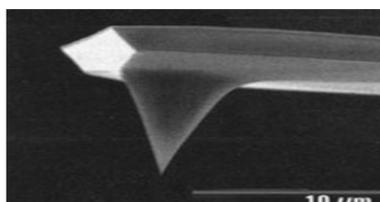


Figure 2.2 AFM Cantilever (Online-Redaktion, 2015)

2.2.2 Quadrant Photodiode Detector

A Quadrant Photodiode Detector functions to detect deflection of reflected light beam and transfer the results to the processing central, which is software LABVIEW in this project. Basically, it is made up of four quadrants (A, B C and D), as shown in Figure 2.3. Total light intensity received by each quadrant will be converted to voltage by photodiode in order to identify position of reflected light beam on it. Figure 2.3 demonstrates the beam deflection technique on the Quadrant Photodiode Detector.

In this FYP, before feeding the signals from photodiode to NI ELVIS Board, a pre-amplifier system and buffer are added after photodiode to ensure that signals can be received accurately by the board. LABVIEW carries out data processing to define deflection of cantilever by sample surface. In Figure 2.4, Quadrant Photodiode Detector is attached on the wall of stage for laser beam detection. Its position on stage wall will be pre-set before the AFM scanning and maintained throughout the scanning process.

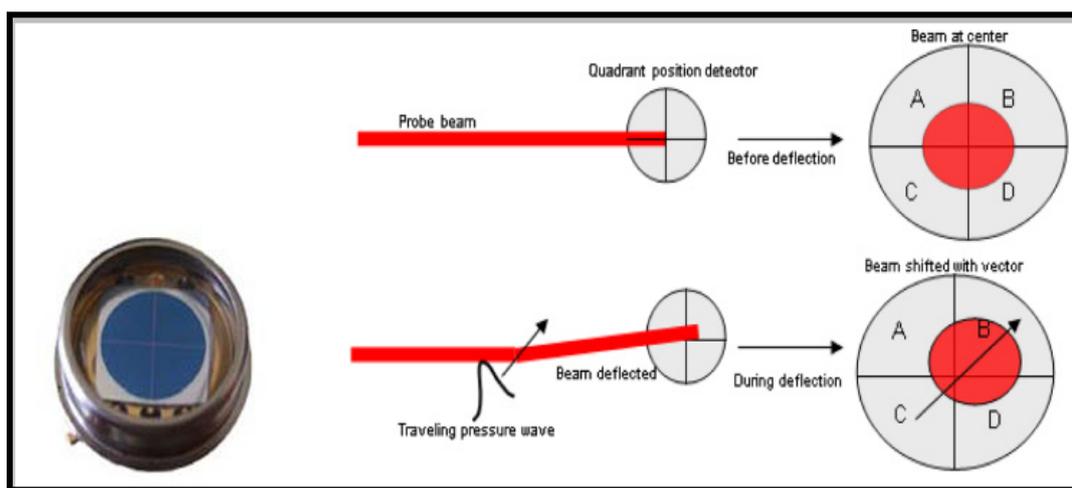


Figure 2.3 Quadrant Photodiode Detector and Beam Deflection Technique

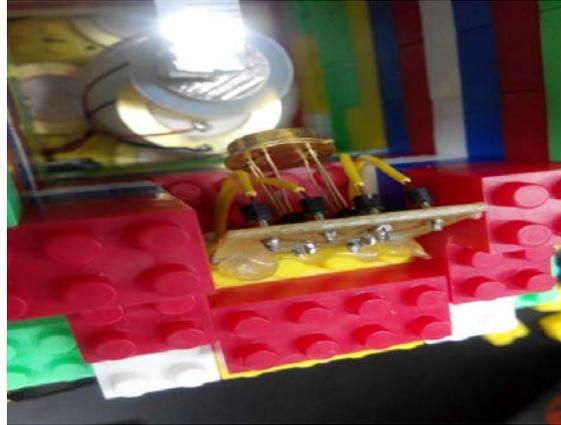


Figure 2.4 Quadrant Photodiode Detector is attached on the Wall of Stage

2.2.3 Laser

A laser pointer is used to emit a narrow light beam to the surface of cantilever. Its position is adjusted and fixed in order to enable the reflected light beam will fall exactly on the origin of photodiode, before scanning process starts. Besides, the focusing lens of laser helps to adjust the narrowness of light beam. Light beam with narrower size appears to be more focused and thus it is helpful to distinguish the measurement on photodiode and then improve accuracy of results. Figure 2.5 shows a laser pointer and the reflected laser light on mirror in the experiment of project.



Figure 2.5 A Laser Pointer and Laser Light on Mirror

2.2.4 XYZ Scanner Body (Stage)

XYZ scanner body acts as a platform, to hold the samples tightly and to enable stage movement in X, Y and Z directions. Performance of XYZ scanner body is evaluated based on its scanning speed and precise movement.

XY direction scanner movement enables every pixels of sample to be scanned thoroughly, in a very small scale. Based on the different pixel height of the sample, they give different laser light deflection on detector and results will be sent and processed by central control unit to identify the exact height of pixels and eventually to figure out the surface shape of sample.

On the other hand, Z direction scanner movement is actually a feedback response from data processor. It will keep on changing the height of the stage until the deflection of cantilever is restored. Z-direction scanner movement will only happen in Constant Deflection scanning mode, but not Constant Height which does not require any feedback response.

In this project, the Piezoelectric Ceramic Buzzers, as shown in Figure 2.6, are used to generate the small-scale movement of stage, in XYZ direction. Software LABVIEW and its hardware NI ELVIS board act as a data processor unit for data handling in order to supply desirable amount of voltage to Piezoelectric Ceramic Buzzer, during stage height adjustment and movement. In Figure 2.7, XYZ scanner body is constructed by using bottle of Vitagen and Yakult in consideration of their material characteristics which are lightweight and low-cost(Teh, n.d.). Buzzers are attached on their bodies to enable the vertical and horizontal stage movement.

Apart from that, LEGO bricks are used to construct a strong wall of stage to hold the buzzer and XYZ scanner, as shown in Figure 2.7. LEGO bricks have different kind of shape, with the same standard size dimensions. In view of this, a firm and strong LEGO-structure stage wall can be built in desirable shape. Another credit to the use of LEGO is, it is cheap and the stage model can be demolished and re-built easily(Kang, n.d.).

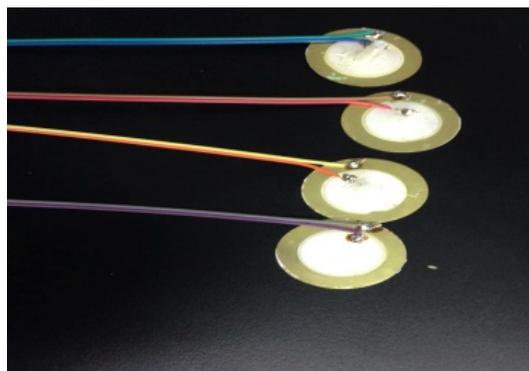


Figure 2.6 Piezoelectric Ceramic Buzzer Elements with Wire Leads

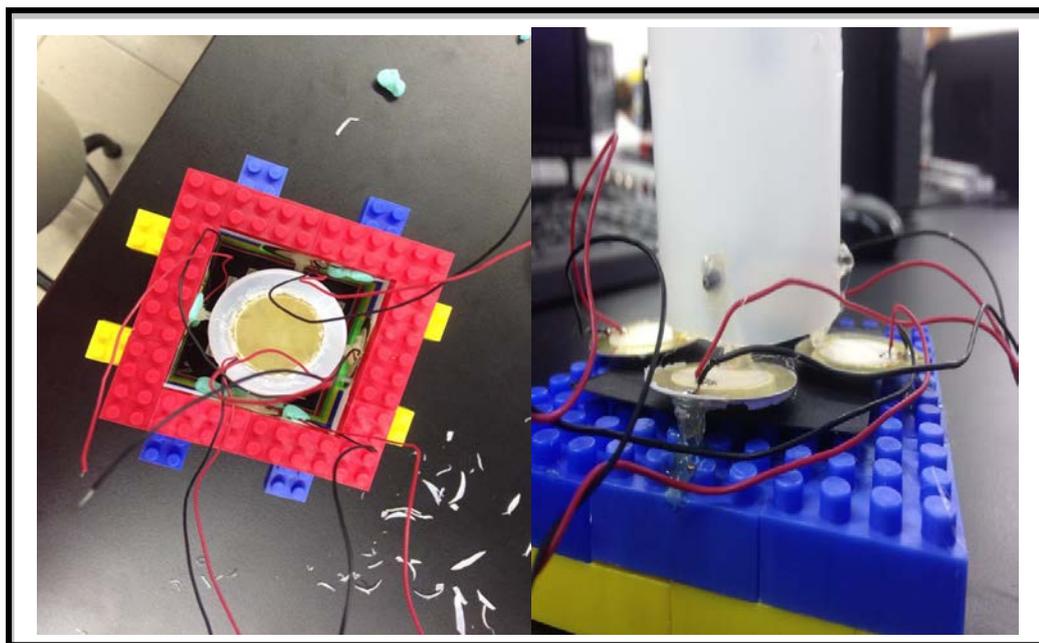


Figure 2.7 Customized XYZ Scanner Body

2.2.5 Photodiode Light Detector Circuit

Photodiode Light Detector Circuit which consists of pre-amplifier circuit and buffers plays an important role in data collection from photodiode. It is normally connected to the pin of photodiode, to obtain outputs from photodiode and process it. In fact, the output from photodiode is current, not voltage. Hence, pre-amplifier circuit is needed to convert the output current from photodiode into input voltage which will then be fed into central control unit (LABVIEW) through NI ELVIS board. Buffers are connected after the pre-amplifier circuit to prevent the next circuit from loading to the previous circuit unacceptably and disrupting the circuit normal operation(Phoong, n.d.).

Therefore, pre-amplifier circuit and buffers are soldered onto a Printed Circuit Board (PCB). There are two LM324 Op-amp, four 10 k Ω resistors, four 10 pF capacitors are needed to build a Photodiode Light Detector Circuit. PCB is then connected to the photodiode and attached on the LEGO wall of stage. Figure 2.8 shows that the Photodiode Light Detector Circuit is constructed on PCB.

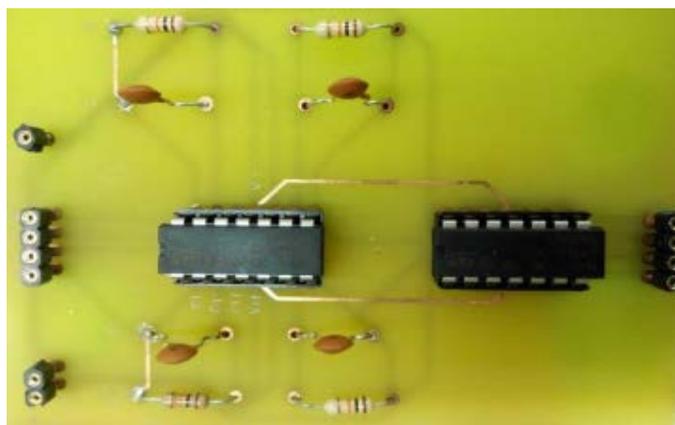


Figure 2.8 PCB of Photodiode Light Detector Circuit

2.2.6 LM741 Operational Amplifier (Op-amp)

The movement of a stage is achieved by Piezoelectric Ceramic Buzzer which works well above ± 20 V. However, the maximum voltage can be supplied by NI ELVIS board is ± 10 V. Therefore, LM741 Op-amp is used to amplify the voltage gained from NI ELVIS board in order to supply sufficient voltage to buzzers. In Figure 2.9, two LM741 Op-amp and four resistors are soldered on a Printed Circuit Board (PCB) to achieve the goal of voltage amplification (Kang, n.d.).

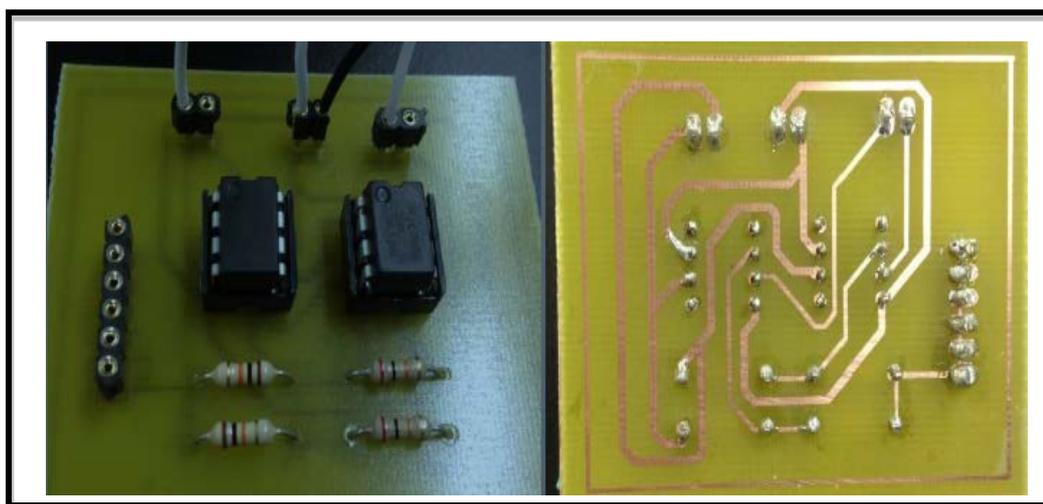


Figure 2.9 PCB of LM741 Operational Amplifier

2.3 LABVIEW Software and Instrument

Laboratory Virtual Instrument Engineering Workbench, which is also known as LABVIEW, becomes the main software used in my project, AFM scanning mechanism. LABVIEW provides a platform to build virtual instrumentation and take an effective graphical system design approach that can effectively leverage the work of modern academic research and development (Ni.com, 2013). It introduces a new kind of programming language, called 'G' or data-flow, which is using graphical method to develop the algorithm, instead of text-based programming language.

LABVIEW possesses a great variety of benefits. The unique G programming language of LABVIEW allows user to quickly tie together data acquisition, analysis and logical operations understanding how data is being modified. It offers a great variety of libraries with different kinds of functions. Therefore, some basic functional algorithm can be included or applied directly in the project. Instead of just having block diagram in the program development platform, LABVIEW has an associated front panel which allows user interface, with generic controls and indicators. Besides, LABVIEW supports interfacing devices like writing direct bus (GPIB, Serial, USB) to enable native control of the devices. Apart from that, it can perform in variety of operating system (MAC OS, Linux) and always adopt advances in personal and embedded computing to implement emerging technology. The programs build in LABVIEW can be conducted in parallel and this allows user to carry out multitask in program. In a nutshell, as shown in Figure 2.10, LABVIEW illustrates numerous advantages and therefore it becomes the main tool used in program development of my project. Also, LABVIEW is normally aimed for data acquisition and instrument control, together with NI ELVIS board which is shown in Figure 2.11.

There are a total of three parts of LABVIEW-based programming algorithms: XY Direction Controller Unit, Z Direction Controller Unit and Data Collection Unit. Three control units are developed by seniors individually, in term of software LABVIEW and hardware. XY Direction Controller Unit aims to enable scanning on next pixel, in X or Y direction, once the scanning of current pixel is completed. For the Z Direction Controller Unit, PID algorithm is applied for stage height adjustment

in order to resume original deflection level of cantilever. This part is only significant for the Constant Deflection Scanning Mode. Besides, the purpose of Data Collection Unit is to collect the data from photodiode and identify position of reflected laser light on photodiode. Since three units are programmed separately, it is very important for me to understand thoroughly LABVIEW-based algorithms built in three controller units in order to combine them into a well-functioning AFM scanning mechanism.

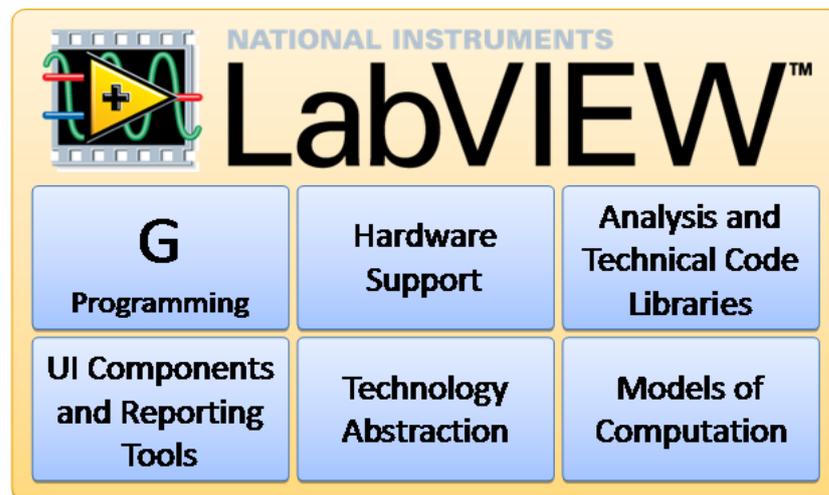


Figure 2.10 Advantages of using LABVIEW (Ni.com, 2013)



Figure 2.11 NI ELVIS Board (Ni.com, 2013)

CHAPTER 3

METHODOLOGY

3.1 Flow Chart of Work

The flow chart shown in Figure 3.1 is the overall procedure for completing my Final Year Project (FYP), within two semesters (28 weeks). Further details will be discussed in the sub topics in this chapter.

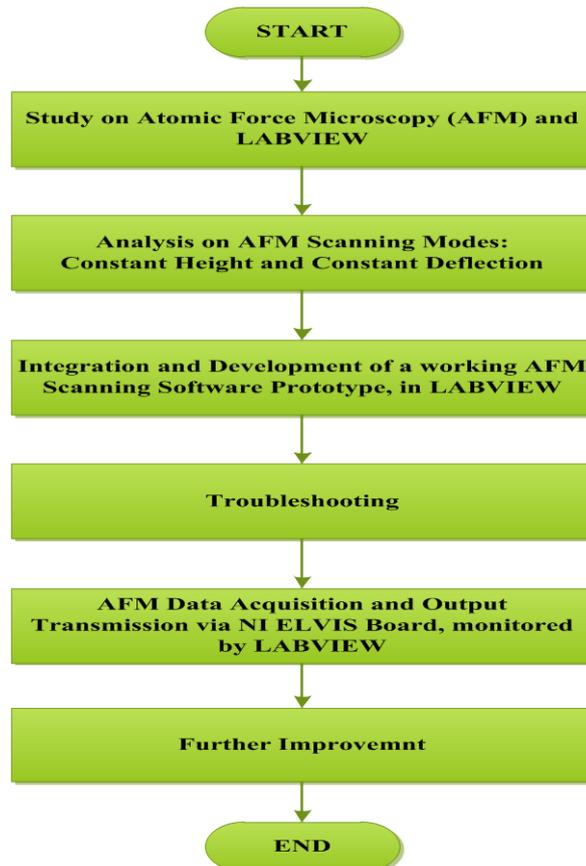


Figure 3.1 Flow Chart of Work

3.2 Timetable and Schedule Estimation

3.2.1 FYP I Progress

Final Year Project (FYP) was conducted in two semesters. FYP I started from June 2015 to September 2015 and the progress is shown in the Table 3.1.

Table 3.1 FYP I Progress

WEEK	PROGRESS		
1	FYP Title Selection and Confirmation		
2	Literature Review	AFM Working Algorithm, Scanning Modes	Keep track on seniors' on going AFM Project
3			
4			
5		LABVIEW Training Part 1	
6			
7			
8		LABVIEW Training Part 2	
9			
10	Analysis on finalised Hardware and Software of AFM Mechanism		
11	FYP I Report and Presentation Preparation		
12			
13			
14	FYP I Oral Presentation		

3.2.2 FYP II Progress

FYP II started from January 2016 to April 2016 and the progress is shown in the Table 3.2.

Table 3.2 FYP II Progress

WEEK	PROGRESS	
1	Analysis on Seniors' AFM algorithms, in term of LABVIEW	
2	Modification and Enhancement on LABVIEW coding to suite integration	Troubleshooting and Verification of Results through LABVIEW Software Simulation
3		
4	Integration and Development of AFM Scanning Mechanism, in LABVIEW	
5		
6		
7		
8		
9	Integration and Testing with NI ELVIS board	
10	Further Improvement	
11	FYP II Poster and Report Preparation	FYP II Presentation and Demonstration Preparation
12	FYP II Poster and Report Preparation Submission	
13	FYP II Poster Presentation	
14	FYP II Presentation	

3.3 Detail of Procedure

In this project, basically the customized AFM scanning mechanism is formed by three parts: XY Direction Controller Unit, Z Direction Controller Unit and Data Collection Unit. Every part involves hardware and software, and was accomplished separately. Therefore, it is important to understand thoroughly about their software's and hardware's underlying logic flow in order to produce the desirable deliverables easily, as shown in Figure 3.2. All of the details and outcomes about controller units will be discussed in the following sub topics.

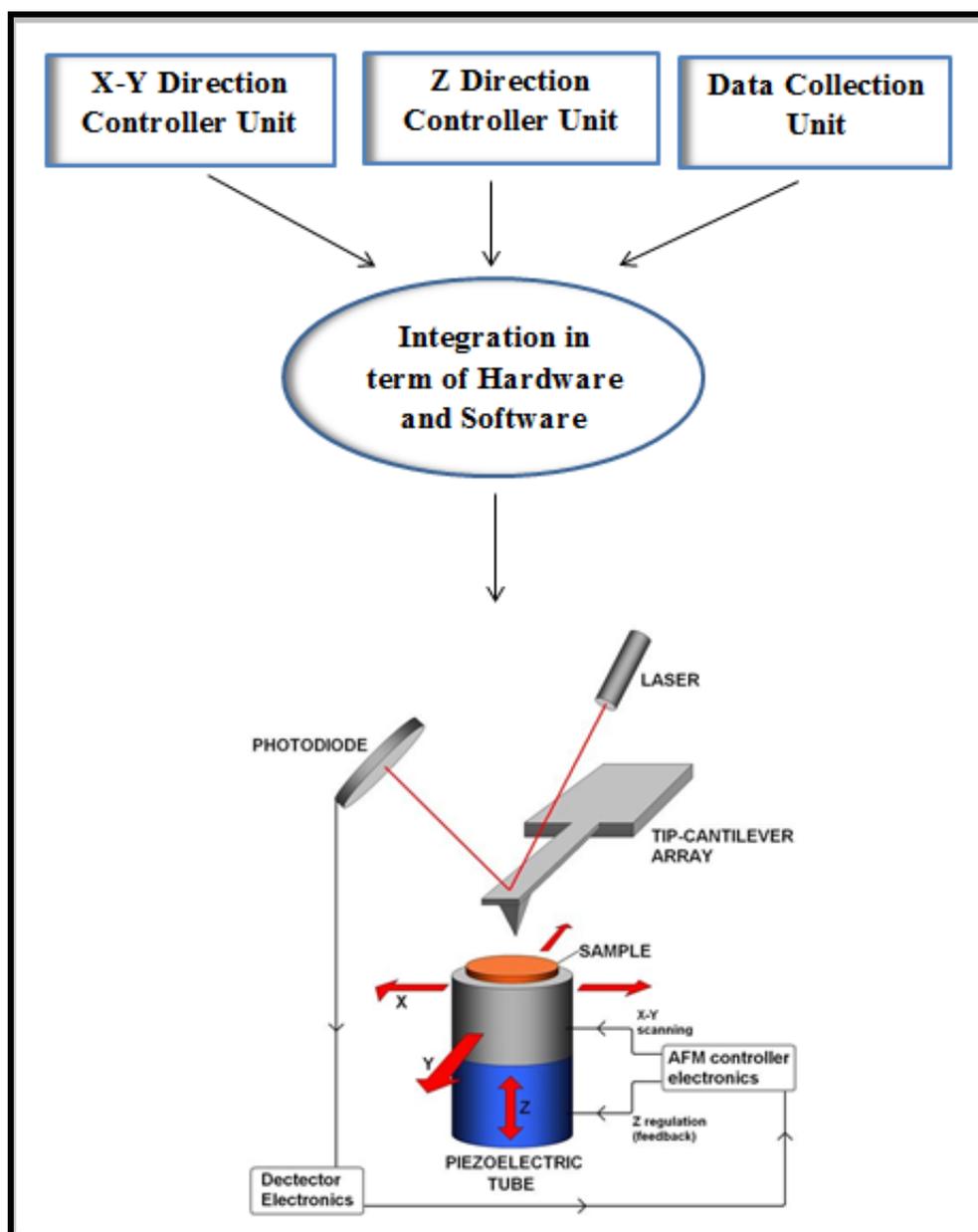


Figure 3.2 Integration of Works to form an AFM Scanning Tool

3.3.1 XY Direction Controller Unit

In year 2015, Kang (2015) developed a prototype unit that controls XY direction of stage motion. The prototype was constructed to help in horizontal stage movement, in X and Y direction, in order to enable the whole sample surface can be fully scanned by cantilever. LABVIEW will be the main platform for the development of program in this project. Entire running of this controller system will be explained through graphical presentation such as flow chart. Flow chart always gives the best description on how the program runs, from the beginning until the closure of design. Therefore, by using Graphical Programming Language, idea explained in flow chart will be transformed to a graphical system design approach in block diagram of LABVIEW, as shown in Figure 3.3.

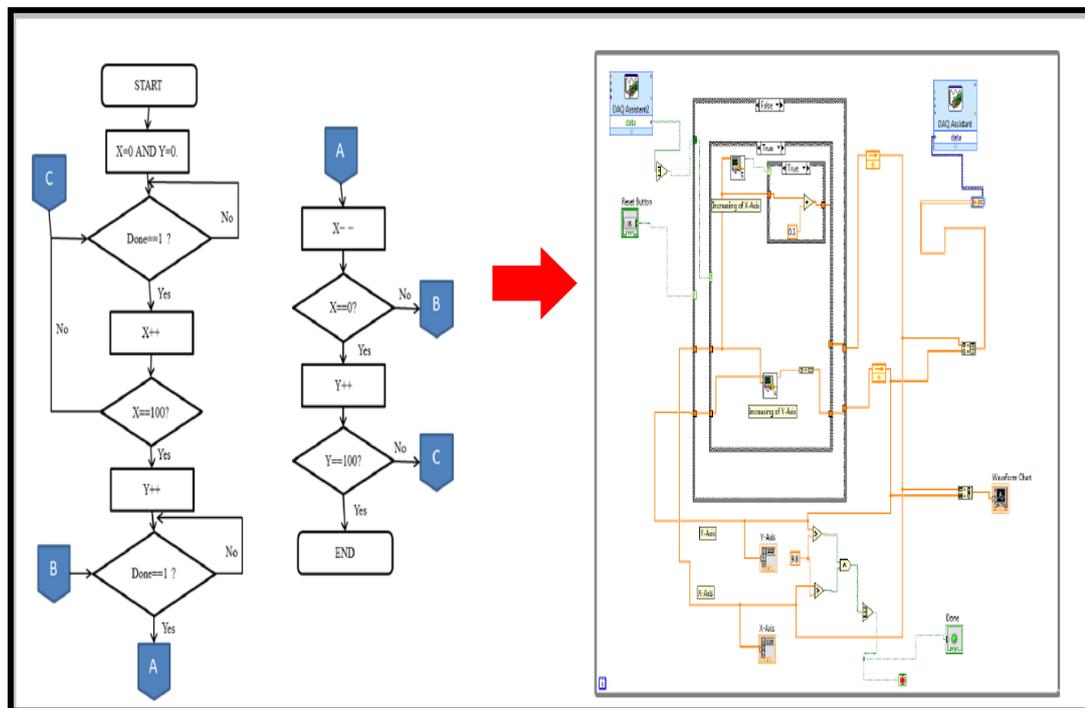


Figure 3.3 XY Direction Controller Unit (Kang, 2015)

Algorithms developed for XY direction stage movement is very simple. Assume that a sample is divided into many smaller scales, called pixels. Sample scanning starts from the pixel located on coordinate (0,0). Once the current pixel is scanned completely, XY Direction Controller Unit in LABVIEW will receive an enabling input command to perform movement to next neighbouring pixel. System will send corresponding voltages to Piezoelectric Ceramic Buzzer to either expand or contract in order to move to next pixel. Left-to-right and right-to-left of stage movement in the X direction will be implemented alternately to perform row scanning. On the other hand, Y direction movement will only happen once the probe of cantilever reaches the last pixel of the row of sample. The scanning flow of sample is illustrated in the Figure 3.4.

In this program, the sample size is divided into 200 x 200 pixel and X/ Y axis output is initialised as -9.9V. 10 V is not used in this case as it will rise to 10.02 V which is forbidden in LABVIEW system, when reset button is pushed. In X axis stage motion, increment of 0.1 V will be given for right movement while decrement of 0.1 V for left movement, responding to every rise of enabling command input. Voltages supplied to Piezoelectric Ceramic Buzzers are gained from analogue output channels of NI ELVIS board, under the LABVIEW monitoring system. Scanning process is allowed to continue until the last pixel of the sample is scanned completely.

For the hardware part, the XY stage is kinematically mated to Piezoelectric Ceramic Buzzer. XY stage is used for positioning the cantilever over a desired location of sample and buzzers are in charge with its raster scanning motion. Intensity level of contraction or expansion for buzzers relies on how much voltages are applied by NI ELVIS board, responding to command from LABVIEW. The maximum output voltage of NI ELVIS board is $\pm 10V$. However, buzzers need voltage up to 20 V only can start to function well. In view of this, a LM741 Operational Amplifier is used together with NI ELVIS board to amplify the output voltages, up to three times. Besides, due to the unstable and less firm of the framework of XY scanner, different versions of the external skeleton of the sample stage are designed. The final version of external skeleton of the sample stage is shown in Figure 3.5.

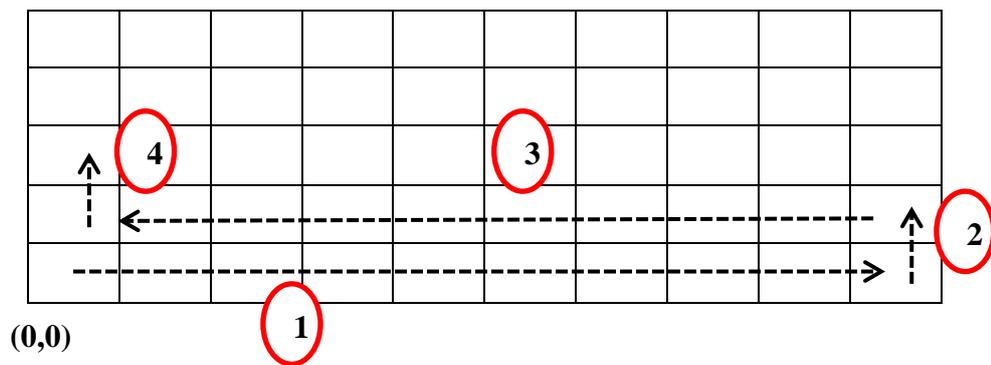


Figure 3.4 Flow of Pixel Scanning

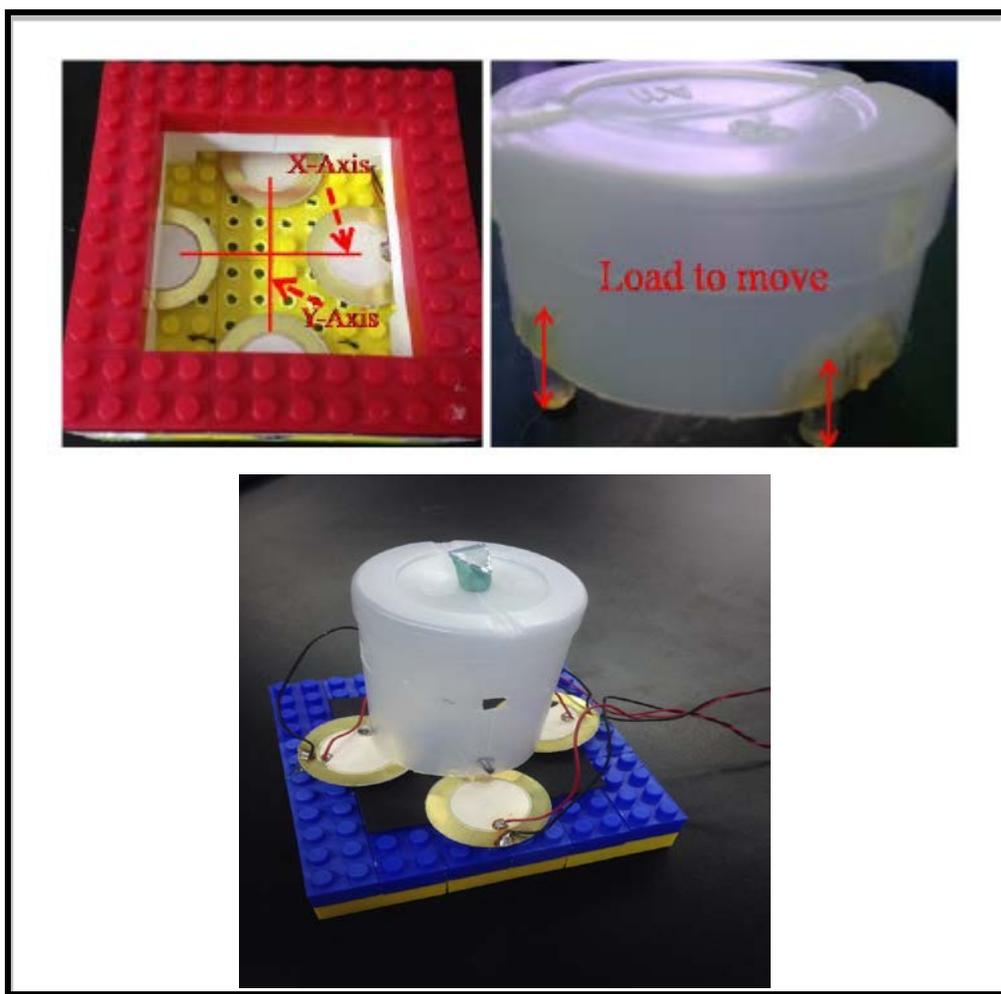


Figure 3.5 Final Version of Framework for Sample Stage (Kang, 2015)

3.3.2 Z Direction Controller Unit

In year 2015, Teh (2015) built a prototype unit that controls Z direction of stage motion. The main function of the prototype is to perform Z direction stage motion for restoration of original cantilever's deflection, through PID implementation. Signals received from photodiode will be processed and computed by this unit in order to send out a voltage which can adjust stage height that resumes pre-set deflection level of cantilever, after several time of negative feedback response. Algorithm of PID controller is developed in LABVIEW, as shown in Figure 3.6.

For every AFM pixel scanning, the height of reflected laser light on photodiode will be received and processed by PID algorithm, in Z Direction Controller Unit. PID stands for Proportional Integral Derivative and its main purpose is to calculate error value as difference between a desired set point and a measured process variable continuously. Thus, based on the error value, suitable output response will be given in order to adjust stage height. The stage height will be adjusted continuously until the reflected laser light falling back onto the origin of photodiode. Position restoration of reflected laser light on detector's origin tells that the original cantilever's deflection is resumed. Based on how much stage has been adjusted, the actual height of pixel on that coordinate is identified. It should be noted that, Z Direction Controller Unit is only important to Constant Deflection scanning mode. A functioning PID control loop feedback mechanism is constructed in LABVIEW. There are various kinds of PID algorithm implementations, such as classical notation, Laplace notation and simple numeric. However, after several troubleshooting in software simulation, implementation of PID algorithm digitally is chosen as the best PID mechanism to control stage height adjustment.

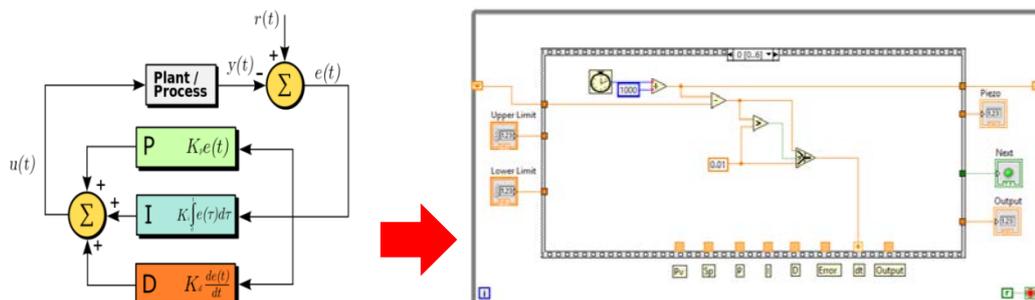


Figure 3.6 Z Direction Controller Unit (Teh, 2015)

For the hardware part of Z Direction Controller Unit, some studies were carried out to find out the characteristics of Piezoelectric Ceramic Buzzers. Analysis on displacement changes of buzzer for different value of voltage supply and characteristic of buzzer expansion/ contraction are critical and helpful in design of framework of sample stage. For example, a total of two Piezoelectric Ceramic Buzzers are needed to achieve desirable displacement changes requirement. In order to improve it, a stack of two Piezoelectric Ceramic Buzzers is put in a certain position such that maximum displacement changes can be achieved and yet it is not overloaded within the range of voltage supply, as shown in Figure 3.7 and Table 3.3. Apart from that, in order to produce low-cost AFM scanning mechanism, bottle of Vitagen and Yakult are chosen to become the sample holder. Figure 3.8 shows that a total of two Piezoelectric Ceramic Buzzers are stacked together and put on the top of drink bottle, to form a scanner body.

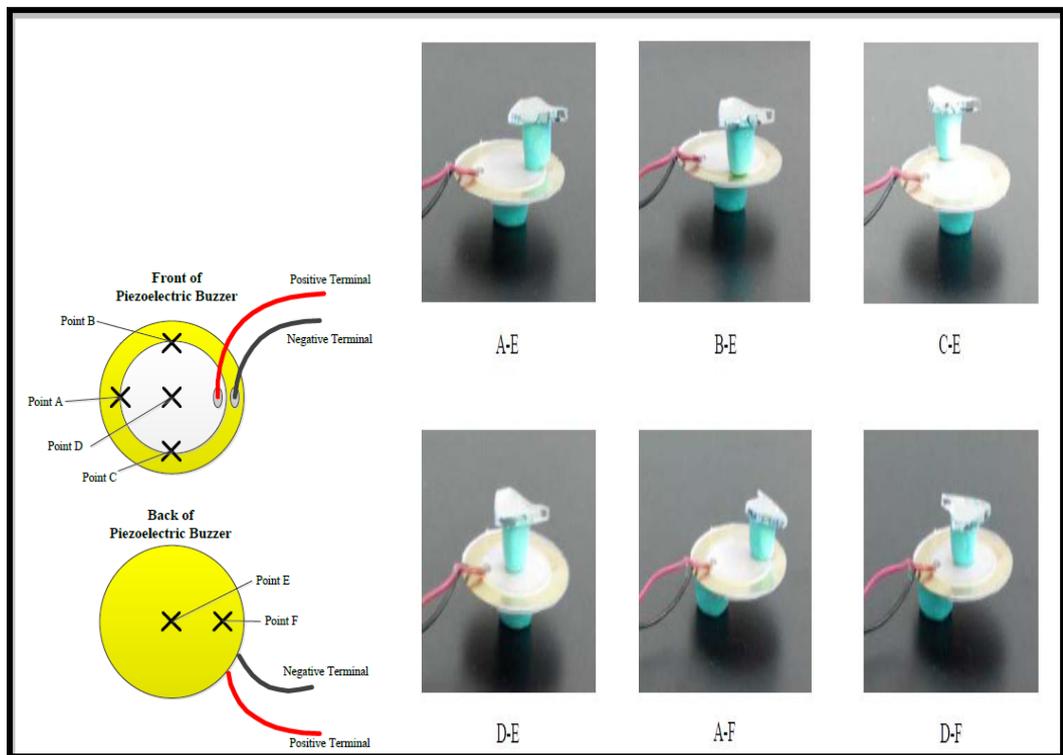


Figure 3.7 Position Combination of Stacked Piezoelectric Ceramic Buzzers

(Teh, 2015)

Table 3.3 Position Combination of Stacked Piezoelectric Ceramic Buzzers and Reviews (Teh, 2015)

Position Combination	Review (Laser position)
A-E	Move vertically
B-E	Move diagonally
C-E	Move vertically but less changes
D-E	Move diagonally
A-F	Move vertically with largest changes
B-F	Move diagonally
C-F	Move vertically
D-F	Move diagonally



Figure 3.8 XYZ Scanner Body with Piezoelectric Ceramic Buzzers (Teh, 2015)

3.3.3 Data Collection Unit

Phoong (2015) constructed a prototype unit that involves in data collection from photodiode. Data Collection Unit is responsible to collect data from photodiode, process and transmit them to the Z Direction Controller Unit. This unit plays an important role to identify the position of reflected laser light beam on photodiode and thus further processing steps will be carried out to determine the actual height of pixels on sample surface.

Same as previous unit, Data Collection Unit is developed in the LABVIEW system platform, as shown in Figure 3.9. Four quadrant photodiode is used and the response of reverse current is proportional to luminance when light beam from laser is reflected on the junction of photodiode. A total of four signal responses will be transmitted out from each quadrant of photodiode. Algorithm, which detects new position of reflected laser light in response to four photodiode outputs, will be constructed in this unit, in term of G-programming language. The Data Collection Unit computes the incoming data and sends the corresponding outputs (position of reflected light) to Z Direction Controller Unit for further coordination. Incoming data reaches in a very fast moment and thus around twenty data will be collected within one second. Data are stored in an array table and updated frequently in LABVIEW.

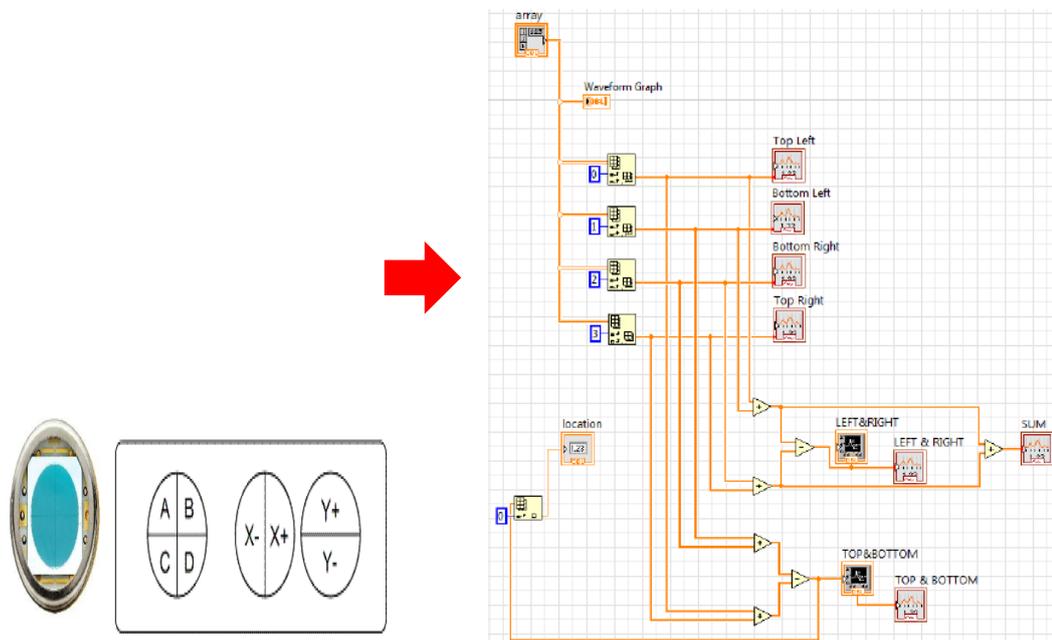


Figure 3.9 Data Collection Unit (Phoong, 2015)

In fact, signals coming out from photodiode are fed into two circuits before reaching to NI ELVIS board: Photodiode Light Detector and Buffer. As mentioned in the previous chapter, they help to convert current into voltage and prevent next circuit from loading previous ones to forbidden circuit disruption respectively. Both circuits are constructed in a PCB and attached nearby the photodiode on the stage, to ease for signals receiving. Figure 3.10 demonstrates the overall configuration of AFM and its components.

Furthermore, an experiment was conducted by Kang (2015) and Teh (2015) to investigate the relationship between displacement changes of Piezoelectric Ceramic Buzzer and laser position changes, as shown in Figure 3.11. It was observed that, by applying Trigonometric method, their relationship can be expressed by:

$$\Delta P = \frac{\Delta L}{2} \quad (3.1)$$

where

ΔP = displacement change of Piezoelectric Ceramic Buzzer

ΔL = change of laser position

Figure 3.12 explains Trigonometric calculation for buzzer displacement. Assumptions such as laser light is emitted in an angle 45° to sample surface, stage is lifted horizontally and no hysteresis are made in ideal case. The Trigonometric calculation is helpful in the LABVIEW software simulation of results, in either Constant Height or Constant Deflection AFM scanning mode.

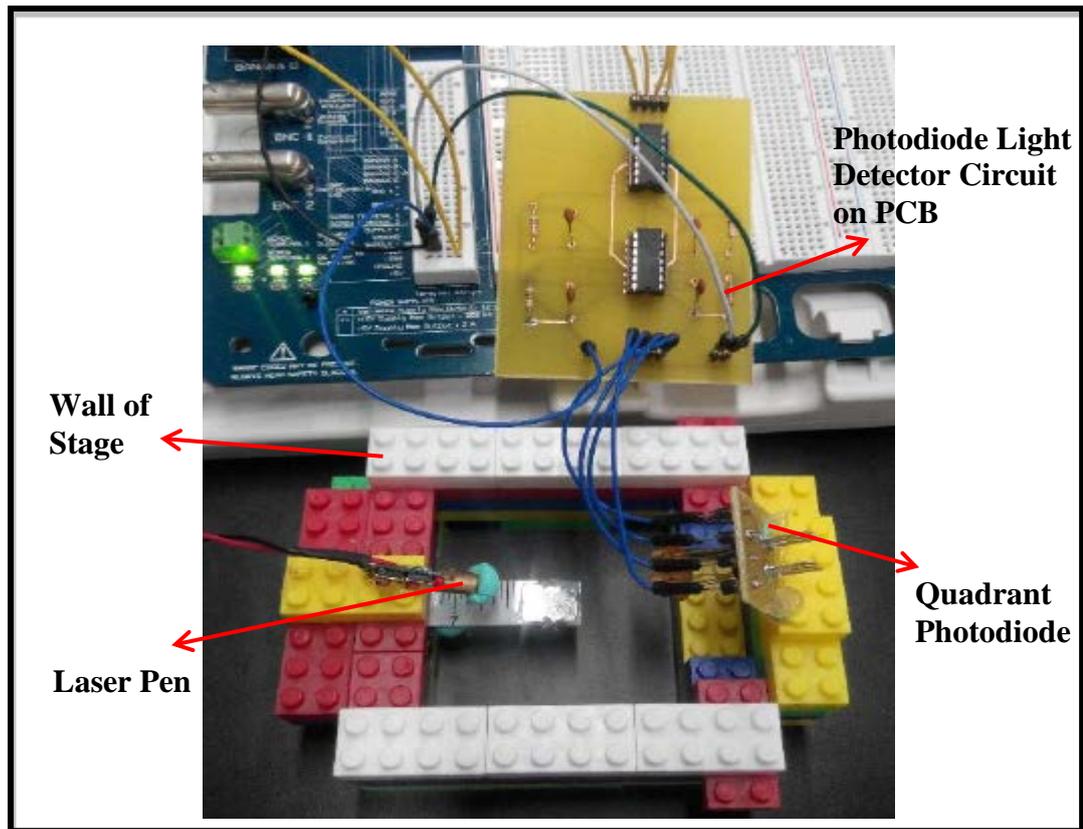


Figure 3.10 PCB of Photodiode Light Detector Circuit (Phoong, 2015)

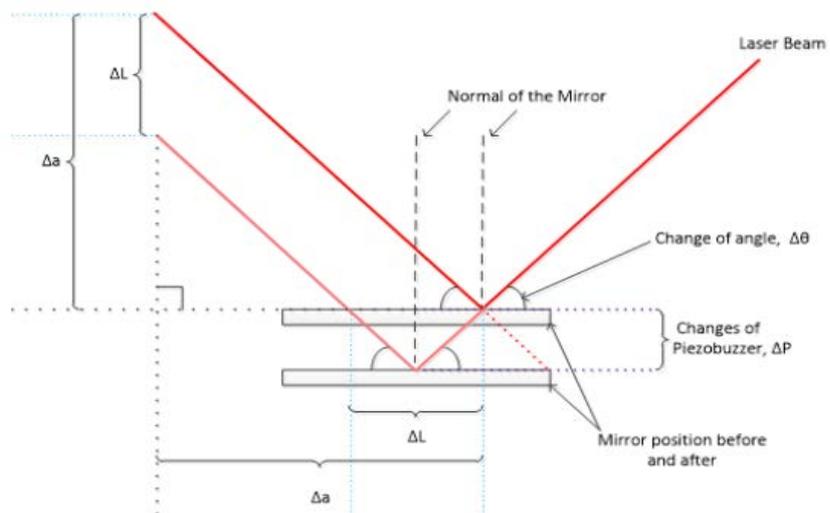


Figure 3.11 Calculation of Buzzer Displacement Changes in Ideal Case (Teh, 2015)

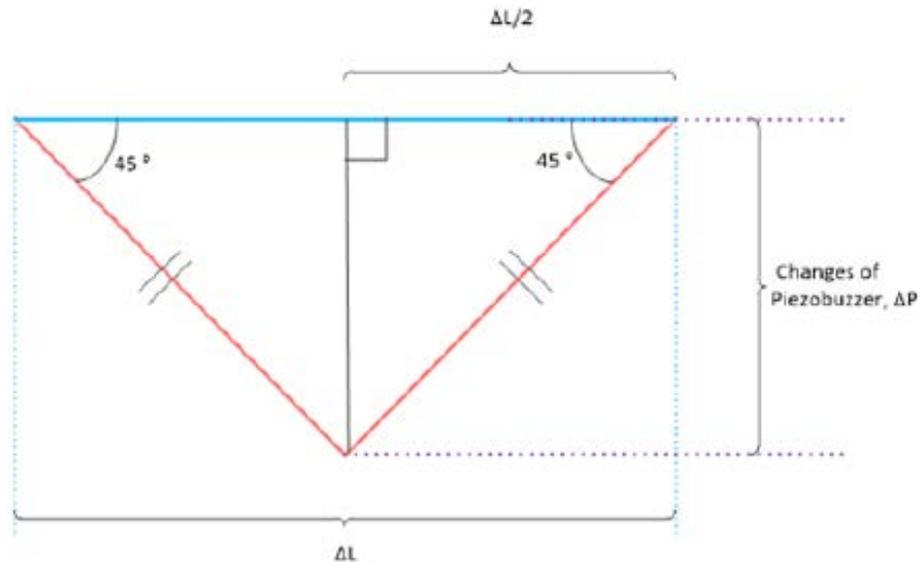


Figure 3.12 Trigonometric Calculation for Buzzer Displacement (Teh, 2015)

3.4 Integration of Controller Units involved in AFM Scanning

The simple flow of Atomic Force Microscopy (AFM) scanning process in this project is illustrated in Figure 3.13. When the tip of cantilever is scanning on a pixel of sample, pixel height causes the cantilever to deflect and reflected laser light falling out of origin of photodiode. Results on photodiode will be sent to Data Collection Unit, through Photodiode Light Detector circuit, to determine the current position of reflected laser light and pass it to Z Direction Controller Unit. In this unit, comparison between current position of laser light and set point will be carried out in order to send out a corresponding output voltage to Piezoelectric Ceramic Buzzers, for stage height adjustment. This process will be repeated until the stage is adjusted in such a height that the reflected laser light falls exactly on the photodiode origin. Then it enables XY Direction Controller Unit to move to the next pixel of sample for a new AFM scanning process. All the data will be collected and recorded, in order to draw a 3D view of sample. Also, this kind of scanning flow is only for Constant Deflection mode of AFM, but not for Constant Height. They use two different algorithms in LABVIEW to define pixel height.

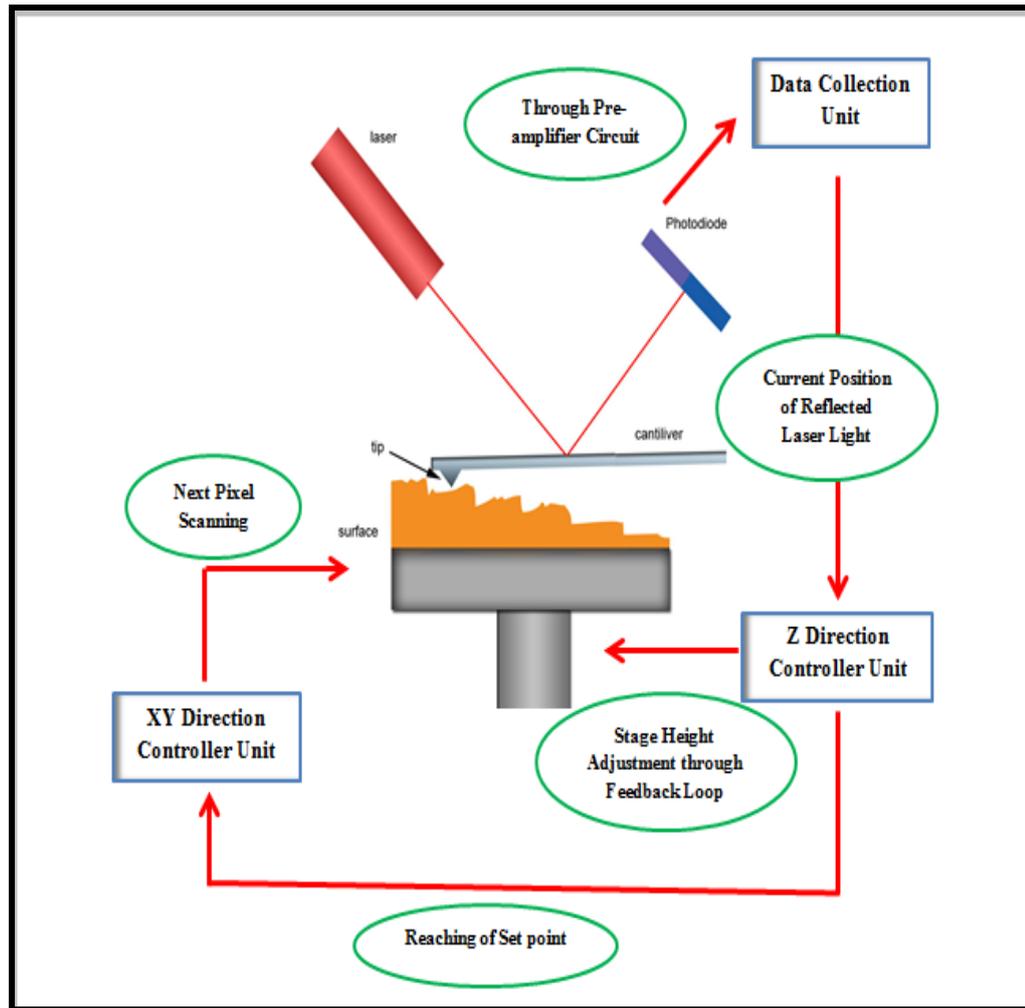


Figure 3.13 Flow of the AFM Scanning Process

3.5 Issues existing in the Integration of Controller Units and Solutions

Even though software LABVIEW and hardware of the three Controller Units are completely constructed and ready for integration, there are a few problems found and therefore solutions must be prepared before starting software and hardware integration of the AFM scanning mechanism.

First of all, hysteresis phenomena exist in most of the hardware components and thus there is no exception in this case. Hysteresis causes movement of scanner fail to follow the same displacement when moving forth and back. In view of this, investigations and experiments about hysteresis of buzzer were carried out and

sigmoid equation regarding to sample hysteresis curve was found. However, problem still exists as different buzzers will have their own specific hysteresis curve and thus the experimental data are used for reference only. Apart from that, the final version of external skeleton of the sample stage for XY direction movement is not working well and not running smoothly for every time. Its external structure is not firm and if it tries to combine with other skeleton structure, it might collapse due to overload.

For the LABVIEW program part, some logical errors which make the program fail to achieve desirable specifications are detected. For example, logical errors happen in the LABVIEW algorithm of XY Direction Movement Unit as program skips the first row scanning and jumps to the second row. Also, PID algorithm will work stably after several times of program running and this is less preferred in program running, especially real-time AFM scanning mechanism. Furthermore, program seems to be lagging in algorithm of Data Collection Unit. This might be caused by the program is overloaded by huge amount of information and simultaneous running of sub modules in LABVIEW.

As a result, for the problems of hardware part, after a few discussion and considerations, decision was made that, the low-cost customized AFM scanner will be excluded in the integration. Another word, only software integration of AFM scanning will be implemented in this project. However, NI ELVIS board will involve in software simulation, to receive external user-defined inputs and give outputs, under the coordination of LABVIEW. Troubleshooting and testing of every LABVIEW sub modules will be done in order to solve the logical errors of program. Program lagging can be eliminated by removing the unnecessary and duplicated algorithms in LABVIEW, such as laser control and data viewer, in order to speed up the program running. The modified and enhanced version of LABVIEW will be shown and discussed in Chapter 4.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Development of Sub VIs in LABVIEW for Atomic Force Microscopy (AFM) Scanning Design

Atomic Force Microscopy (AFM) scanning program can be designed and implemented in the LABVIEW development environment, by using G-Programming Language. In this project, a well-developed AFM algorithm is built, with the combination of six sub modules (Sub VIs): X-axis, Y-axis, Initial Position, Height, PID Algorithm and PID Simulation, as shown in Figure 4.1. Each Sub VIs has its unique and specific task to be performed in the system. Three main benefits to using Sub VI within a Main VI are: modularity (large program is divided into a set of small program), reusability (a sequence of instructions is written for once) and validation (coding verification as expected).

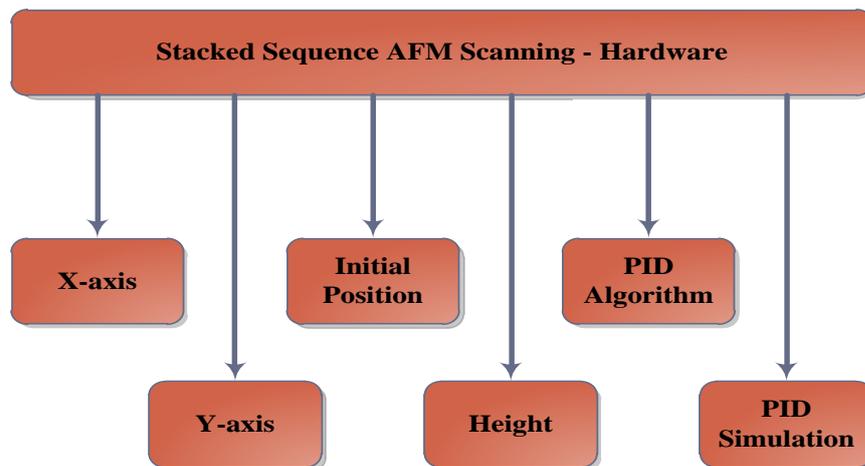


Figure 4.1 Main VI Stacked Sequence AFM Scanning-Hardware and its Sub VIs

4.1.1 Sub VI of X-axis

Sub VI of X-axis functions to monitor the X-axis movement of stage. This module will be included in another sub module, Initial Position, to check and decide horizontal movement of stage during the scanning of sample surface. Figure 4.2 and Figure 4.3 refer to the Sub VI of X-axis in LABVIEW and its flow chart respectively.

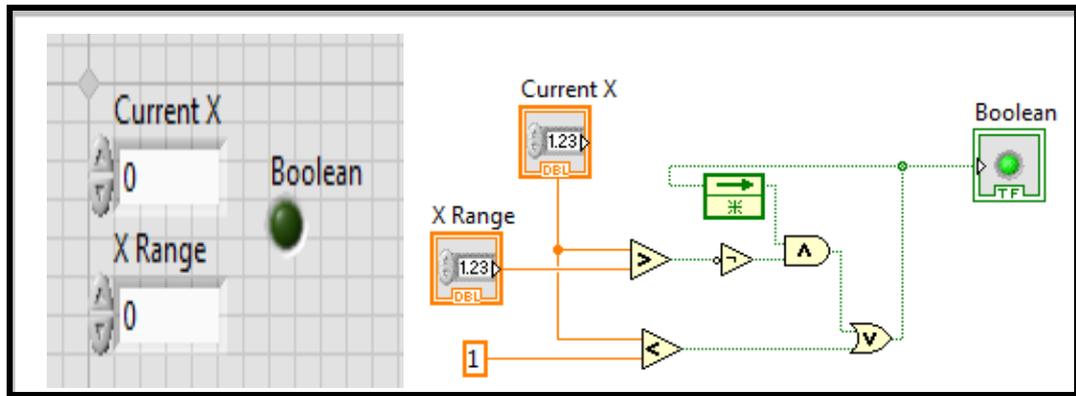


Figure 4.2 Front Panel and Block Diagram of X-axis

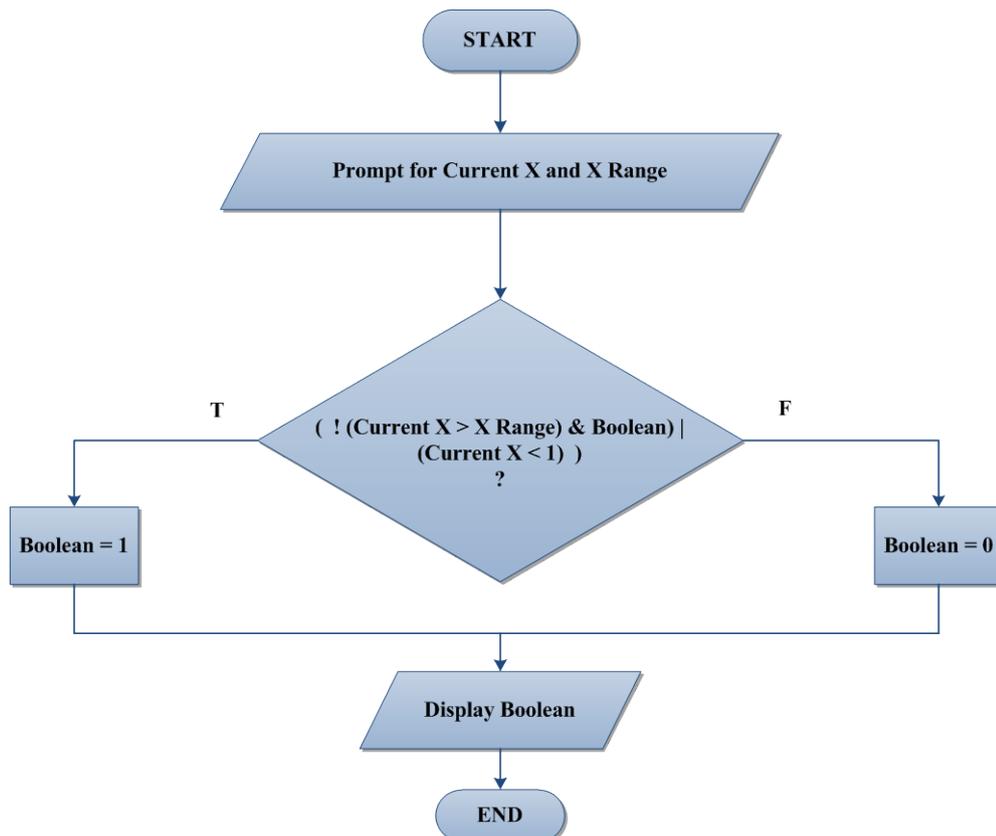


Figure 4.3 Flow chart of X-axis

When this Sub VI is triggered, it will ask for the value of Current X and X Range. In LABVIEW, default integer value is 0 while default Boolean is 0 (false). After that, it comes to a decision box which consists of a logical equation. This logical equation helps to determine whether the stage moves to left or right. If the equation is true, Boolean will be equal to 1 (true) which permits right movement of stage, otherwise Boolean will be equal to 0 (false) and left movement of stage will take place. Result of Boolean will become the only output in this Sub VI. It can be noticed that a feedback node coming out from Boolean LED, as shown in Figure 4.2. Based on this, it tells clearly that result of Boolean will be saved and used for next cycle, when the Sub VI is triggered again.

4.1.2 Sub VI of Y-axis

Sub VI of Y-axis contributes for the stage movement in Y direction and it also involves in the Sub VI of Initial Position. LABVIEW-based algorithms of Y-axis and its flow chart are shown in Figure 4.4 and Figure 4.5 respectively.

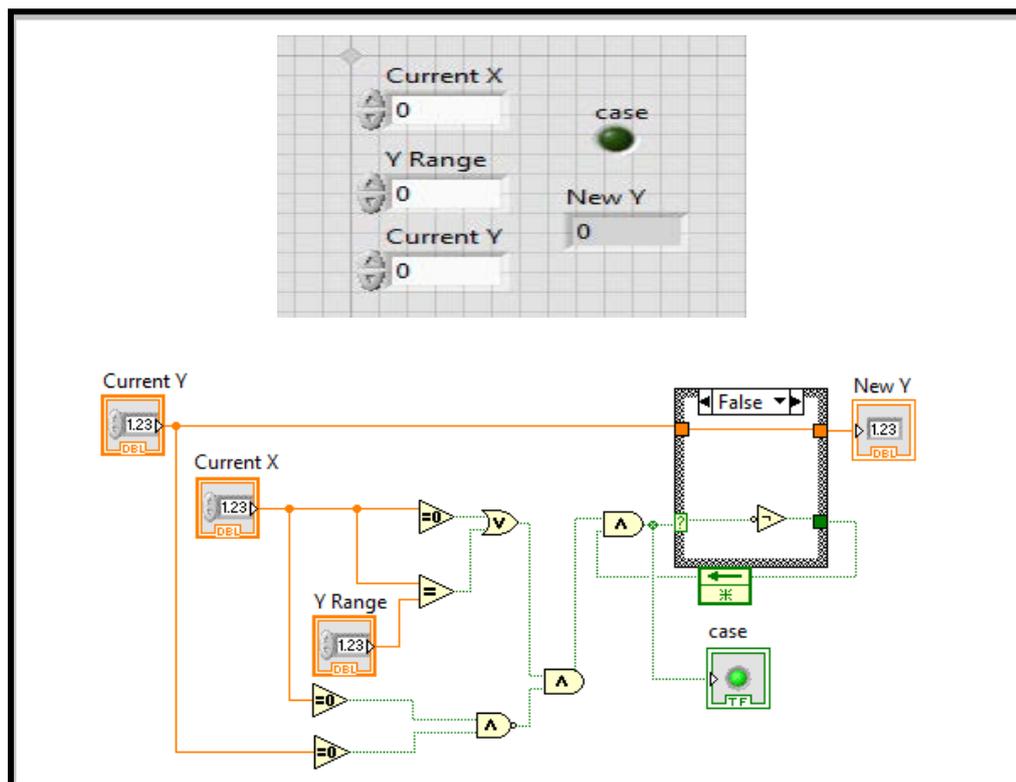


Figure 4.4 Front Panel and Block Diagram of Y-axis

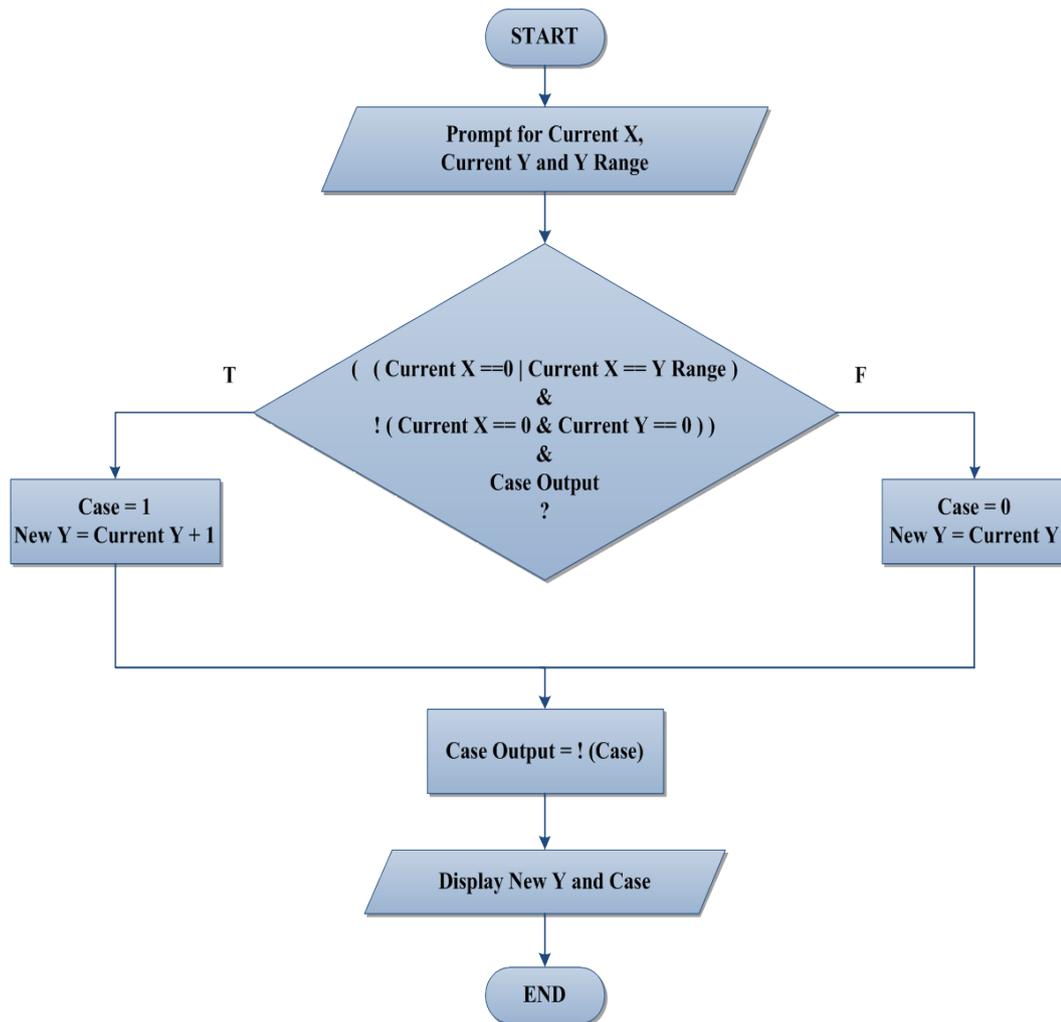


Figure 4.5 Flow chart of Y-axis

It is started by prompting for value of Current X, Current Y and Y Range. A Boolean expression, as shown in decision box in Figure 4.5, is used to control Y-axis movement of stage. If the Boolean statement is true, Case will be 1 and New Y is equal to Current Y + 1. Stage is allowed to move one step up in Y direction. On the other hand, if the statement is false, Case will get 0 and New Y is equal to Current Y. The stage movement in the Y direction is forbidden in this case. Case Output is equal to complement of Case. Result of Case Output will be updated and saved for next cycle of Y-axis VI triggering and this step is very important as it ensures that the Y direction stage movement will not happen consecutively. Result of New Y and Case become the outputs of this part.

4.1.3 Sub VI of Initial Position

Sub VI of Initial Position is in charge with the horizontal stage movement. It will be triggered when the movement of stage to the next pixel is needed. Algorithm of Initial Position is built in LABVIEW, as shown in Figure 4.6. Furthermore, its working flow is explained in flow chart in Figure 4.7.

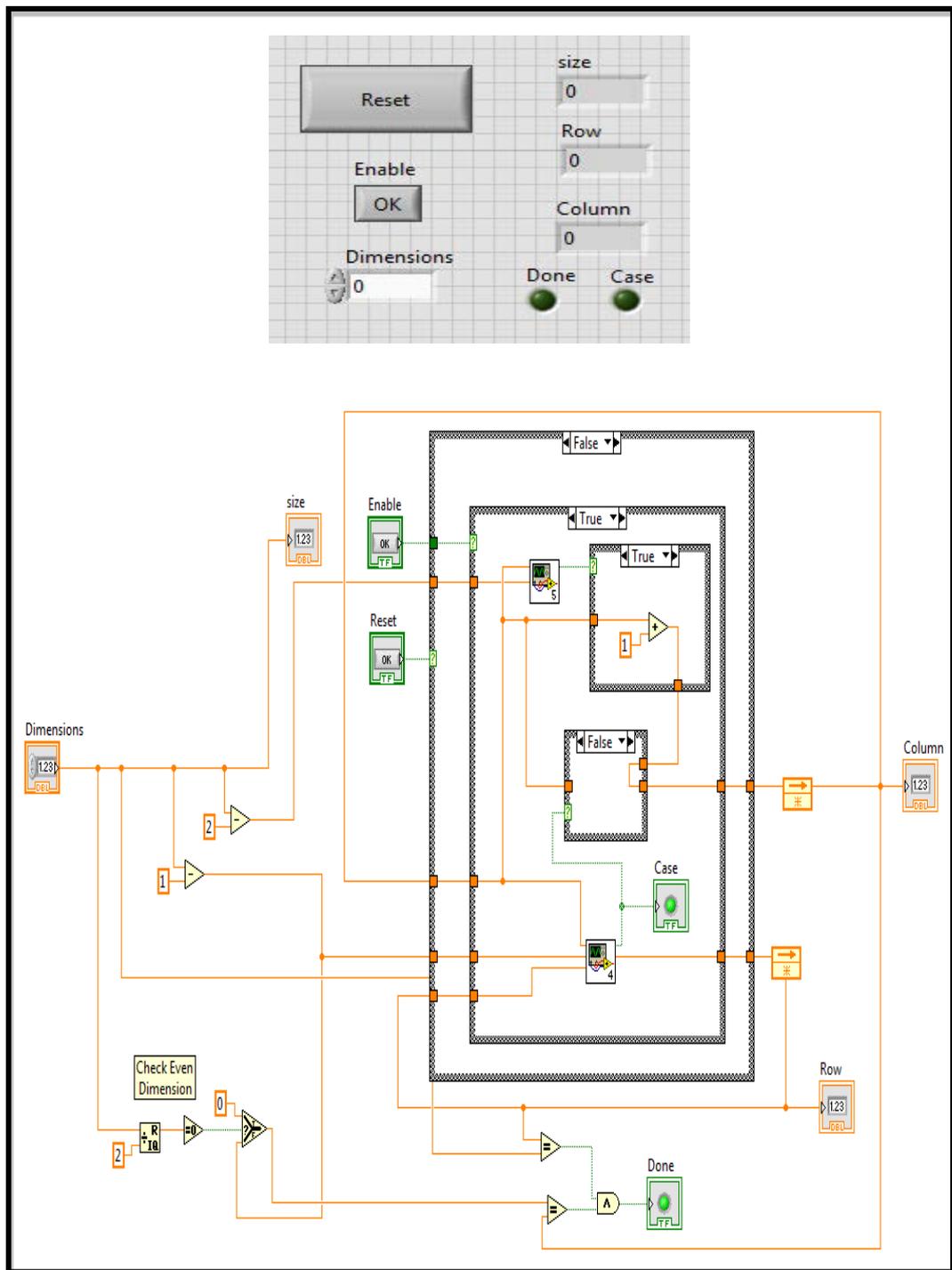


Figure 4.6 Front Panel and Block Diagram of Initial Position

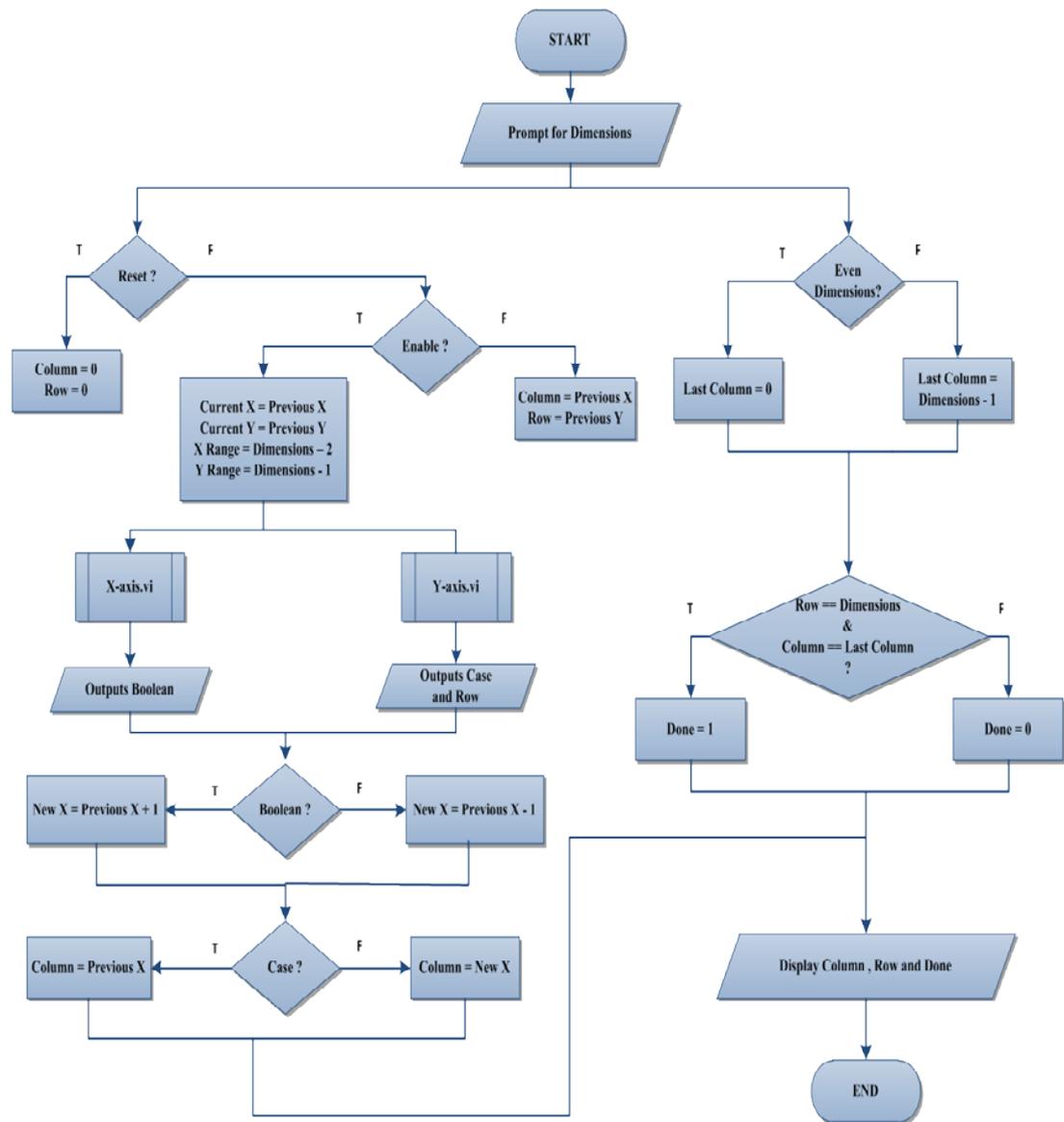


Figure 4.7 Flow chart of Initial Position

First of all, the program will request for Dimensions which represents the scanning pixels per line of sample. After that, there are two different tasks will be carried out simultaneously in this part: one task helps for stage movement in X and Y direction, while another contributes for decision making, either continues or halt of AFM scanning is permitted after this cycle.

In the first task, pushing of Reset button will be examined. If the Reset button is pressed, program will be reset and Column = 0, Row = 0; otherwise it will proceed to next stage, to determine the triggering of Enable button. If Enable button is not

pushed, it means that program is not reset and it hopes the stage to remain at the same position. On the other hand, triggering of Enable button tells that stage movement is required for this round and a series of programmed activities will be initiated. This step is followed by requesting for Current X, Current Y, X Range and Y Range accordingly. Sub VI of X-axis and Y-axis are called to determine Boolean, Case and Row. Boolean and Case are important to decide, whether stage moves to left, right or remain unchanged. Concurrent stage movement in two directions is prohibited in this program. Therefore, stage will remain unchanged in X direction, when it is moving in Y direction.

For the second task, a logical expression is applied to identify whether the Dimensions are even or odd. If it is even, the last pixel should be on $\text{column} = 0$, otherwise $\text{column} = \text{Dimensions} - 1$. Therefore, when the stage reaches last column and last row of sample, Done will be equal to 1 and this causes the scanning process to stop after this cycle. Otherwise, Done will become 0 and scanning process will be carried out continuously. Sub VI of Initial Position will output results of Column, Row and Done.

4.1.4 Sub VI of Height

A series of mathematical equations will be implemented in this part, in order to calculate and obtain the height of reflected laser light on photodiode, based on the voltage intensity gained from the four quadrants. However, it was assumed that roughness of sample surface only causes the reflected laser light to move vertically and it happens in the second quadrant, which is the top left quadrant. Therefore, value of 0 will be assigned to first, third and fourth quadrant. Sub VI of Height in LABVIEW and its flow chart are illustrated in Figure 4.8 and Figure 4.9 respectively.

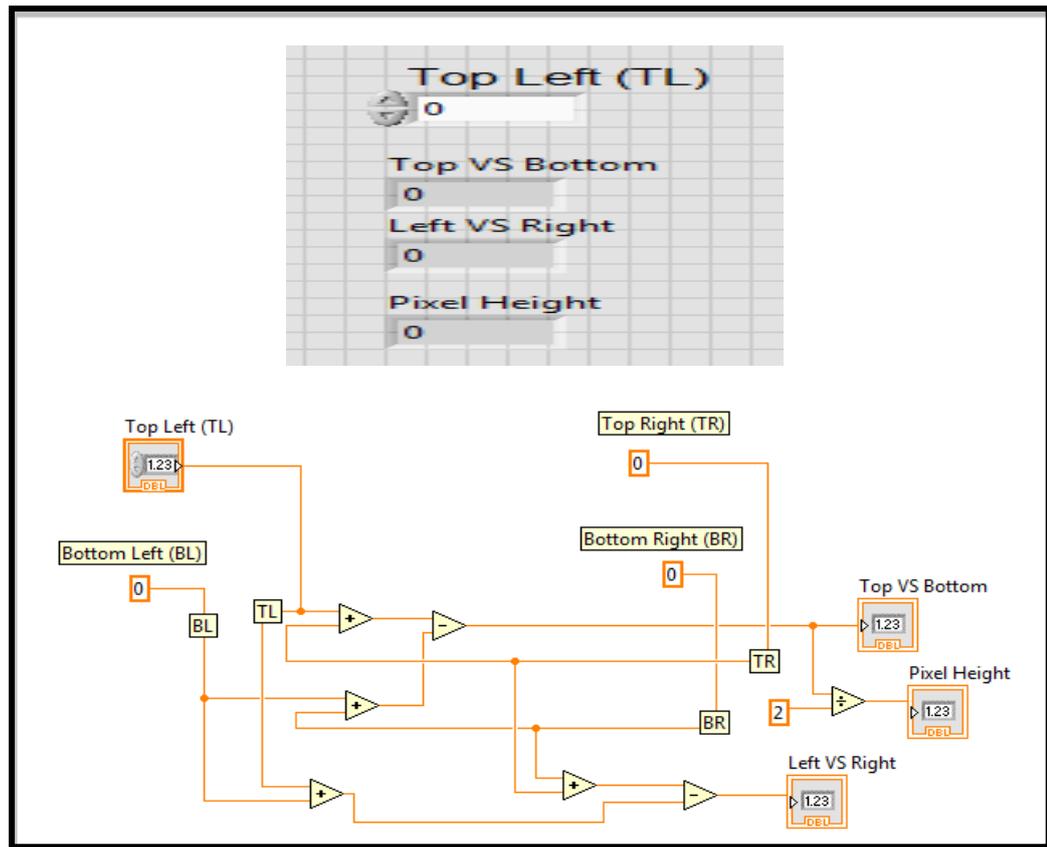


Figure 4.8 Front Panel and Block Diagram of Height

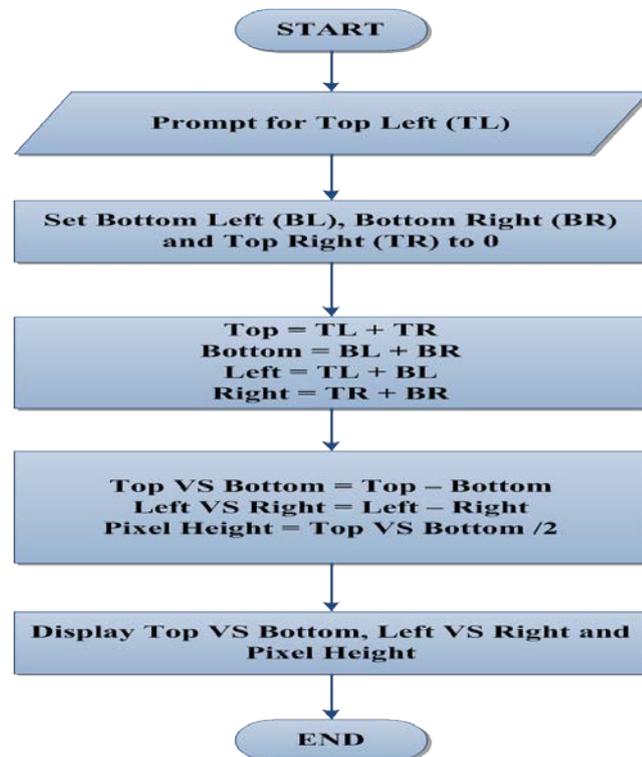


Figure 4.9 Flow chart of Height

Sub VI of Height prompts for value of Top Left (TL) which is resulted by roughness of sample surface on different pixels. Assumption is made that the value of Bottom Left (BL), Bottom Right (BR) and Top Right (TR) is initialised as 0. After that, mathematical equations, as shown in flow chart of Figure 4.9, are carried out to identify value of Top VS Bottom, Left VS Right and Pixel Height. Pixel Height is identified through the Trigonometric calculation, Equation 3.1, in which the half of laser position changes is equal to Piezoelectric Ceramic Buzzer displacement. Result of Top VS Bottom, Left VS Right and Pixel Height will be output at the end of this Sub VI.

In fact, there should be a value obtained from the other three quadrants which are BL, BR and TR as change of reflected laser light's deflection is impossible only happen in one quadrant in real-case of AFM scanning process. Assumption made here is to ease the calculation part.

4.1.5 Sub VI of PID Algorithm

Sub VI of PID Algorithm works as PID controller, according to the basic PID equation:

$$u(t) = Kp e(t) + Ki \int_0^t e(\tau) d\tau + Kd \frac{de(t)}{dt} \quad (4.1)$$

where

Kp = proportional gain

Ki = integral gain

Kd = derivative gain

$e(t)$ = difference between setpoint and process variable

This Sub VI is only useful for the Constant Deflection mode of AFM scanning. It attempts to minimize the difference between origin of photodiode and height of reflected laser light on photodiode over time by adjustment of output

voltage which manipulates stage height continuously. Front Panel and Block Diagram of PID Algorithm are shown in Figure 4.10 and Figure 4.11. Also, flow of program can be figured out by referring to the flow chart in Figure 4.12.

Stacked sequence structure which can consist of more than one sub-diagram, is used for development of PID controller in LABVIEW. In Figure 4.11, PID algorithm is divided into six different stages of implementation and each of them is constructed and arranged sequentially into six different sub-diagrams of stacked sequence structure. It ensures that a sub-diagram is executed before or after another sub-diagram in a correct order.

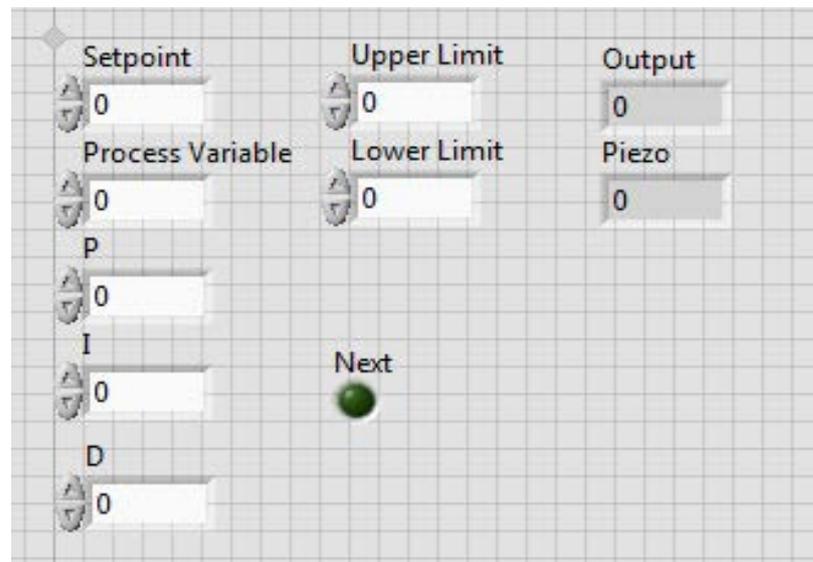


Figure 4.10 Front Panel of PID Algorithm

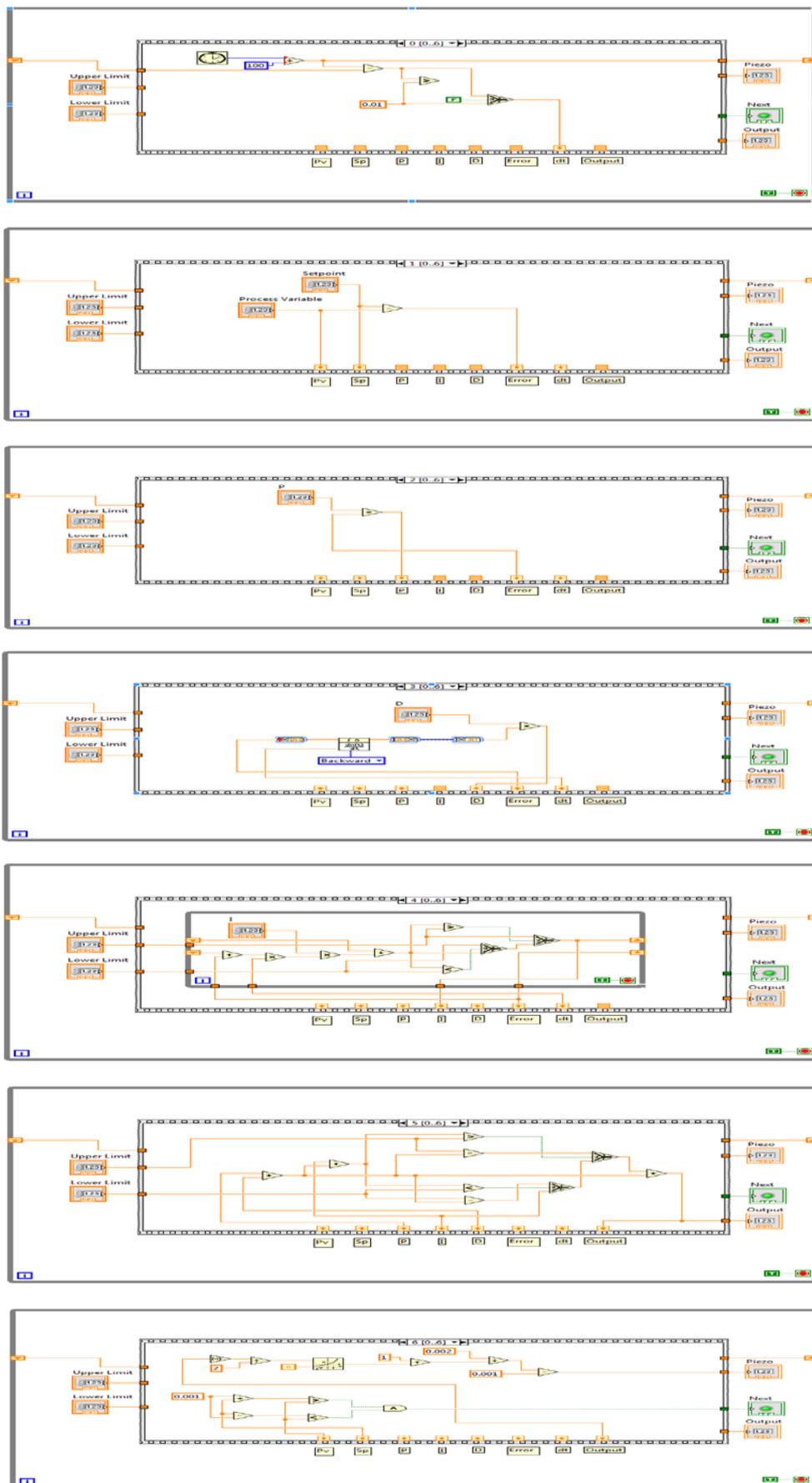


Figure 4.11 Block Diagram of PID Algorithm

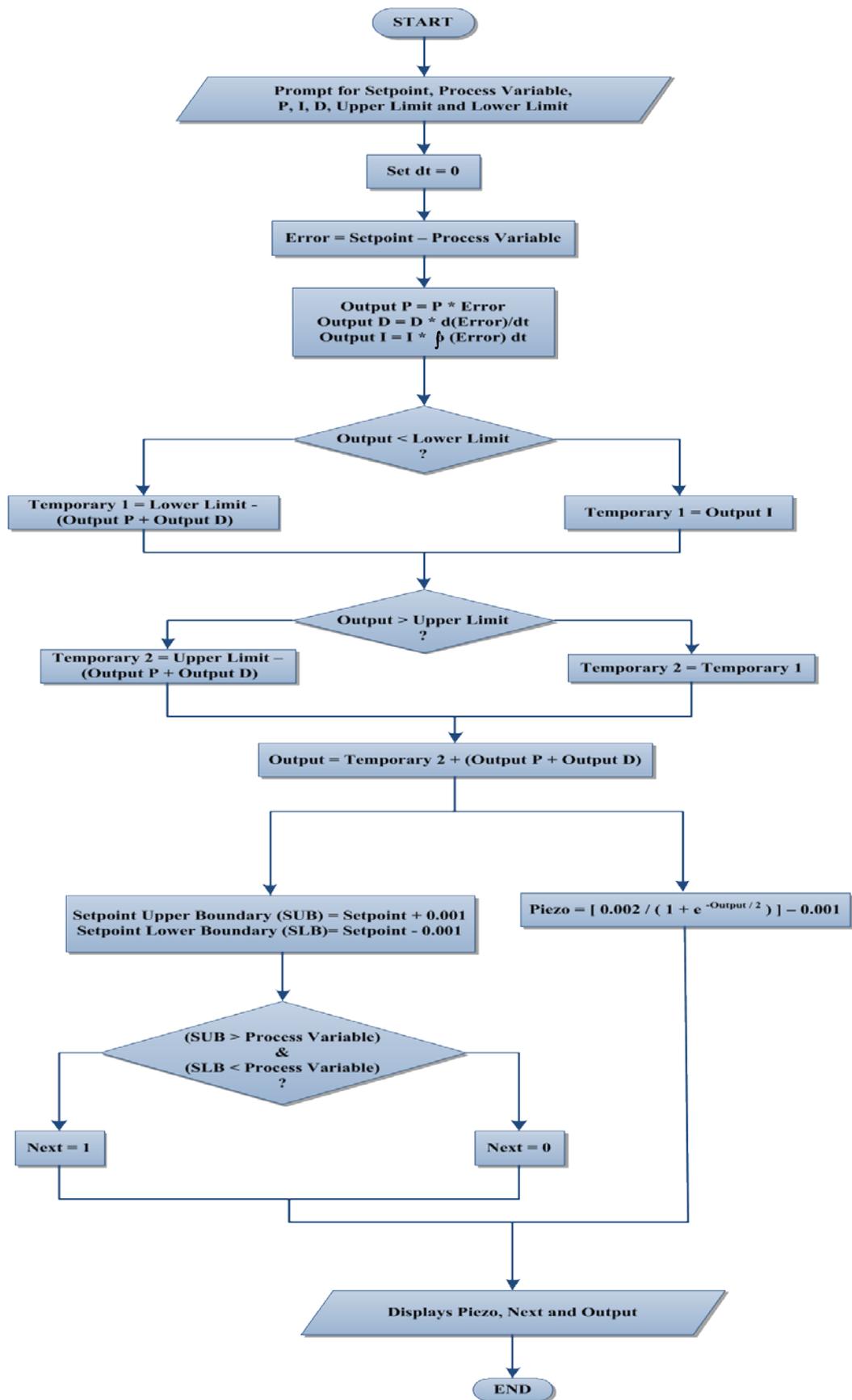


Figure 4.12 Flow chart of PID Algorithm

First of all, the PID algorithm starts by prompting for the value of Setpoint, Process Variable, P, I, D, Upper Limit and Lower Limit. Setpoint is initialised as 0 as it refers to origin of photodiode. Value of P, I and D represent the coefficient of K_p , K_i and K_d in the PID equation respectively. K_p helps to improve response of system; K_i supports for elimination of steady state error; and K_d monitors on the overshoot of system. Upper Limit and Lower Limit act as a boundary to identify how close value of Process Variable is to Setpoint. In the first sub-diagram, since real-time AFM scanning mechanism is excluded, value of dt can be set as 0. Sequence Local, which only exists in stacked sequence structure, is used to bring result from current sub-diagram to the other sub-diagrams. Thus, value of dt is fed to one of the Sequence Locals.

It is followed by the second sub-diagram, which aims to calculate the difference between Setpoint and Process Variable to obtain Error. In the following third, fourth and fifth sub-diagram, Output P, Output D and Output I are defined by multiplication, differentiation and integration accordingly, following strictly PID basic equation. When it comes to sixth sub-diagram, Output is obtained after going through different kinds of requirement checking which is to ensure that the Output falls within range of Upper Limit and Lower Limit.

In the last diagram, the result of Next and Piezo are identified simultaneously. Comparator is used to check whether Process Variable falls within or out of the Setpoint Boundary. If it is true, Next will be 1 and PID implementation will be ended after this cycle, otherwise Next will be 0 and it allows continuous running of PID algorithm. Another word, Sub VI of PID Algorithm will be called repeatedly until the value of Process Variable falls within the Setpoint Boundary. The value of Output for the last cycle will be treated as the total voltage required to lift up or down the stage in order to let the reflected laser to fall back to the origin of the photodiode. Besides, by modifying sigmoid equation, equation of displacement changes in Piezoelectric Buzzer with respect to every single step of output voltage was found and implied in LABVIEW through G-programming language in order to get Piezo. Modified sigmoid equation 4.2 refers to sigmoid graph shown in Figure 4.13. However, Piezo is less significant in AFM scanning as different buzzers will have

different hysteresis curve and therefore this part is just for a reference. Eventually, program will display result of Piezo, Next and Output.

$$\Delta P = \frac{0.002}{1 + e^{\frac{-Output}{2}}} - 0.001 \quad (4.2)$$

where

ΔP = Displacement Changes in Piezoelectric Buzzer

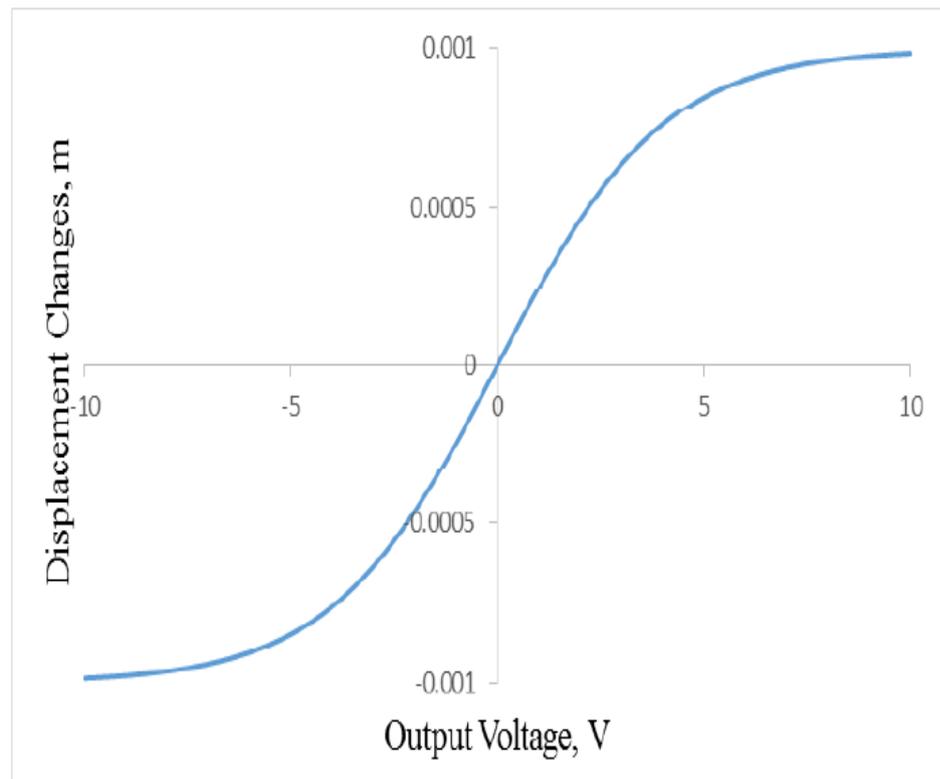


Figure 4.13 Graph of Displacement Changes in Piezoelectric Buzzer versus Output Voltage

4.1.6 Sub VI of PID Simulation

PID Simulation is developed to create a virtual simulation environment in LABVIEW, responding to PID negative feedback given by Sub VI of PID Algorithm. It obtains Output from PID Algorithm and uses it to simulate a position of reflected laser on photodiode. After that, simulation result will be fed into input of Process Variable for further PID implementation processing, to complete a negative feedback cycle. Construction of PID Simulation algorithm is displayed and explained in Figure 4.14 and Figure 4.15.

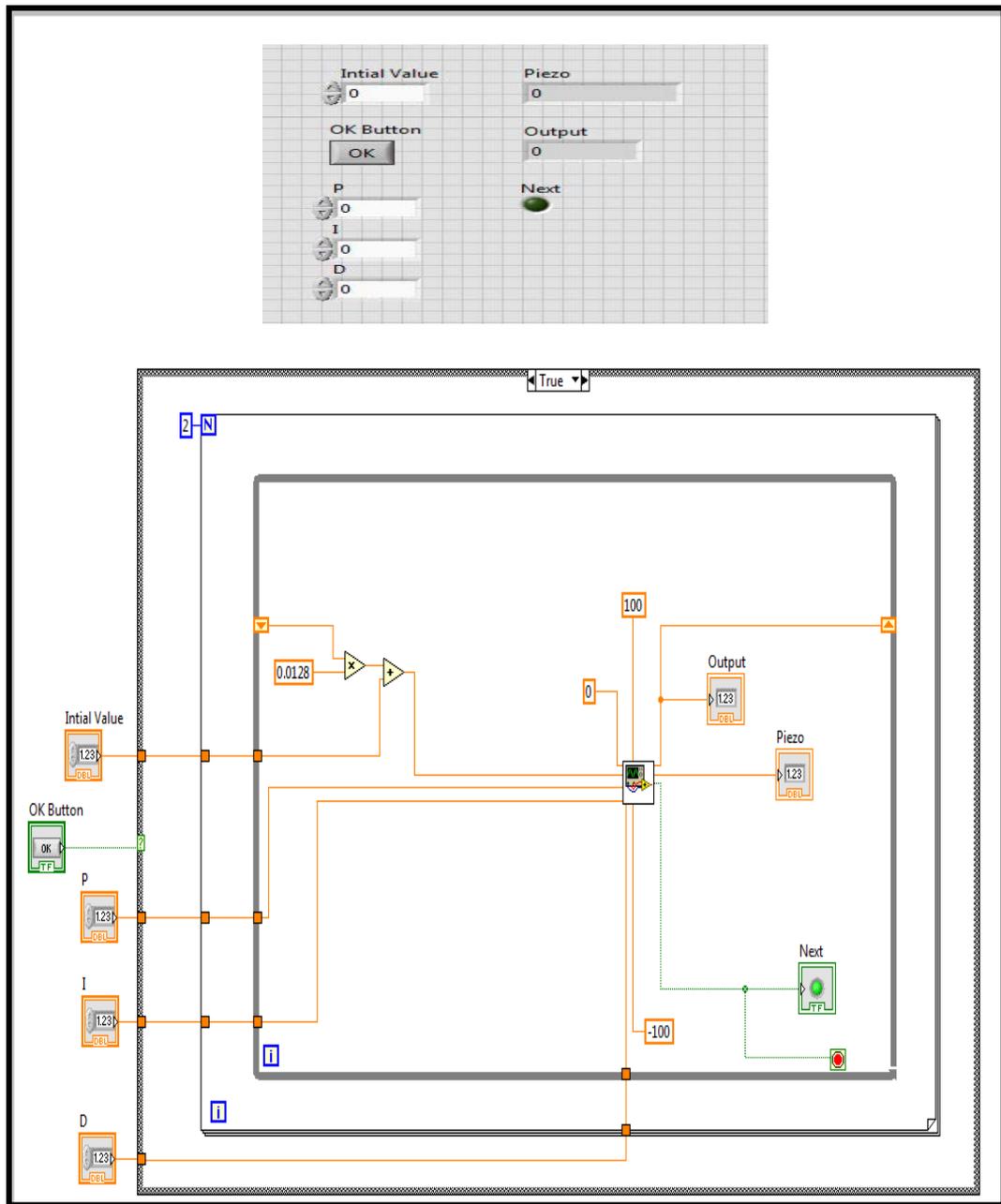


Figure 4.14 Front Panel and Block Diagram of PID Simulation

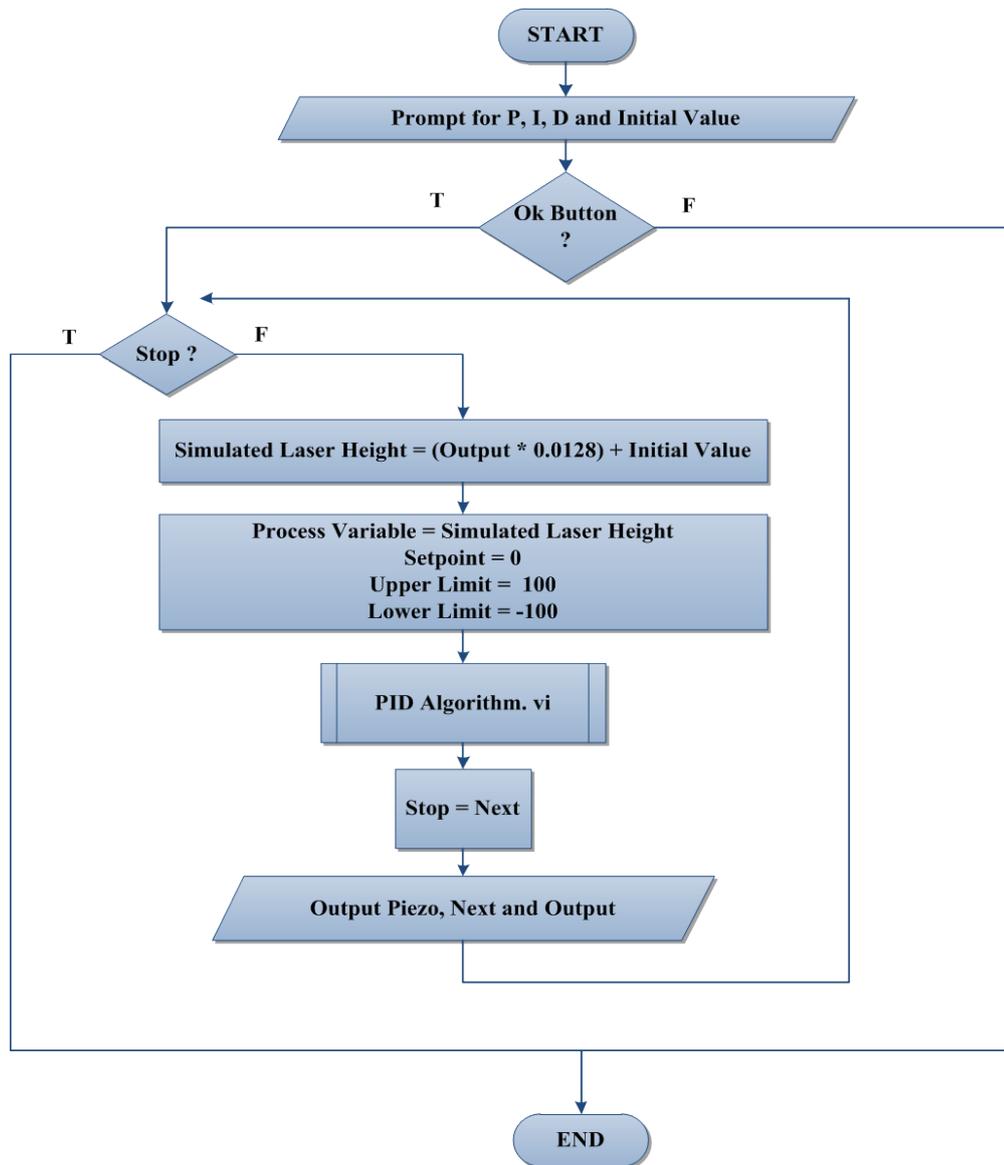


Figure 4.15 Flow chart of PID Simulation

In fact, if the program is connected to the real-time AFM scanning hardware, this Sub VI can be abandoned. However, due to the failure of AFM scanning hardware, this sub VI is needed to create a simulated result that responds to the negative feedback of output from PID Algorithm VI.

First of all, value of P, I, D and Initial Value is required in order to feed into inputs of Sub VI of PID Algorithm. When OK button is pressed, it will then check Stop button, otherwise this part of VI will end directly. If Stop button is true, it will jump out of the While Loop and it comes to the end of VI, otherwise a series of PID

implementation and simulation will be carried out. Instead of using Piezo, value of Output from Sub VI PID Algorithm is used to define Simulated Laser Height. According to the experiments done by Teh (2015), a simulation equation 4.3 was created to find the Simulated Laser Height, without having the real-case AFM scanning process.

$$\text{Simulated Laser Height} = (\text{Output} \times 0.0128) + \text{Initial Value} \quad (4.3)$$

After that, inputs of PID Algorithm VI are connected to different variables accordingly. For instance, Process Variable is equal to Simulated Laser Height, while value of Setpoint, Upper Limit and Lower Limit are initialised as 0, 100 and -100 respectively. Sub VI of PID Algorithm is called in order to determine result of Piezo, Stop and Output. This step is followed by loop back to decision box of Stop. In this case, result of Stop decides when the end of PID Simulation is and it will be true only when Process Variable falls within Setpoint boundary after few times of PID implementation. True statement of Stop will jump out of the While Loop and it comes to the end of VI.

4.2 Original Version of Main VI

There are two versions of Main VI: Original version and Final version. Final version of Main VI is the improved version of Original version, after rearrangement and reconstruction of structures in Block Diagram and Front Panel. This is important as it eliminates the repeated structures to solve program lagging problem, and also tries to tidy up the circuit connection to ease errors tracing.

As observed in Figure 4.16, the Front Panel is divided into two parts: Constant Height and Constant Deflection. Each part displays the result of sample surface, in term of Array Table, Intensity Graph and 3D Surface Graph. Once the pixel height of sample in different AFM scanning mode is obtained, it will be updated instantly in the table and graph form. Option controls like AFM Scanning

Mode, Scanning Time per Pixel, Sample Size, Pixel per Line, P, I and D are built to enable pre-setting of program. Besides, indicators like Row, Column, X Buzzer and Y Buzzer show the latest information of program when AFM scanning is running.

The Block Diagram for algorithm of Constant Height and Constant Deflection mode is referred to Figure 4.17 and Figure 4.18 respectively. Case structure is implied to differentiate the two AFM scanning mode implementations. In fact, the only difference in between them is Constant Deflection mode requires an additional Sub VI which is PID Simulation. Hence, circuit connections in Block Diagram can be greatly reduced if proper circuit arrangement is designed. Idea of AFM scanning algorithm is reconstructed in LABVIEW to create another more concise and systematic Main VI.

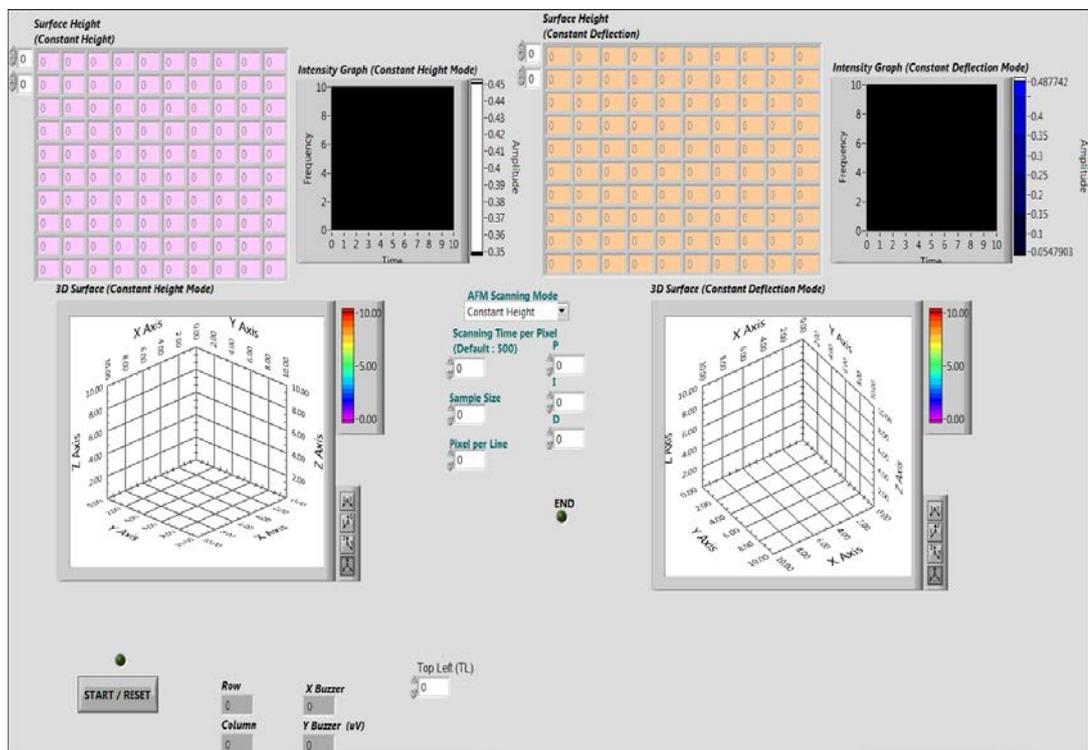


Figure 4.16 Front Panel of Original version of Main VI

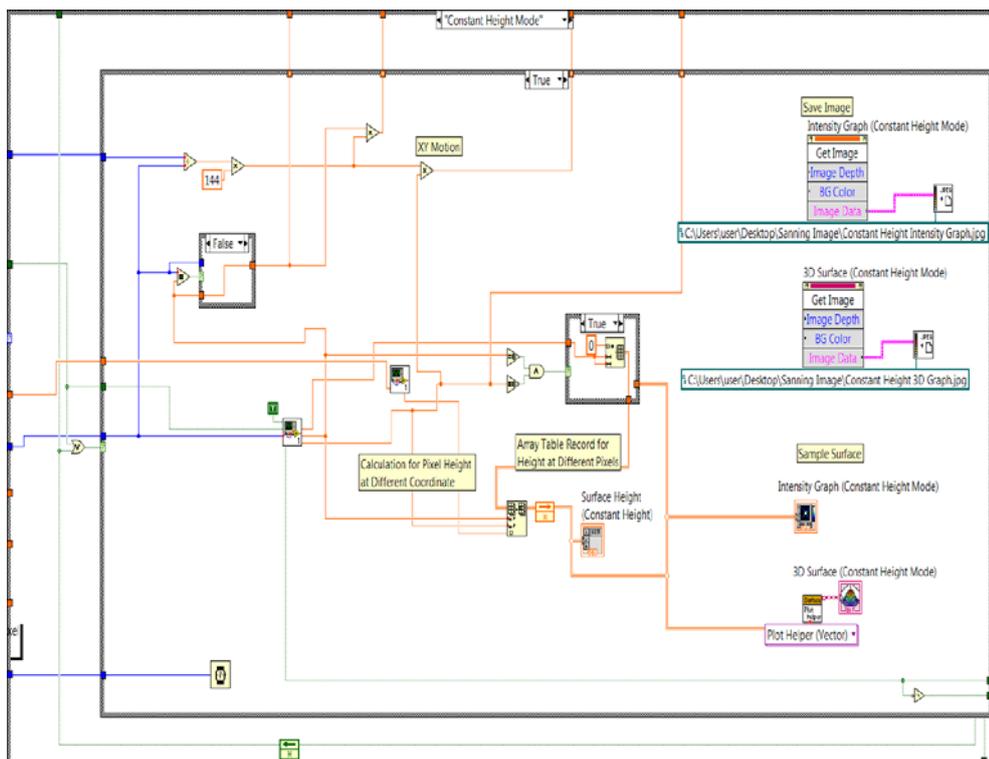


Figure 4.17 Block Diagram of Original version of Main VI- Constant Height

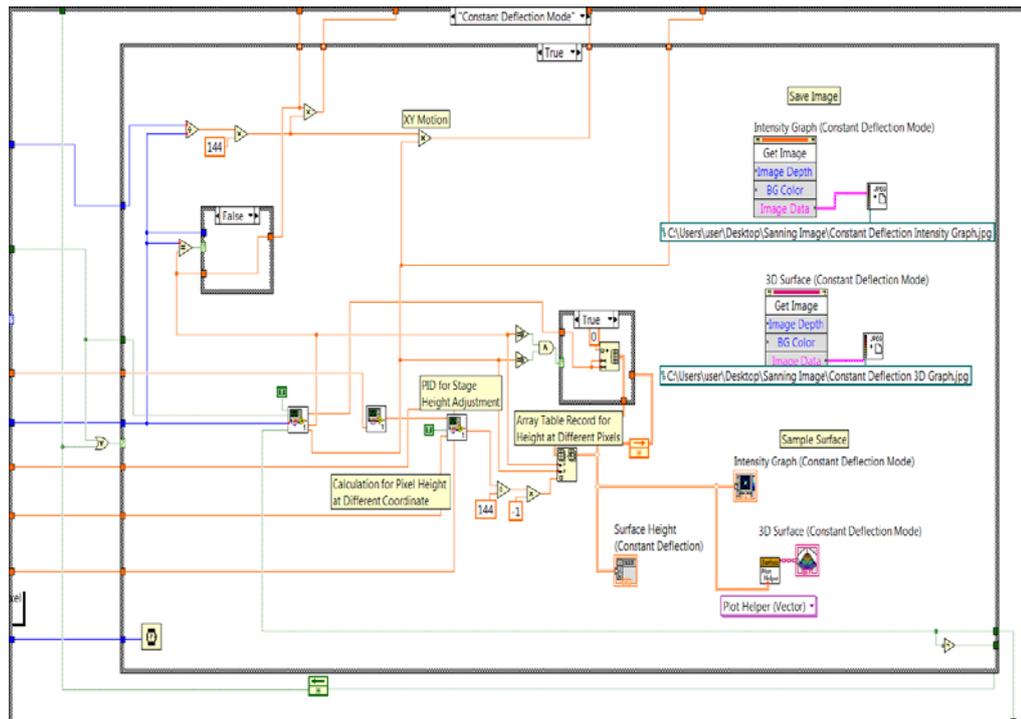


Figure 4.18 Block Diagram of Original version of Main VI- Constant Deflection

4.3 Final Version of Main VI

Main VI of Stacked Sequence AFM Scanning-Hardware serves the function of AFM scanning implementation with the combination of six sub modules of LABVIEW. As mentioned previously, reconstruction of structures developed in Original version was carried out to create the Final version of Main VI for AFM imaging in LABVIEW simulation. Coding validation for every Sub VI was conducted, before adding them into Main VI to ensure the functionalities of modules are correct.

4.3.1 Front Panel

Figure 4.19 shows Front Panel of Final version of Main VI. Controls and indicators are differentiated by using two different colours: words in blue green colour represent controls while words in purple colour represent indicators. Controls like Scanning time per Pixel, Sample Size, Pixel per Line, P, I, D, AFM Scanning Mode and Location for saving Intensity Graph/ 3D Graph are available in Front Panel so that they can be pre-set by user before the execution of program.

Scanning Time per Pixel indicates the speed of scanning time and its default value will be 1000. Sample Size and Pixel per Line helps to simulate the desirable sample size and estimate the required buzzers scanning movement from one pixel to the next. Apart from that, option of AFM Scanning Mode: Constant Height and Constant Deflection, is provided to perform two different kinds of AFM scanning mechanism. In fact, P, I and D are coefficients for proportional, integral and derivative terms respectively, which are important to manipulate the working of PID algorithm. According to the experiments conducted by Teh (2015), it proved that PID controller works the best when P, I and D are pre-defined as 1, 0.5 and 0.1 accordingly. In view of this, the optimal PID coefficients are set as their default value. Besides, Intensity Graph and 3D Graph will be captured and saved in a pre-defined location and they will be updated for every single scanning. It will only keep the latest pictures of graphs unless you rename the graphs before the AFM scanning.

AFM scanning process will be initialised by the START/RESET button. During the scanning, indicators will display the current state of scanning, current row and column, output voltage of X Buzzer and Y Buzzer, and graphs. It can be noted that, a Progress Bar with an indicator of Input Voltage is attached in Front Panel, as shown in Figure 4.20. Since hardware of AFM scanning mechanism does not involve, laser height voltage is obtained from the Variable Power Supply Manual Control of NI ELVIS board. Progress Bar and indicator are used to urge user to give simulated laser height through NI ELVIS board within the given time. Sample shape will be defined at the end of scanning and displayed in the three different ways: Array Table, 3D Surface Graph and Intensity Graph. They show every pixel height of sample instantly and eventually shape of sample surface can be obtained.

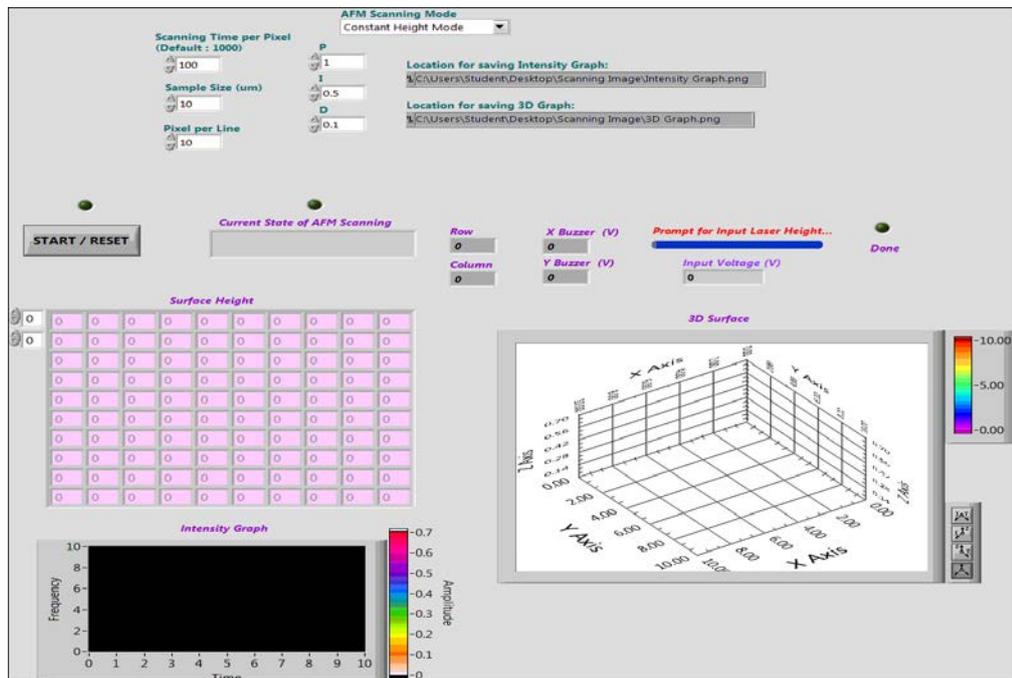


Figure 4.19 Front Panel of Main VI Stacked Sequence AFM Scanning-Hardware

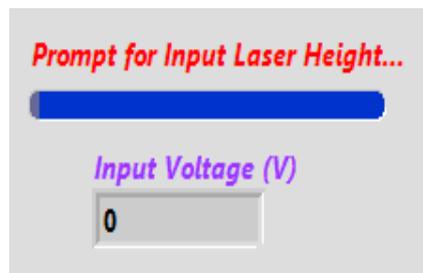


Figure 4.20 Progress Bar prompts for Input Laser Height

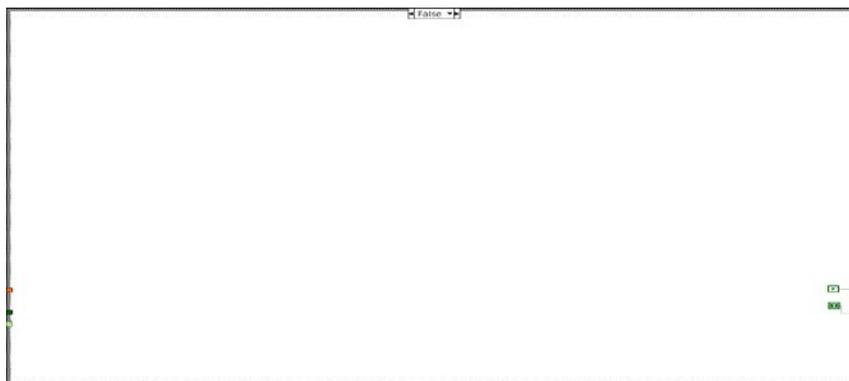


Figure 4.22 False Case when START/ RESET button is not pressed

When button is pressed, Case structure will enter the true statement which triggers a series of AFM scanning implementations. There are a total of four frames of stacked sequence structure required in the Main VI Stacked Sequence AFM Scanning-Hardware. Triggering of START/ RESET button will make you encounter the first frame of stacked sequence, as shown in Figure 4.23.

In this frame, Current State of AFM Scanning will display “Current Scanning Pixel Location” to tell that program is in progress to find location of pixel which will be scanned for this cycle. Scanning Time per Pixel, Pixel per Line and Sample Size are obtained from the controls in Front Panel in order to determine how much voltages should be supplied to buzzers in order to make it move to position of current scanning pixel. Sub VI of Initial Position is included in this frame in order to output the current row, column and Boolean signal to Done.

For your information, current pixel height will be updated in 3D Surface Graph and Intensity Graph on the next cycle of AFM scanning due to LABVIEW pre-set characteristics. Therefore, AFM scanning is allowed to run one more round in order to display the last pixel height of sample on graphs. In order to ensure that the value of row displayed in Front Panel is permissible during the last scanning, Case of Last Round is constructed, as shown in Figure 4.24. When the case is true, Row will display the previous row value, otherwise Row will be the same as value obtained from Sub VI of Initial Position during false statement. Column will not be affected in this case.

Experiments show that voltage supply of 10 V to buzzer will make it expand 20 μm . Based on this, Equation 4.4 and Equation 4.5 are formed to determine how much voltages supplied to X and Y buzzer for every pixel-to-pixel row scanning, in order to satisfy the fact of buzzer expansion. Equations will be constructed graphically in LABVIEW to acquire output voltages for X and Y Buzzers which will then be transmitted out of LABVIEW, through NI ELVIS board.

$$Y \text{ Buzzer} = \frac{\text{Sample Size}}{2 \times (\text{Pixel per Line} - 1)} \times \text{Row} \quad (4.4)$$

$$X \text{ Buzzer} = \frac{\text{Sample Size}}{2 \times (\text{Pixel per Line} - 1)} \times \text{Column} \quad (4.5)$$

Row and Column are also displayed in the indicators of Front Panel. Besides, Select structure is used to determine input value to Wait structure. If the Case of Last Round is true, 0 ms is sent to Wait; otherwise value of Scanning Time per Pixel will become input of Wait. This ensures that any scanning activity is passed quickly in the last round of scanning. As mentioned before, by using Sequence Local, results from one frame can be passed to another frame. Therefore, results like Row, Column, Done, Size and Last Round are connected to Sequence Locals.

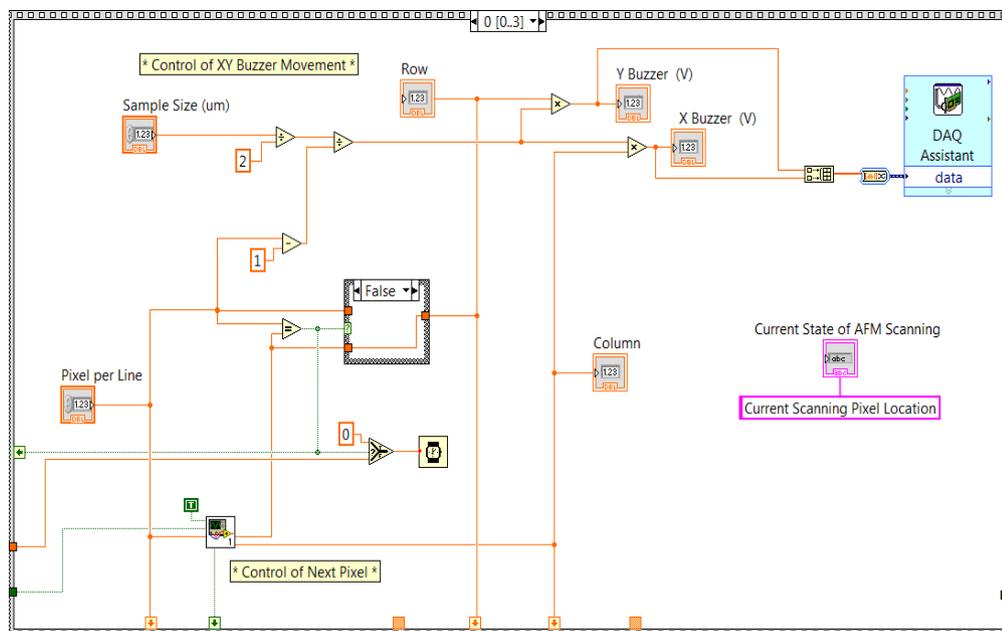


Figure 4.23 First frame of Stacked Sequence Structure

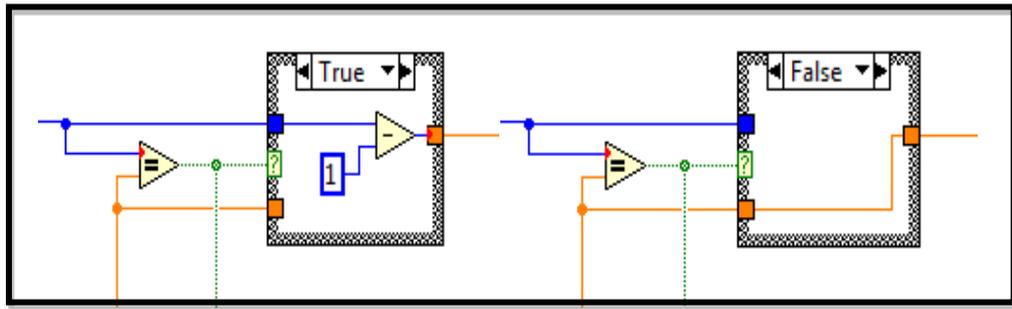


Figure 4.24 Case of Last Round

After that, program reaches the second frame of stacked sequence, as shown in Figure 4.25. Indicator of Current State of AFM Scanning will display “Prompt for Height of Reflected Laser Light on Photodiode” on Front Panel. The main function of this frame is to obtain Simulated Laser Height from Variable Power Supply of NI ELVIS board, within specific time duration. Users can adjust the positive Voltage Adjust knob to define input Simulated Laser Height voltage, from 0 V to 12 V. Due to the input voltage limitation, which is 0 V to 1.2 V, existed in PID controller, Simulated Laser Height voltage will be divided by 10 to satisfy the voltage requirement. For loop and Wait structure are included for time delay and they are working with Progress Bar. Simulated Laser Height voltage will then be passed to next part, through Sequence Local.

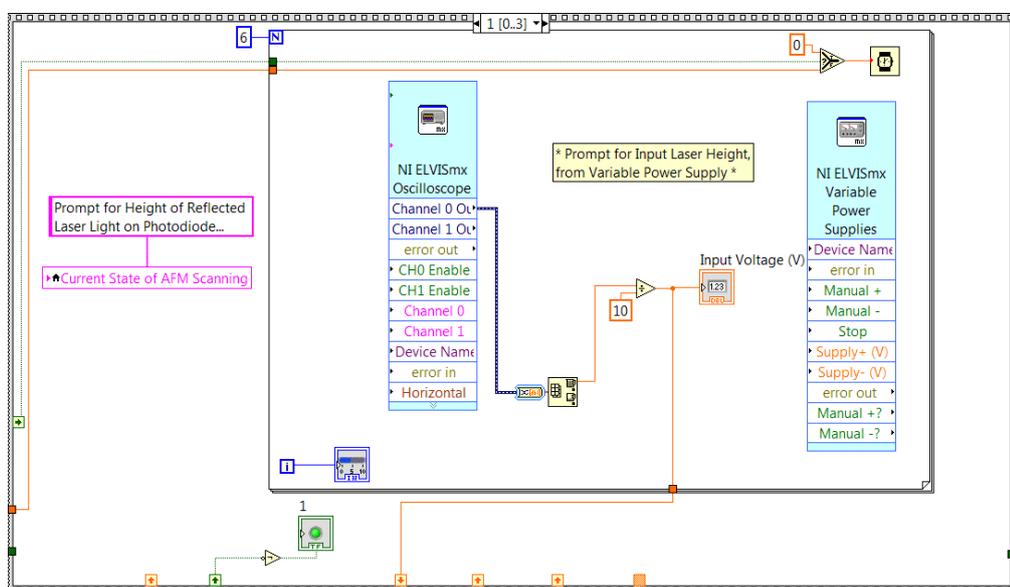


Figure 4.25 Second frame of Stacked Sequence Structure

When the program gets to the third frame of stacked sequence structure, the Block Diagram will appear as shown in Figure 4.26. This is a processing step to identify the pixel height based on the Simulated Laser Height voltage. Simulated Laser Height voltage is sent to Sub VI Height which involves in identification of pixel height based on the simple mathematical calculations. When Constant Height mode is chosen, the pixel height can be obtained directly from output of Sub VI Height. On the other hand, if Constant Deflection mode is selected, PID algorithms will be implemented as in Figure 4.27.

Pre-defined value of P, I and D are fed to inputs of PID Simulation to carry out PID implementation. PID controller works in this part to identify the total voltage needed to Z Buzzer in order to return reflected laser light to origin of photodiode. In Constant Deflection Mode, pixel height is determined based on the how much stage moves vertically to make reflected laser light falling back onto the origin of photodiode. Therefore, relationship between total output voltage from PID controller and pixel height was studied based on the experiments carried out by Teh (2015) and equation was created:

$$\text{Pixel Height (mm)} = \frac{1}{144} \text{ Total Voltage required (V)} \quad (4.6)$$

Based on this equation, the pixel height can be found during the Constant Deflection scanning mode. Positive voltage supply to buzzer means pixel height is lower than flat surface of sample, while negative voltage supply to buzzer means pixel height is higher than flat surface of sample. Therefore, inversion of sign of voltage helps to satisfy this statement in order to calculate pixel height accurately. Output from the Case structure of AFM Scanning Mode is connected to the Sequence Local of pixel height.

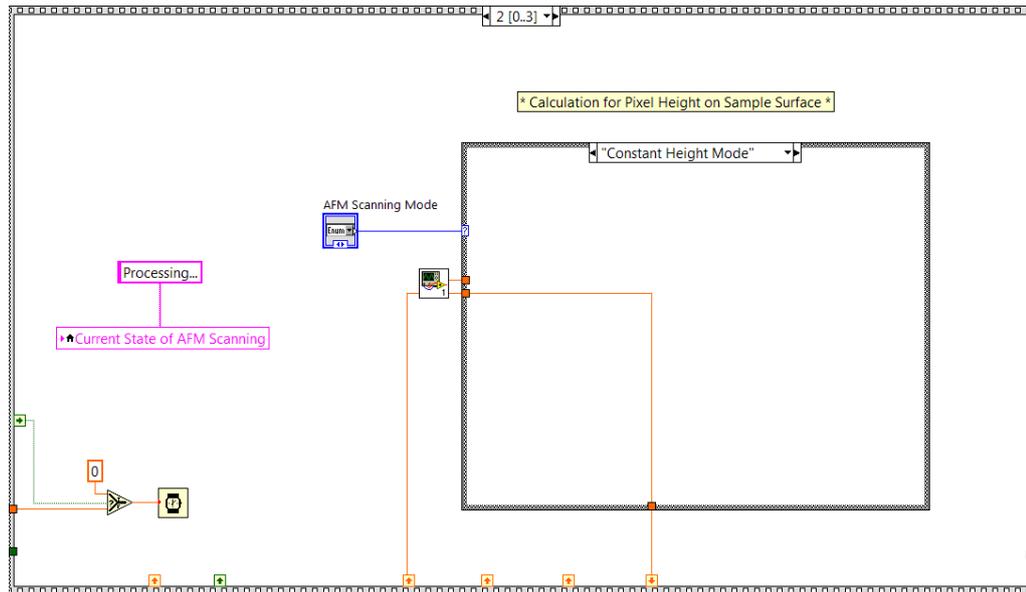


Figure 4.26 Third frame of Stacked Sequence Structure

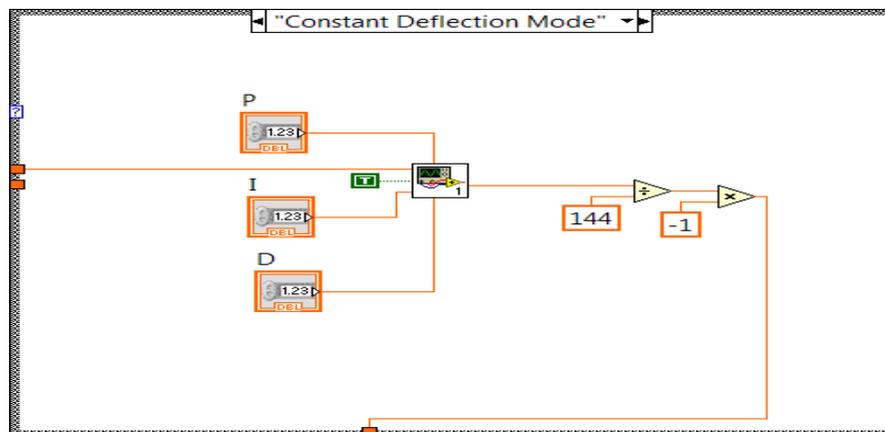


Figure 4.27 Case of Constant Deflection Mode

Finally, the program reaches the last frame of stacked sequence structure, as shown in Figure 4.28. The main contribution of the last frame is to display results in three forms: Array Table, 3D Surface Graph and Intensity Graph. A Case structure helps to update value of pixel height in different location of array table. The first time of AFM scanning will give true statement to the Case and this creates a new array table, which is filled by default value 0. On the other hand, if this is not the first time of AFM scanning, false statement will be yielded and existing array table will be used, as shown in Figure 4.29. Array table will be updated by pixel height on the

specific location, based on Row and Column. Colour enhancement of Intensity Graph can be done through assignment of different colours for different pixel height.

After that, the program will jump out of stacked structure and the halt of program will be examined here. If Done = 0, program is allowed to continue and the next pixel scanning will happen. Complement of Done, feedback node and OR gate with START/ RESET button are constructed outside the stacked structure in order to enable the continuous AFM scanning of sample surface, although START/ RESET button is not pushed. On the other hand, if Done = 1, program will jump out of While loop and it comes to the end of AFM scanning. Another word, AFM scanning on sample surface is complete. The thorough sequence of steps and decisions needed to perform a complete AFM scanning can be referred to flowchart in Figure 4.30.

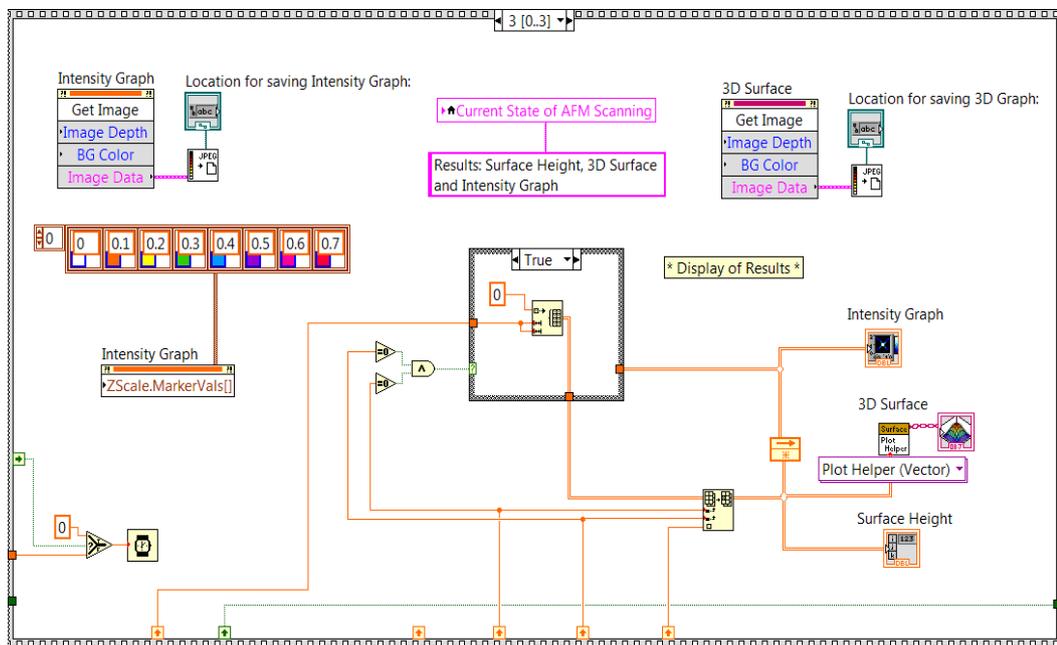


Figure 4.28 Last frame of Stacked Sequence Structure

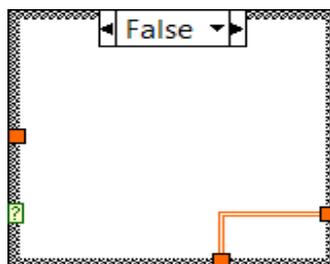
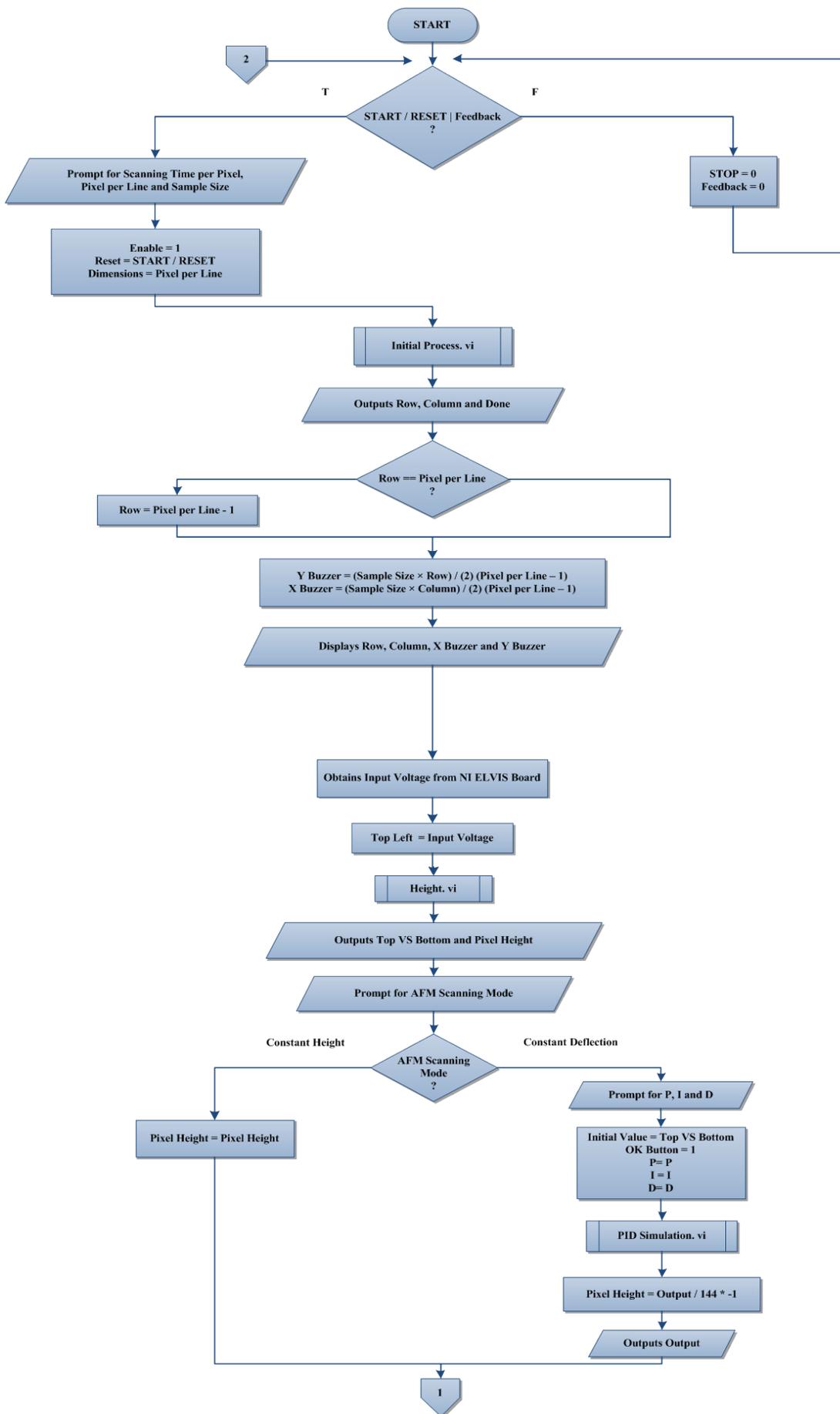


Figure 4.29 False Case of Array Table



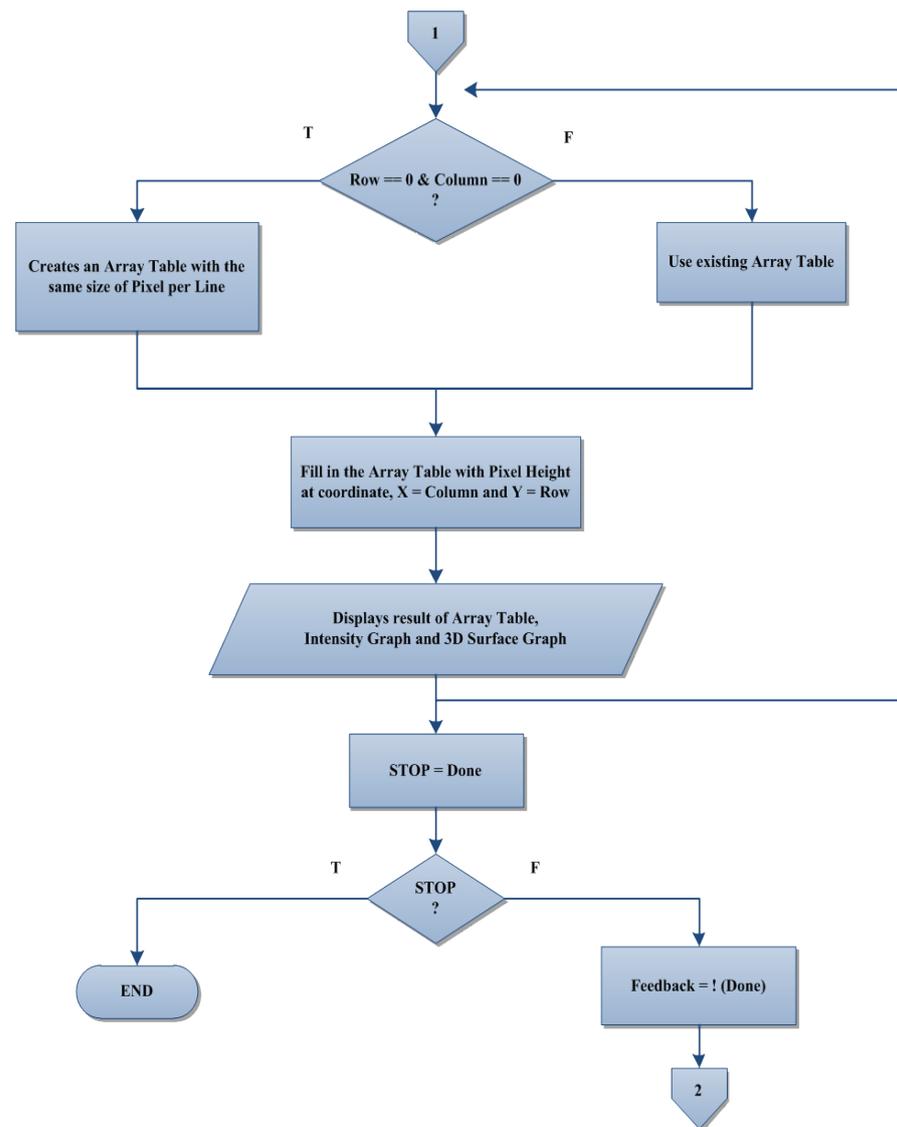


Figure 4.30 Flow chart of Main VI Stacked Sequence AFM Scanning-Hardware

4.4 Results of AFM Scanning Mechanism

4.4.1 Software – LABVIEW

In Figure 4.31, 2D Array Table, 3D Surface Graph and Intensity Graph are used in Front Panel of LABVIEW to show the shape of sample surface, after going through AFM scanning simulation. 2D Array Table aims to keep and display every pixel height on different location of sample surface accordingly. By default, 10 X 10 Array Table is built in Front Panel and thus if array size of sample is more than 10 X 10, Array Table can be expanded by dragging it outward to show all pixel height. Intensity Graph will update and show pixel height, in term of colour intensity, synchronously with the AFM scanning process. Display of results instantly enables users to simply adjust the pre-set control values accordingly and observe the effect of the change of control values on results. Therefore, studies on the further improvement of AFM scanning simulation can be carried out in LABVIEW. 3D Surface Graph is graph that can show the clearest and the most distinct shape of sample surface. Its colour intensity is pre-defined by LABVIEW and different height of pixel will give different colour intensity. Also, 3D Surface graph can be viewed in 2D, in term of XY, XZ and YZ direction, as demonstrated in Figure 4.32.

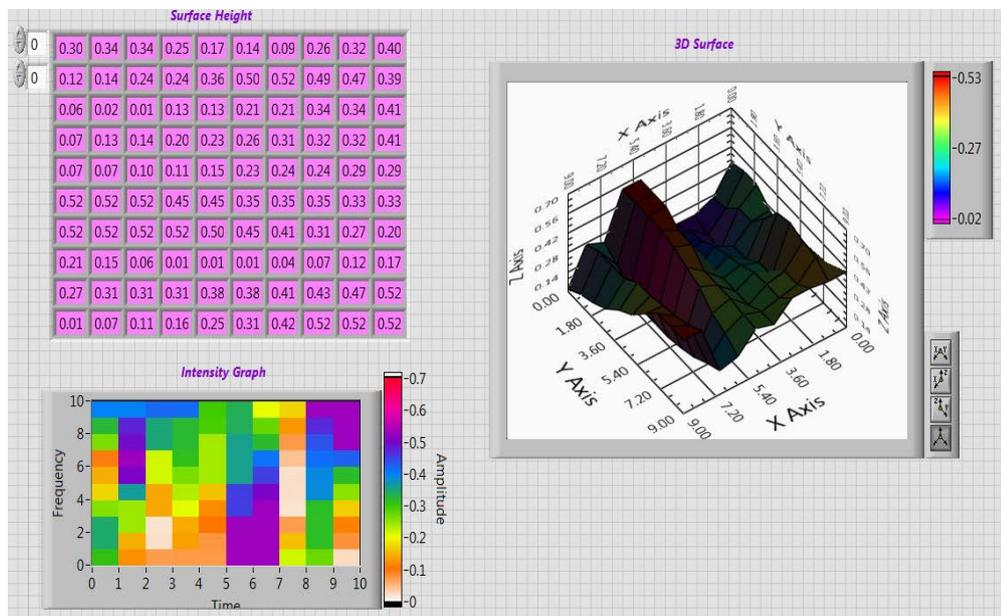


Figure 4.31 Result Display of AFM Scanning Mechanism in LABVIEW

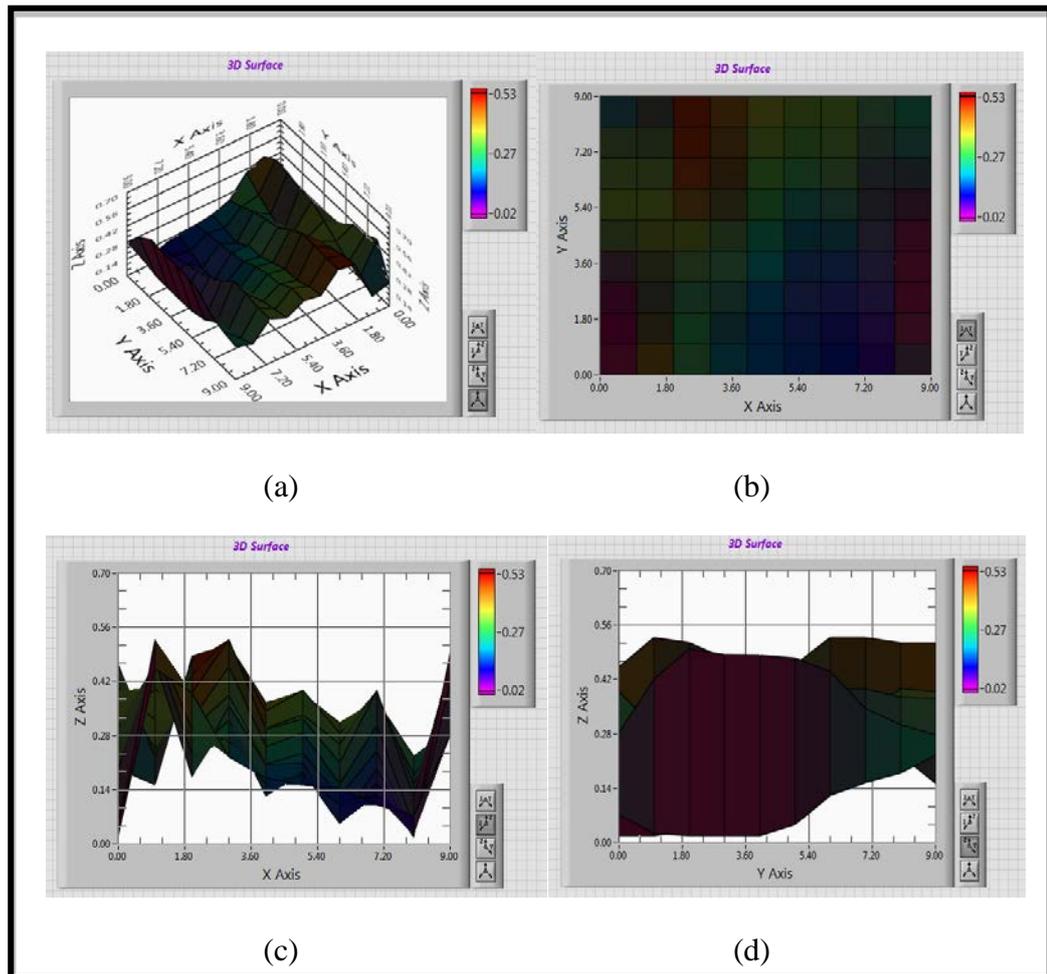


Figure 4.32 (a) XYZ (b) XY (c) XZ (d) YZ view of 3D Surface Graph

4.4.2 Hardware – NI ELVIS Board

The NI ELVIS board has two main functions: voltage acquisition from Variable Power Supply and output voltage transmission under monitor of LABVIEW. By adjusting the positive Voltage Adjust knob, user can define Simulated Input Laser voltage and send it to the AFM scanning mechanism in LABVIEW. Output voltage from Variable Power Supply is connected to AI0 Signal Row, with proper grounding, as shown in Figure 4.33. In view of this, desirable Simulated Input Laser voltage can be set by the positive knob, referring to the Progress Bar with an indicator of Input Voltage, as shown in Figure 4.20.

In the meanwhile, NI ELVIS board can output voltages under the command of LABVIEW, with the requirement of correct circuit connection on the board. As seen from Figure 4.33, analog outputs, AO0 and AO1 terminals, are connected to two external digital multimeters in order to display total output voltages. External digital multimeter on the left is linked to Y Buzzer port while the other is connected to X Buzzer port. Based on Figure 4.34, when Y Buzzer = 0 V and X Buzzer = 5 V in Front Panel of LABVIEW, external digital multimeters will display 0 V and 5 V respectively. On the other hand, when Y Buzzer = 0.5555 V and X Buzzer = 5 V in Front Panel of LABVIEW, external digital multimeters will display 0.556 V and 5 V respectively, as shown in Figure 4.35. This proves that output voltages gained from A0 and A1 terminals of NI ELVIS board will behave exactly the same as voltages in LABVIEW, as long as DAQ Assistant for analog outputs is set correctly.

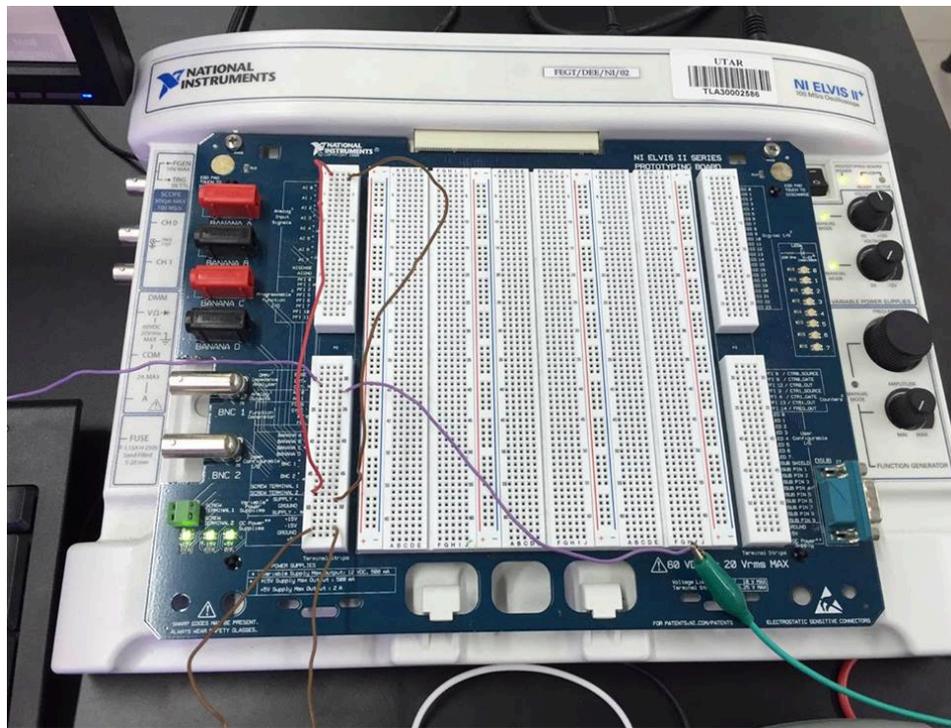


Figure 4.33 Wire connection on NI ELVIS board



Figure 4.34 Output Voltage of Y Buzzer = 0 V, X Buzzer = 5 V

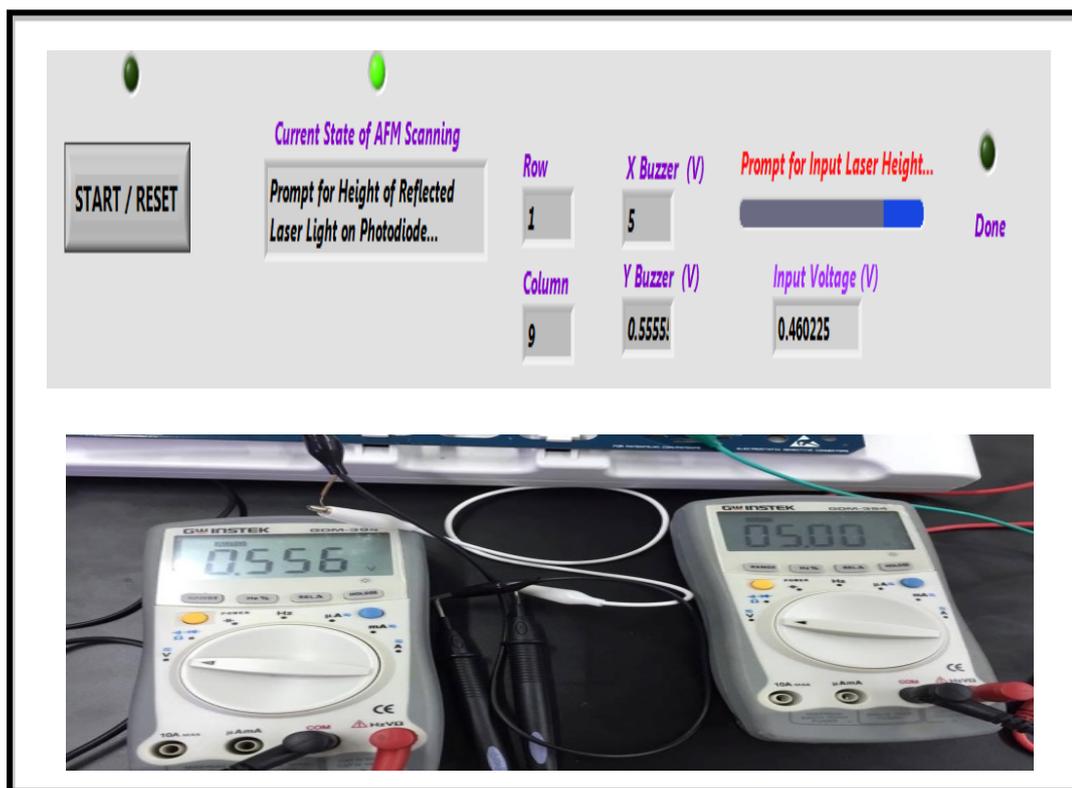


Figure 4.35 Output Voltage of Y Buzzer = 0.556 V, X Buzzer = 5 V

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this project, a comparative study of Constant Height and Constant Deflection mode in Atomic Force Microscopy (AFM) imaging was carried out. LABVIEW serves as a development platform to build a system which can work as an AFM scanning mechanism during software simulation. Three independent controller units are studied and integrated into a well-developed AFM scanning system in LABVIEW. AFM imaging system developed in LABVIEW can image different size of sample surface, in either Constant Height or Constant Deflection scanning mode, and display its shape in the form of Array Table, 3D Surface Graph and Intensity Graph instantly.

AFM scanning mode of Constant Height obtains the image of sample surface based on the displacement of reflected laser light on photodiode detector, after change of cantilever deflection caused by pixel height. On the other hand, Constant Deflection scanning mode scans and defines sample surface, regarding to change of vertical stage movement to restore original deflection level of cantilever.

Hardware of AFM scanning mechanism is excluded in this project due to the unstable customized framework of XY scanner and the incompatibility between software and hardware integration. However, NI ELVIS board will be used in the signal reception from user and voltage transmission to buzzers. Simulated Laser input is obtained from the Variable Power Supply Manual Control of NI ELVIS

board and also it helps to output voltages which are required in stage movement. In fact, these functions are reserved for future work, once a well-working hardware of AFM scanning mechanism is built readily to combine with this well-developed AFM scanning system.

In a nutshell, the customized AFM scanning system developed in LABVIEW will definitely help user to visualise the scanning outcomes. Nonetheless, there are still some limitations and weaknesses in the system. Due to the absence of AFM hardware, the results discussed in this report are based on ideal case in software simulation. Further research needs to be carried out in order to study the performance of AFM system in real life situation.

5.2 Recommendations

Constant Deflection mode of AFM imaging requires X, Y and Z direction movement of stage and thus at least three output voltages will be given out from LABVIEW. However, NI ELVIS board has only two analogue output ports which are insufficient for the demand of outputs. In view of this, problem of insufficient output port can be solved by either making use of built-in digital output ports on NI ELVIS board or changing to another engineering development kits.

Besides, Piezoelectric Buzzers may not be a good choice for AFM stage movement due to its unstable and fragile structures. Therefore, design of custom AFM stage using software AUTOCAD or SolidWorks and then construct it using CNC cutting or 3D printing is preferable for better precision movement. Also, for the photodiode part, improvement on laser quality and removal of unwanted laser noise are recommended in order to improve accuracy of results.

For the software LABVIEW part, it is recommended to utilize Sub VI fully in order to minimize the capacity of program and ease process of troubleshooting. Apart from that, some of the LABVIEW system issues, like display of 3D Surface Graph after one more cycle, must be noticed otherwise it will affect the accuracy of results.

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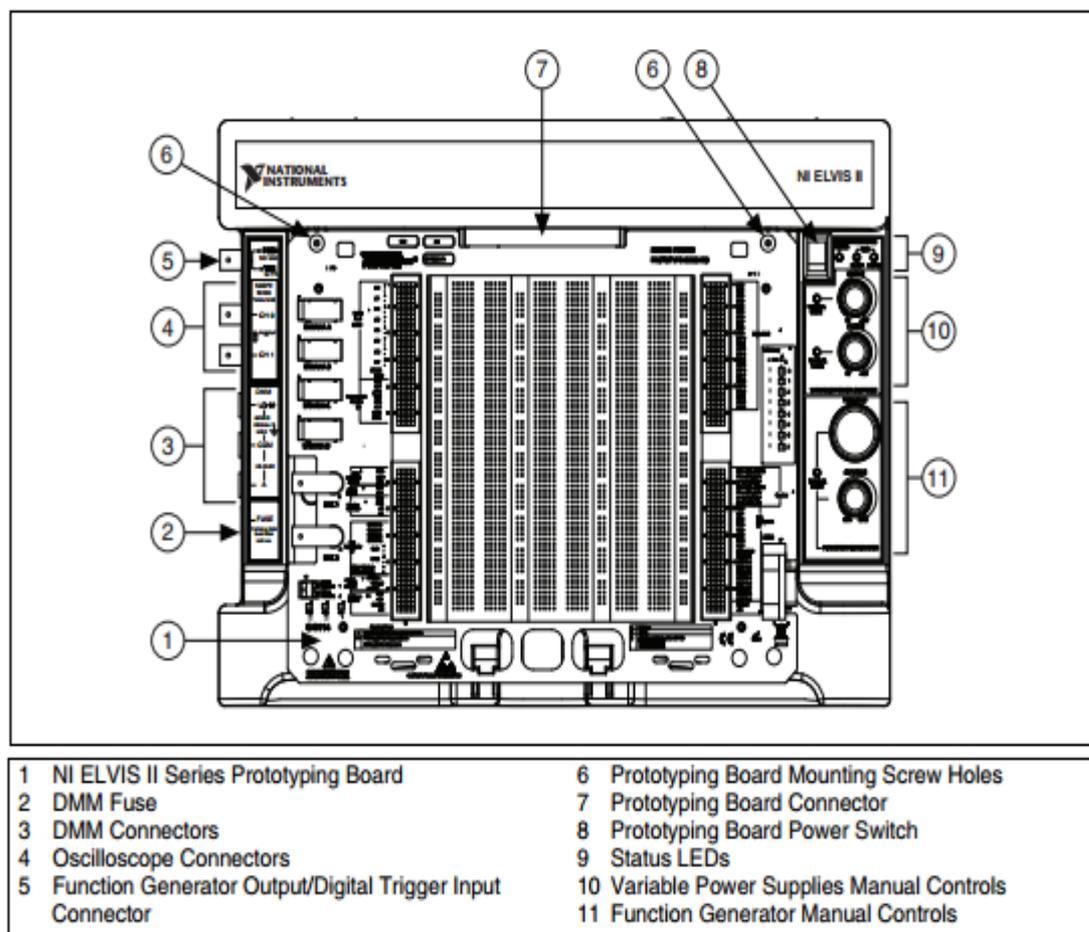
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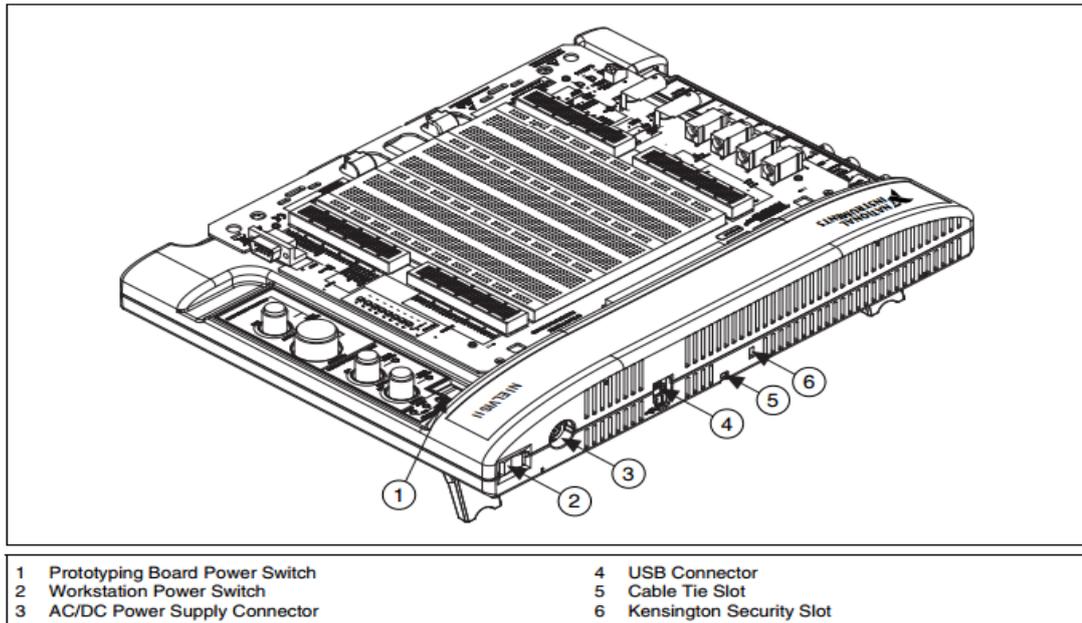
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APPENDICES

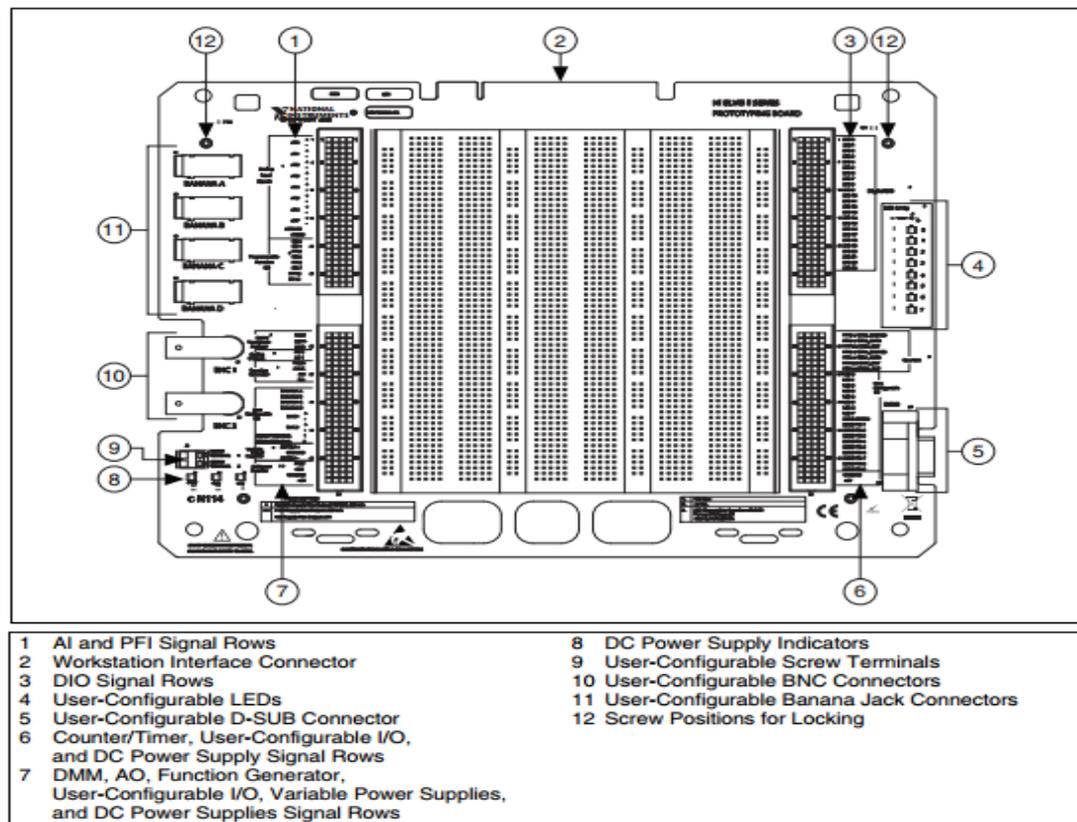
APPENDIX A: NI ELVIS II Data Sheet



Top View of NI ELVIS II Workstation with Prototyping Board



Rear View of NI ELVIS II Series System



NI ELVIS II Series Prototyping Board

Signal Name	Type	Description
AI <0..7> ±	Analog Inputs	Analog Input Channels 0 through 7 ±—Positive and negative input channels lines to differential AI channels.
AI SENSE	Analog Inputs	Analog Input Sense—Reference for the analog channels in nonreferenced single-ended (NRSE) mode. For more information about AI modes, refer to Appendix A, <i>Theory of Operation</i> .
AI GND	Analog Inputs	Analog Input Ground—Ground reference for the Analog Input signals.
PFI <0..2>, <5..7>, <10..11>	Programmable Function Interface	PFI Lines—Used for static DIO or for routing timing signals.
BASE	3-Wire Voltage/ Current Analyzer	Base excitation for bipolar junction transistors.
DUT+	DMM, Impedance, 2- and 3-Wire Analyzers	Excitation terminal for Capacitance and Inductance measurements (DMM), Impedance Analyzer, 2-Wire Analyzer, and 3-Wire Analyzer.
DUT-	DMM, Impedance, 2- and 3-Wire Analyzers	Virtual ground and current measurement for capacitance and inductance measurements (DMM), the Impedance Analyzer, 2-Wire Analyzer, and 3-Wire Analyzer.
AO <0..1>	Analog Outputs	Analog Output Channels 0 and 1—Used for the Arbitrary Waveform Generator.
FGEN	Function Generator	Function Generator Output.
SYNC	Function Generator	TTL output synchronized to the FGEN signal.
AM	Function Generator	Amplitude Modulation Input—Analog input used to modulate the amplitude of the FGEN signal.
FM	Function Generator	Frequency Modulation Input—Analog input used to modulate the frequency of the FGEN signal.
BANANA <A..D>	User-Configurable I/O	Banana Jacks A through D—Connects to the banana jacks.
BNC <1..2>±	User-Configurable I/O	BNC Connectors 1 and 2 ±—Positive lines tie to the center pins of the BNC connectors; negative lines tie to the shells of the BNC connectors.

Signal Description

Signal Name	Type	Description
SCREW TERMINAL <1..2>	User-Configurable I/O	Connects to the screw terminals.
SUPPLY+	Variable Power Supplies	Positive Variable Power Supply—Output of 0 to 12 V.
GROUND	Power Supplies	Ground.
SUPPLY-	Variable Power Supplies	Negative Variable Power Supply—Output of -12 to 0 V.
+15 V	DC Power Supplies	+15 V Fixed Power Supply.
-15 V	DC Power Supplies	-15 V Fixed Power Supply.
GROUND	DC Power Supplies	Ground.
+5V	DC Power Supplies	+5V Fixed Power Supply.
DIO <0..23>	Digital Input/Output	Digital Lines 0 through 23—These channels are general purpose DIO lines that are used to read or write data.
PFI8 / CTR0_SOURCE	Programmable Function Interface	Static Digital I/O, line P2.0 PFI8, Default function: Counter 0 Source
PFI9 / CTR0_GATE	Programmable Function Interface	Static Digital I/O, line P2.1 PFI9, Default function: Counter 0 Gate
PFI12 / CTR0_OUT	Programmable Function Interface	Static Digital I/O, line P2.4 PFI12, Default function: Counter 0 Out
PFI3 / CTR1_SOURCE	Programmable Function Interface	Static Digital I/O, line P1.3 PFI3, Default function: Counter 1 Source
PFI4 / CTR1_GATE	Programmable Function Interface	Static Digital I/O, line P1.4 PFI4, Default function: Counter 1 Gate
PFI13 / CTR1_OUT	Programmable Function Interface	Static Digital I/O, line P2.5 PFI13, Default function: Counter 1 Out
PFI14 / FREQ_OUT	Programmable Function Interface	Static Digital I/O, line P2.6 PFI14, Default function: Frequency Output
LED <0..7>	User-Configurable I/O	LEDs 0 through 7—Apply 5 V for 10 mA device.
DSUB SHIELD	User-Configurable I/O	Connection to D-SUB shield.
DSUB PIN <1..9>	User-Configurable I/O	Connections to D-SUB pins.
+5 V	DC Power Supply	+5V Fixed Power Supply.
GROUND	DC Power Supply	Ground.

Signal Description (Continued)