Thesis for the Degree of Master of Engineering

Design and Implementation of Acoustic Scanner for Non-Destructive Testing Application

by

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Department of Mechanical Design Engineering

The Graduate School

Pukyong National University

August, 2021

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(비파괴 테스트 애플리케이션을 위한 음향 스캐너의 설계 및 구현)

Advisor: Prof. Seon-Jin Kim, PhD

Co-Advisor: Prof. Jung-hwan Oh, PhD

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A thesis submitted in partial fulfillment of the requirements for the degree of

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In

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Master thesis

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August 27th, 2021

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Acknowledgment

"It takes a village to raise a child" African proverb

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Abstract

Acoustic scanners refer to scanning a sample using ultrasound wave. Due to the nature and capability of sound to go through different materials and in return exhibits distinct feedback as it travels through different medium, ultrasound stands out in detecting and identifying defects in nondestructive way.

In this research work the principles of Hilbert transformation along with gray color contour mechanism is used for data acquisition, Process and image formation. In order to get expected result LabVIEW based motor control, scanning function blocks are constructed. For ease of user (inspection personnel) end user graphical user interface is developed. System level development and integration is achieved from using immersion transducer, Motion control and OHlabs pulser receiver. Encoder signal is collected using ATmega processor for synchronized tasking between motor driver and pulser receiver as well as National Instrument (NI) based digital oscilloscope.

As a result, top surface scanning is conducted and encouraging output is observed. However, for an advanced and precise result the writer of this paper believes that further study and detailed work is needed.

Chapter 1 Introduction

The ability to produce complexity and delicate products is rising as the market demand for simple agronomy but advanced functionality is souring. And a collective growth and advancement in the manufacturing industry sector is playing a great role in realizing such sophisticated, delicate and scaled-down sizes into operation.

However, this advancement and delicacy in return brings about a significant constraint on methods applied to inspect products reliability and validity. By adopting state of the art inspection methods, leading companies and manufacturers of versatile products-batteries[1], steel[2], probes[3], can save a significant level of spending (insurance, warranty). For this reason, component testing requires new inspection techniques that save time, efficient and safe.

Acoustic scanning (Scanning Acoustic Microscopy) technique has strong potential which can be applied to microelectronic scanning[4], measurement[5], packaging defect detection[6] and material quality evaluation[7] precisely, timely and effectively without any side effects.

In this thesis ultrasound wave is used for non-destructive testing to inspect any defect of sampled units. For this inspection technique an overall system is constructed, and result is gained.

1.1 Introduction to SAM Project

Scanning Acoustic Microscopy Project is an active research work in the NBMLab, OH Labs Corps. that integrates mechanical, electrical, software development. And the goal is to front bring a competitive product that can satisfy the customer interest in relating to customized NDT solutions.

The aim of this study is to apply the theories and principles and setup system level integration, prepare suitable program and test and discuss its result.

1.2 Research Questions

The thesis work is categorized under team of the ongoing research work of SAM Project. In this case my work is expected to answer the following research question

Having a sample on the test bed can the SAM system scan the sample and enable the end user to identify any defect, if any?

To answer this research question, it is important to consider the following sub questions:

A) *How can be sound used for scanning purpose?*
B) *What type of technique could be used to retrieve information from the ultrasound?*
C) *How can an image be constructed?*
D) *Can this technique be used for other applications as well?*

1.3 Contribution

The main contribution of this research work can be summarized as follows:

A) Integration of SAM system
B) Programing and Test of ESP300 Motor Control Unit
C) Design Graphical User Interface of acoustic scanner system
D) Implement mathematical model to process echo signal.

1.4 Thesis Outline

The rest of the thesis is organized as follows. In chapter 2 theory of inspection mechanism and prior works are described. In addition, theoretical principles of ultrasound and governing mathematical equations, and applications of ultrasound regarding to non-destructive testing are covered with emphasis. Chapter 3 describes system level integration and materials, tools and software environment used. Conducted experiments, obtained results and inferences found using concepts, tools and techniques mentioned in previous part of the thesis are put together in chapter 4. Discussion part of the thesis is in chapter 5. Finally, conclusion, limits and recommendation for future work are stated in chapter 6. This is followed by Appendices and bibliography in the respective order.

Chapter 2 Theory and Related Works

2.1 Introduction to Ultrasound

Sound is created due to a mechanical vibration of any medium and the process of transmission of the energy induced in each particle creates sound waves. This mechanical phenomenal behavior exhibits distinct characteristics that makes it to stand out in comparison to other types of energy. Not only that, but sound wave can also propagate in transverse(shear wave)- perpendicular to the vibration, longitudinally- in parallel to the vibration of particles, the other types of sound waves are surface waves and plate waves[8] . Both firstly mentioned types of propagation are most common and have their own advantage on applying sound for medical and industrial applications.

Focusing on ultrasound, it is nothing, but a sound waves a frequency higher than 20KHz.By that it means that it is no longer audible to the human ear but machines. In other word, the sound wave can be “heard” when it goes through mediums or reflected using acoustic transducers. And those transducer’s electrical response can be interpreted into a useful data that can talk about the mechanical properties of that given sample medium.

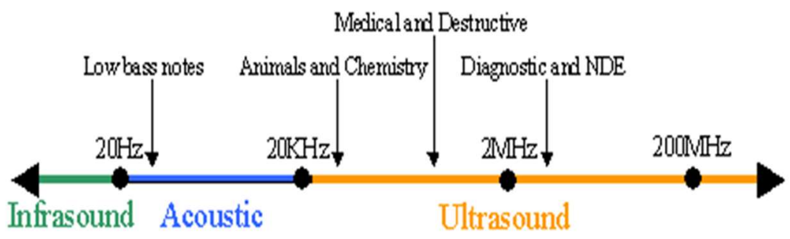

Figure 1 Sound frequency spectrum

Ultrasound has the capability of freely penetrating through hardened or soft materials and different mediums namely, air, liquid and solid. But while propagating through those materials the behavior of the reflected sound is changed and this characteristic helps to study flaws or hidden and easily unseeable situations through it. More importantly its capability to be focused and straightly transmitted as well as nondestructive nature makes it a dominant among others when it comes to investigating and inspection[9][10] or medical imaging as well.

2.2 Introduction to Inspection Techniques

In the industry sectors of product manufacturing process, achieving quality and market-competitive unit is a primary goal. For this reason, number of industries adopt inspection techniques into their manufacturing procedures. Some of trending inspection techniques use optical inspection methods. Others also use X-ray based inspection methods though X-ray computed tomography are better at analyzing the internal characteristics of an object but it has a short coming when it comes to assessing ultrasonic transducers[3]. Other techniques include Infrared ray which commonly results in low image clarity while electron microscopes in other hand takes a long time to scan a sample which is not applicable in a very time constrained industries[7][8][2]

2.3 Ultrasonic Inspection

Ultrasonic inspection method can be explained as using the sound wave property and the travelling speed difference in different materials can be manipulated to study and 'see through' any materials unlike optical transducers or X-ray computed tomography[3][7]. Figure 2 and figure 3 show how acoustic scanner are used for nondestructive technique.

The signal that is sent to and collected from the acoustic transducer- immersion transducer, is a sinusoidal wave form in pattern of bursts. Those sinusoidal electric waves when sent to the transducer it agitates and force it to vibrate which in return creates an ultrasonic wave. Those ultrasonic waves depend on the level of frequency to go and penetrate deeper or only scan shallow surface with high resolution. It is possible that to say the frequency range of transducer is inversely related to penetration[5] [4][11]

To analyze a given sample properties it is the reflected sound wave that holds the data. For this reason, in order to decode the analog electrical signal that is received from the transducer that is working in pulse echo mode. When an electrical signal is sent it converts it into ultrasonic signal, conversely when the transducer is hit back by reflected ultrasound wave it converts it into corresponding analog signal. This analog signal needs to be changed into digital signal but first should be transformed without losing it time domain format unlike Fast Fourier transform. Since acoustic signals are sampled at a very small-time difference and the domain is needed to be kept as it is Hilbert Transform comes to a consideration.[12]

$$H\{x(t)\} = \tilde{x}(t) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau \qquad (1)$$

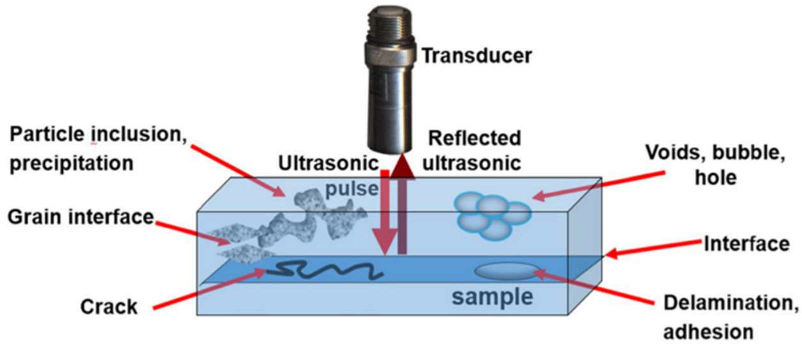

Figure 2 Transducer Pulsing and echoing from sample with numerous defects[1]

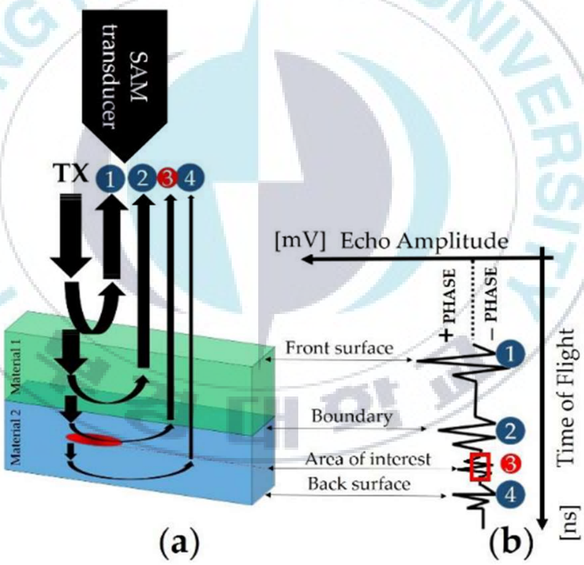

Figure 3 A-scan or Amplitude Scan through target object[2]

[1] Image source: [7]
[2] Image source:[3]

Chapter 3 Methods

This chapter grouped in two categories. The first part will thoroughly describe the technologies materials applied, and tools used throughout this work. Part two of the chapter will focus on the developed Process flow diagram for each sub systems as well as development environments.

3.1 Material and Tools

In this part all components are discussed one by one to show how the integration was developed and draw the picture of the whole system since improving or changing part of the materials has a potential to bring about significant alteration on the result side. Therefore, the writer believes that stating some line about the materials and tools of the work will give a clear image for prospective upgrading and future improvement.

3.1.1 Immersion Ultrasonic Transducer

The ultrasonic search units[13] one of the main component of the acoustic scanner system and it can impact the final result significantly. For research purpose it is not uncommon own's lab product. For this reason, in this research work OHLab 50 MHz transducer is used.

Figure 4 50 MHz Immersion Transducer

3.1.2 Ultrasonic Pulser Receiver

The ultrasonic pulser receiver unit is a sub system of the acoustic scanner that plays a great key functionality in generating the excitation signal for the ultrasound beam formation. Moreover, it amplifies an echo signal that come from immersion transducer in time of operation sequentially.

The table below (Table 1) shows the main specification and parameter of OHLabs pulser receiver[3]. Snap figure of GUI windows application software is also included.

[3] OHlabs Pulser Receiver is one of finalized products of OHlabs Corp. and is under continual upgrading research stage. http://ohlabs.co.kr/en/pulser-receiver/

Table 1 Detailed specification of Pulser sub-module

Pulser	
Pulse Type	Positive Impulse
Pulse Duration	7ns, 10ns, 20ns
Available Pulse Voltage (no load)	80V
Operation Mode	Pulse-Echo / Thru-transmission (Selectable)
Trigger Mode	Internal trigger / External trigger (Selectable)
Number of Trigger	One or two trigger ports (Optional)
Internal Pulse Repetition Rate	0.1, 0.2, 0.5, 1, 2, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50 kHz
External Pulse Repetition Rate	50 kHz max
Synch Output Pulse	5V 50% Duty TTL compatible
External Trigger Input	Rising edge triggered. 5V TTL compatible, 2V minimum

Table 2 Detailed specification of Receiver sub-module

Receiver	
Maximum Bandwidth	300 MHz (-3 dB)
Voltage Gain	9 to 40dB in 1dB step (Selectable)
Phase	0º (noninverting)
Low Noise Figure	4.5dB max
Power Supply	12V, +/- 5V
Maximum Input Power	13dBm
Maximum Output Power	18.4dBm

Table 3 Power specification of Pulser Receiver unit

Unit	
Input/Output	All SMA connectors. USB type B connector.
Power Requirements	15VDC, 2A

Figure 5 Pulser Receiver Board

3.1.3 Motion Generator and Controller Unit

This section introduces the reader how the motion of the system is assembled, programmed and controlled. In this regard it is preferable to partition into two groups: Motion Generator and Motion Controller

A) Motion Generator

For Motion generation section two Newport linear motor stages are used in X-Y assembly fashion. Both DC motors specification is described in Appendix B. Motors are assembled in a fashion that is depicted as below.

Figure 6 Newport linear motor stage [4]

B) Motion Controller

For Motion controller purpose Newport Universal Motion Driver is used[14]. For the purpose of integrating and commanding the motion controller for the designed system, stating how the command is received and processed has uppermost role in understanding motion controller methodology. In the following part.

Figure 7 Command Format of ESP300 motion control[5]

The general format of a command is a two-character mnemonic (**AA**). Depending on the command the command package can also have preceding (**XX**) that indicates motor axis and following (**nn**)- speed, distance or etc. parameters.

The syntax for sending a command to the motion controller is displayed as follows in figure 8.

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[4] Imagesource: https://www.newport.com/mam/celum/celum_assets/MC-UTS150CC___UTS50CC_XY_300w.jpg

[5] Image source: [14]

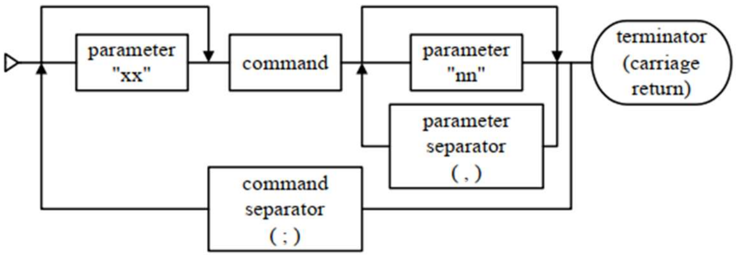


Figure 8 Command Syntax of ESP 300 Motion Controller[6]

The main command sets to program the intended motion are summarized in table format in table 4.

Table 4 Main commands used for programming ESP300 Motion Controller

Mnemonics	Description of mnemonics
DH	Define Home
PA	Move to absolute position
PR	Moves to relative position
TP	Read actual position
TS	Read controller status
VA	Set Velocity for a given axis

3.1.4 National Instruments Unit

For this research work the following NI units are used as a platform for signal acquisition, data processing and control along with LabVIEW development environment. Details of instruments are included in Appendix.

[6] Image source:[14]

Figure 9 NI PXle 8133 Embedded Controller[7]

Figure 10 NI PXle 5153 Digitizer

3.1.5 Microcontroller

For the purpose of counting the encoder signal of the motion controller ATmega2560 microcontroller with Arduino platform is used. The main purpose of the microcontroller is to facilitate the movement and echoing synchronization in between Newport motion controller and OHlabs TransReceiver.

[7] Image source: https://www.artisantg.com/TestMeasurement/94214-1/National-Instruments-PXIe-8133-1-73-GHz-PXI-Express-Controller

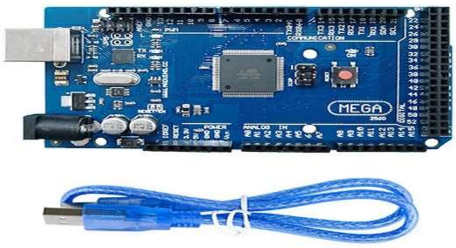


Figure 11 ATmega2560 Board[8]

3.2 System Setup and flow Diagrams

For the system to function properly it needs two arrangements both hardware and software. For the hardware side the system setup will be explained, and the working principle is described step by step thoroughly. The second part is the software section, which displays the generalized flow diagram. The flow diagram will be elaborated in detail. In the two sections (System setup, System flow diagram) how the system was configured, how it works and how it processes the data will be clarified.

[8] Image source: https://www.elecrow.com/elecrow-mega-2560-r3-board-atmega2560-atmega16u2-usb-cable-for-arduin.html

A) System Setup

The hardware setup of the system is mainly composed of Ultrasonic Transducer, Ultrasonic Pulser Generator & Receiver, Motion controller, Gantry table having two motors set one over the other in XY axis, PXIe oscilloscope and NI chassis as depicted in figure 13.

The Ultrasonic transducer will emanate high frequency sound when triggered by the ultrasonic pulser receiver at around 50 MHz. In fact, the ultrasonic transducer has two usages in this scenario since it is working in pulse echo mode. The pulse echo interval is set by the ultrasonic pulser generator, but the timing of processing is adjusted in accordance with the movement and space coverage of the motors. Hence, the X axis motor encoder signal can be collected using ATmega processor and used as a trigger both for pulser receiver unit and PXle 5153 oscilloscope.

To elaborate more what mean by enabling trigger using the motor rotation, few lines will be stated below. The below figure 11 depicts how the scanner (motor axis that that transducer holds onto) moves along and the coverage of distance before pulse echo is triggered.

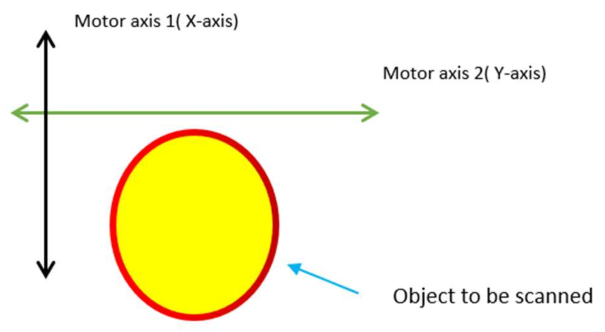


Figure 12 Motor set up for object scanner

The above figure partially gives the idea behind setting up in XY axis so that the scanning process will be done slice by slice. In this aspect only Motor on X-axis has an encoder. And the encoder that comes with the motor this encoder sends a signal for every 2µmeter distance is covered.

However, while capturing 2µm spaced echo signal makes our scanned data more quality but it also introduces a memory issue to our system. So, to overcome such case it is mandatory to implement a mathematical sampling technique.

In this work step size sampling method is implemented, by implementing step size mechanism the load of controlling pulse echo relay on ATmega processor.

$$Distance\ in\ X = Step\ size(X) \times record\ length \tag{2}$$

$$Distance\ in\ Y\ or\ B\ scan\ length = Step\ size(Y) \times raw\ length \tag{3}$$

The same spaced blue squares represent number of pulse echoes. Linearly sequenced amplitude scans (A scan) are called B scan as formerly explained in chapter 2. Those lines in Figure 12, that are equally spaced by the Y-step size latter will form a fully completed scan image of a given test sample. But due to the directional difference of scan data occurs to be misaligned. This misalignment is solved and is explained in section B.

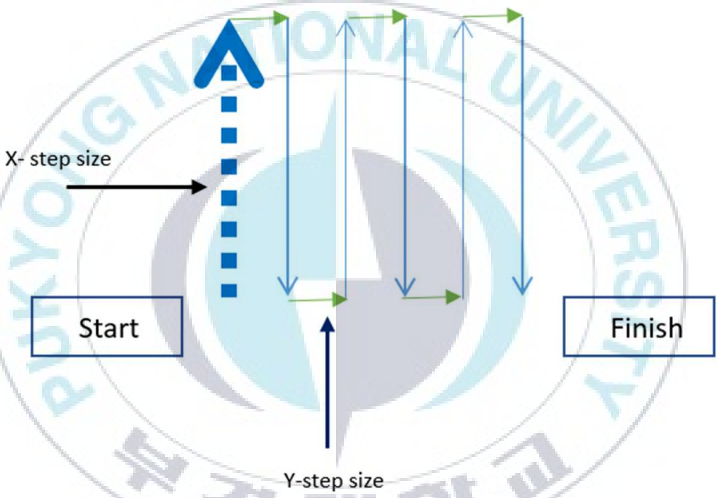


Figure 13 Step size and Scanning Start- Finish pattern

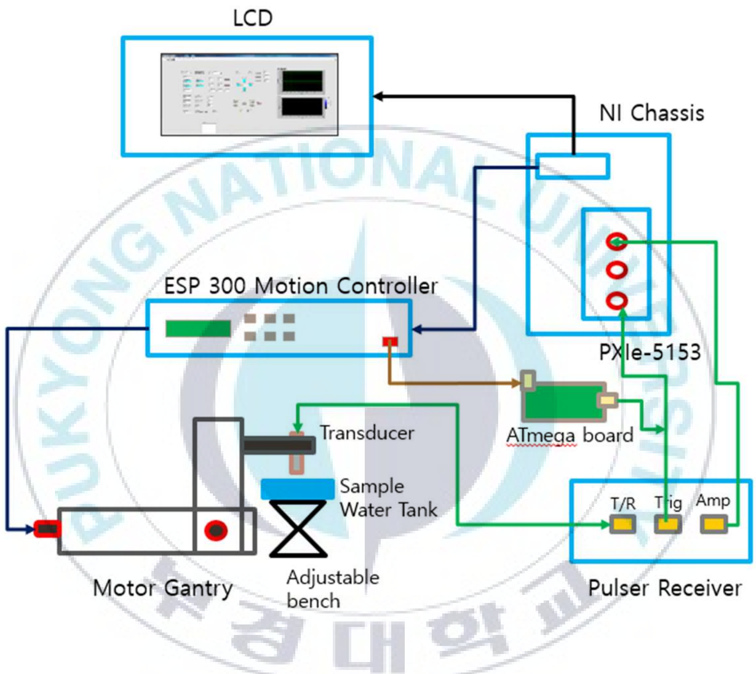


Figure 14 Acoustic Scanner Setup

Using ATmega processor and the motion controller[15] it was possible to calibrate and adjust X-step size as to scanning step size interest. By doing this the resolution of image can also be affected, for this reason selecting optimized step size comes after numeral trials.

$$X \ step \ size = Encoder \ step \ size \times Pulse \ count \quad (4)$$

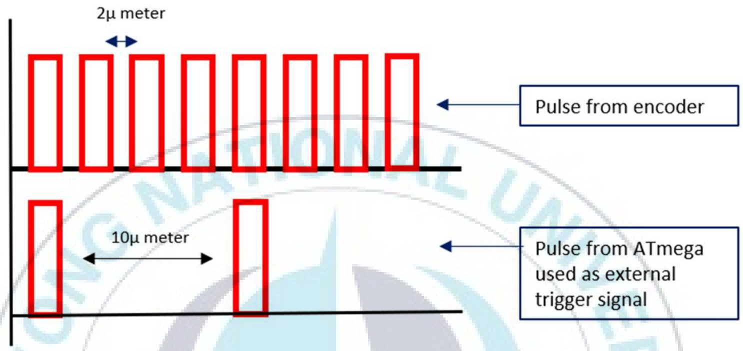


Figure 15 Automating Calibration of step size by pulse counting

As shown in Figure 14 by changing the interrupt counting feature of ATmega processor it is doable to increase or decrease the step size value. By that it also affects almost linearly the resolution of the scanned sample.

B) System flow diagram

This section is about how the system performs its task sequentially. Operating the end user graphical user interface is one thing but understanding the effect of each modules gives an effective alternative in mitigating an added-up error value.

As depicted in Figure 16 the steps from setting up a sample to finally getting a result are clearly communicated. The system block diagram can be explained in three parts for the purpose of clarity.

The first part is physical setting up of a sample. This can be done automatically with a bit help of setting manually the adjustable table for the Immersion transducer in Z-direction (referencing in three axis coordinate system). once the height difference between immersion transducer and sample is defined it stays constant for the rest of process. However, for XY axis, since the transducer will move both in X and Y direction sequentially, setting it up using GUI is necessary. For this the end user is expected to define its “Home” position, step size in X axis and number of scanned B scan will be equated using equation (2).

The second part is setting up the parameters for digital oscilloscope. This includes setting up sampling rate- this value is mostly depend on what kind of digital national instrument digital oscilloscope (NI PXIe) we are using. In this work 1 up to 2 GS/sec can be used. Time of flight or pulse echo trigger delay also need to be set by adjusting the exact position and after assuring a maximum amplitude echo signal is achieved.

The third part is setting up image resolution zoom value and background contour white-black ratio. This defines that which signal should be read and recognized as maximum and which a minimum. By doing so it- the white-black resolution of the image can be affected linearly. Since the signal is converted into to 2^8 bits so the white-black contour will expand from 0 to 250 while 0 holds for black and 250 corresponds to white. Here, figure 16 shows that how the pulse echo signal that is transformed using Hilbert transform is sequenced and aligned to form an image.

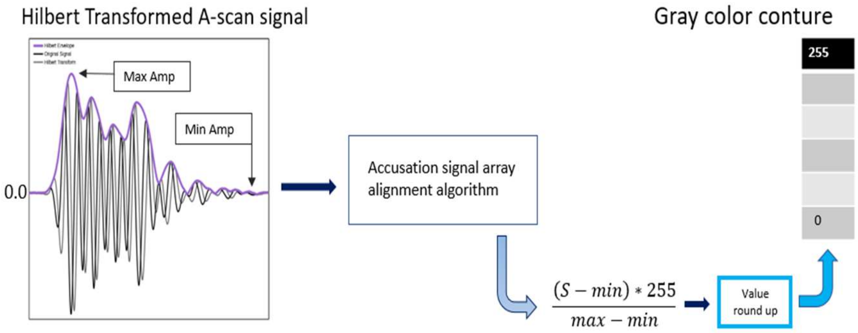


Figure 16 Acoustic signal to image formation

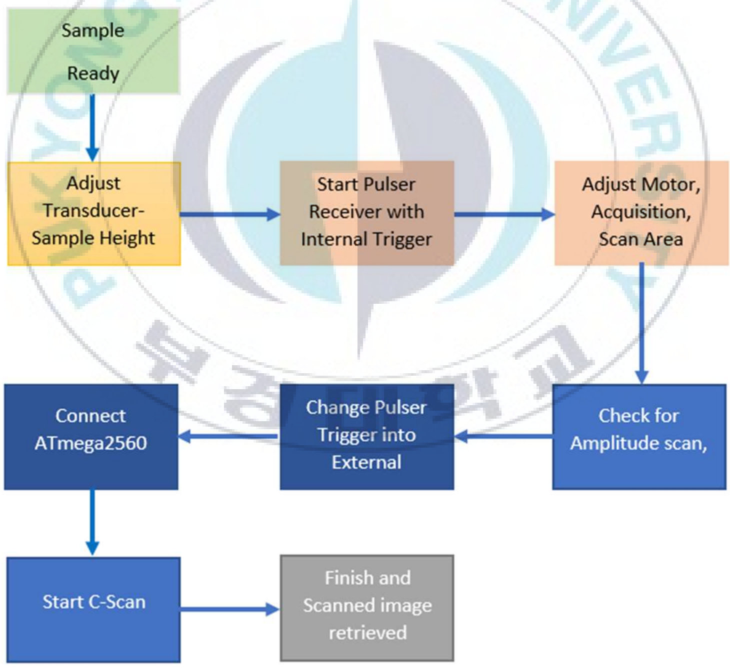


Figure 17 Flow diagram of Acoustic Scanner

Chapter 4 Experiment and Results

Acoustic scanning for inspection application is experimented in this chapter and results are found. Those results alongside the theoretical and technical interpretation will be covered, respectively.

4.1 Experiment

The experiment conducted was scanning 2.5 by 5mm area and check if any defects are there inside. For purpose, the circuit shown below is used. The size of the circuit board is $45mm^2$ the portion indicated by yellow box is scanned. The images are displayed in the result section. Feed data to the acoustic scanner program are categorized in table. For comparison 10 cent coin is also scanned both at 20μm and 10 μm resolution space.

Figure 18 coin sample-10 cent for scanning inspection

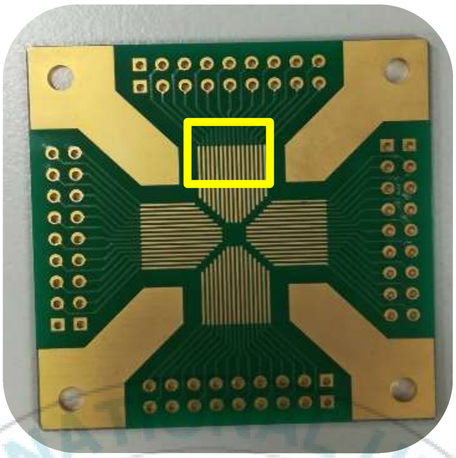


Figure 19 Sample PCB for Acoustic scanner inspection

Table 5 scanning configuration

Parameters	Value
Immersion Transducer	50 MHz
Sampling rate	1GS/sec
Record length	1000
Trigger delay	14.5μs

4.2 Result

Three scans were performed for the circuit board, for the first two the setting for the max gray contour value was 1.5 and 0.8 for this reason blackish and bright scan was achieved and the considerable defects were not detected.

However, on our third trial considerable defects were observed and when the writer of this paper (inspector in this case) study the surface of the PCB there were a bubble residue on the board (figure 23).

For the 10-cent coin, two scans were performed with different sampling step size while maintaining same white-black contour to minimum of 0.02 and maximum 0.8.

Scanning step size: 20μm   Scanning step size: 10μm

Figure 20 Scanned 10 cent coin with different sampling step size

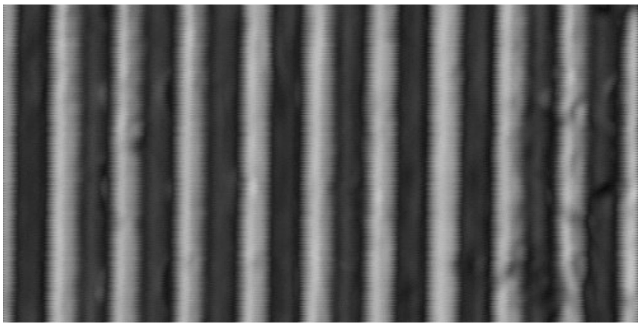


Figure 21 Scanned PCB with grey contour level Max 1.5 with Min 0.02

Figure 22 Scanned PCB with grey contour level Max 0.8 with Min 0.02

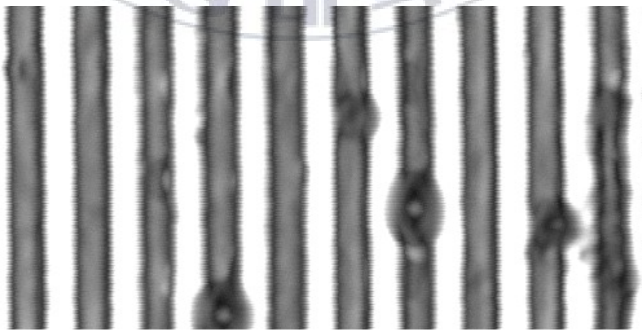


Figure 23 Scanned PCB with grey contour level Max 0.8 with Min 0.02

Chapter 5 Discussion

From the results it was observed by applying Hilbert transformation mechanism a signal can retrieved and image can be constructed. Image can also replace optical images when it is well optimized and able to scan inner parts of samples. Not only that by catching the dynamic pulse echo signal it is observed that layers of a given sample can be scanned as Hyunung Yu mentioned in his work[7]. In our work the main purpose was to test top layer scan and for this as shown in figure 20-23 scanning with different step size and image resolution was proofed. Jian Chen and his team worked on measuring scan sample features[5]from the raw data collected during scanning time, In this work, thickness of a sample was tried during testing time using echo signal flight time. Having the flight time of A scan a thickness of an object can be measured. It was shown than in Sebastian Brand and et al [4] work that using high resolution transducers faults can be detected, same as that in some aspect, this work performed millimeter sized scan with only using 50 MHz transducers.

Chapter 6 Conclusion and Future work

In this thesis, setting up and system integration was undergone. Motion control system was programed to meet the requirements of scanning process. In addition, using appropriate NI instrument digitizer and supported software GUI is developed to enable inspection personnel perform intended investigation with ease.

6.1 Conclusion

It has been observed that since SAM system is an integration of several sub systems that can stand out as a major research topic by themselves, the efficiency depends on each element. For this reason, in this work scanning of single layer performed fully.

The application of Hilbert transformation mechanism in signal acquisition and processing is explained and applied. Encouraging results are found that gives more energy and feedback on how to take work more in in depth and wider.

However, key limits are also noted during experiment expectation and results. The main limits were scanning bottom layer from top side. The writer believes that this limitation is coming from two points described below followed by future work.

- The efficiency of Transducer used.
- The lack effective optimization of writer's program.

6.2 Future Work

Acoustic scanning technique is one of the newly attention getting approaches for inspection application. The core part of this work was scanning millimeter sized samples. However not only scanning, but it can also be developed further, and analysis and customization can be undertaken to meet specific customer demands for numerous applications that fulfills interests.

It is shown that ultrasound can be used in replacement of optical inspection due to the feature ultrasound poses when it comes to analyzing inner part of samples. However, this distinct quality relay on high quality low frequency transducers, high sample rate wide bit size digitizers and customization of the processing methodology in a way that can catch the dynamic amplitude differences (gate catching).

Appendices

A Figures of LabVIEW Block Function

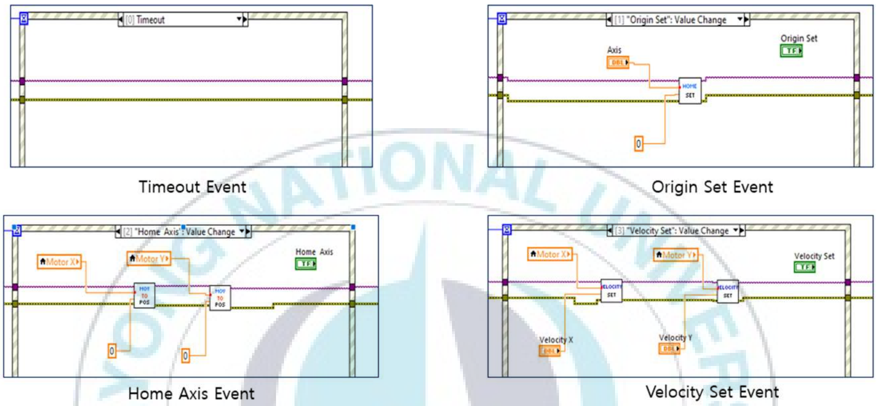


Figure 24 Motor functions used for setting Origin, Velocity and Time out state

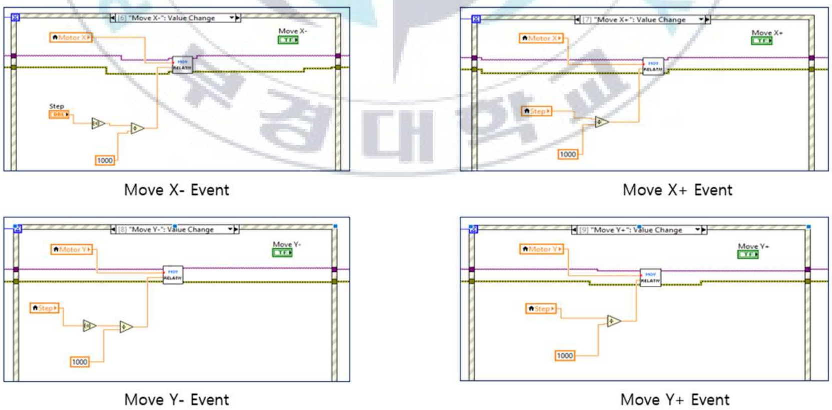
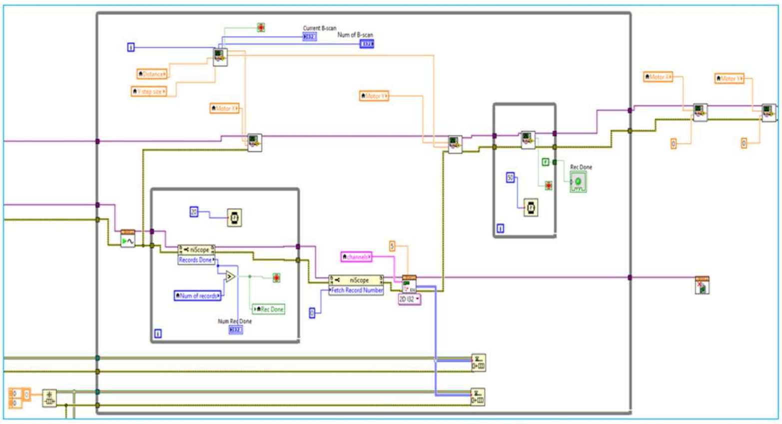
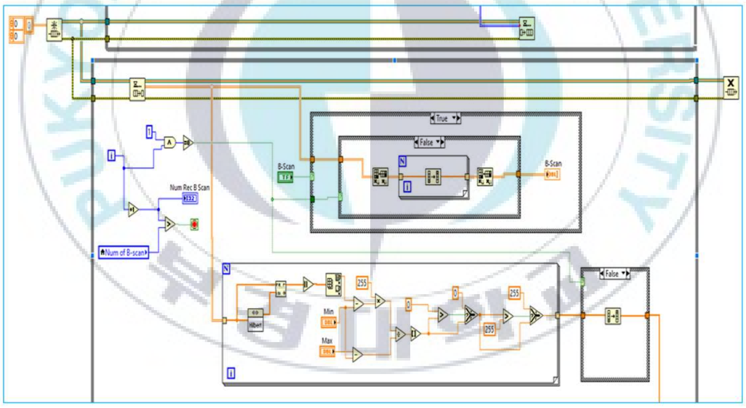


Figure 25 Motor function used for setting scan area and related movements



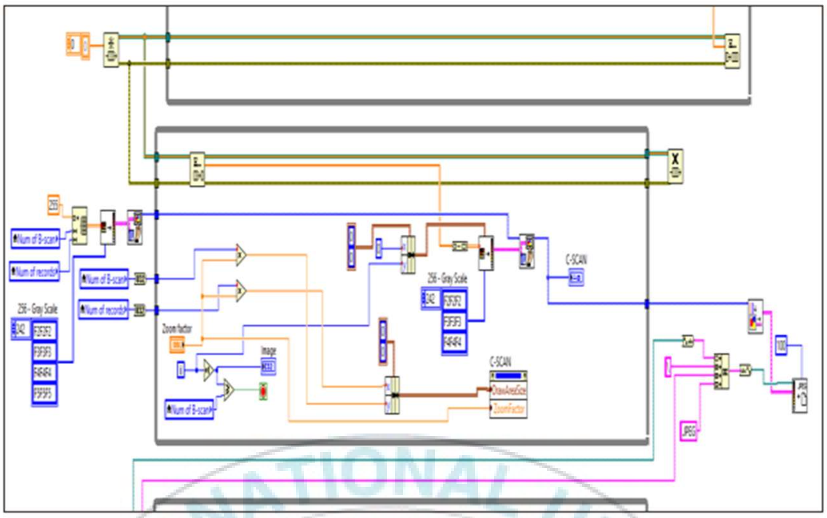
Dynamic motor control Block function

Figure 26 Dynamic Motor movement controller function for X-Y scanning



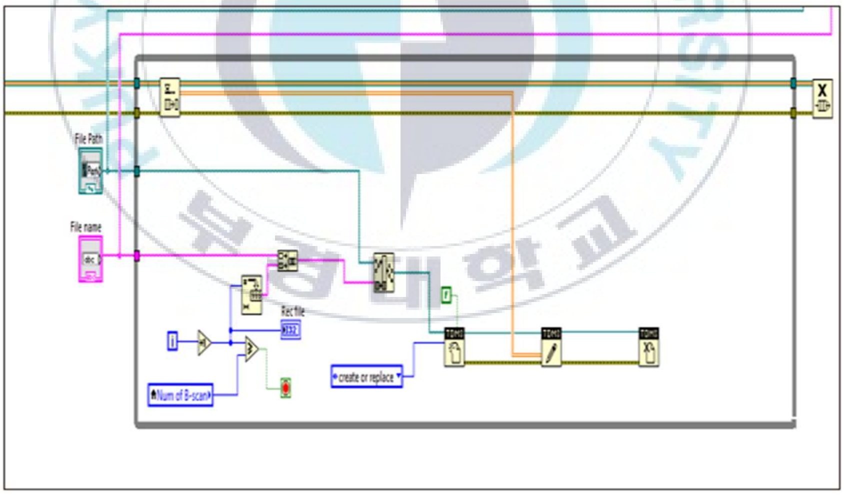
Dynamic B-scan Block function

Figure 27 Cross sectional scan or B scan controller unit



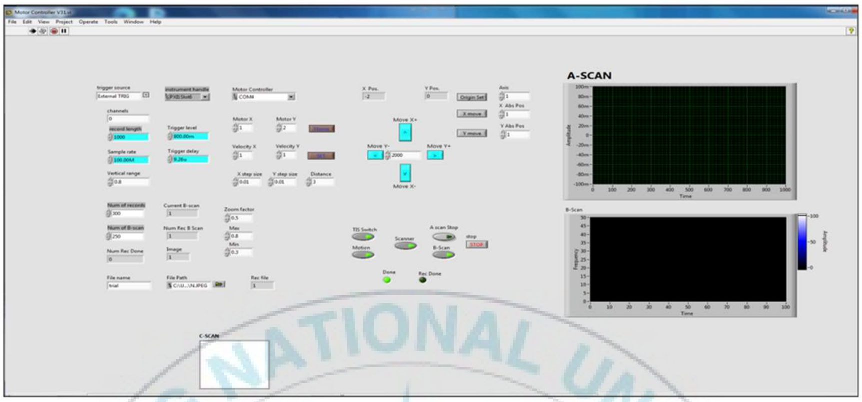
C-scan Block function

Figure 28 Lateral scan or C scan controller



Data storage Block function

Figure 29 Final Data storage or image storage file path controller



Front End GUI Block

Figure 30 End User compatible Graphical User Interface

B Newport Motor Performance Specifications

	Resolution (μm)	Speed (mm/sec)	Motor
(M-)UTMCC.1	0.1	5	UE33CC
(M-)UTMCC1HL	1	20	UE404CC
M-UTMCC.5HA	0.5		

Figure 31 Resolution and speed max limit of UE33CC and UE404CC Motors[9]

[9] Image source: [15]

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Korean Abstract

비파과 테스트 애플리케이션을 위한 음향 스캐너의 설계 및 구현

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요약

음향 스캐너는 초음파를 사용하여 샘플을 스캔하는 것을 말합니다.
소리가 다른 재료를 통과하고 그 대가로 다른 매체를 통과할 때 뚜렷한 피드백을 나타내는 특성과 능력으로 인해 초음파는 비파괴적인 방식으로 결함을 감지하고 식별하는 데 탁월합니다. 이 연구에서는 데이터 수집, 프로세스 및 이미지 형성에 회색 윤곽 메커니즘과 함께 힐베르트 변환의 원리를 사용합니다. LabVIEW

기반 모터 제어를 기반으로 기대한 결과를 얻기 위해 스캐닝 기능 블록이 구성됩니다.
사용자(검사 직원)의 편의를 위해 최종 사용자 그래픽 사용자 인터페이스가 개발되었습니다. 시스템 수준 개발 및 통합은 침지 변환기, 모션 제어 및 OHlabs 펄스 수신기를 사용하여 달성됩니다. 인코더 신호는 내쇼날인스트루먼트(NI) 기반 디지털 오실로스코프뿐만 아니라 모터 드라이버와 펄스 수신기 간의 동기화된 작업을 위해 ATmega 프로세서를 사용하여 수집됩니다.
그 결과, 상부 표면 스캐닝이 수행되고 고무적인 출력이 관찰됩니다. 그러나 본 논문의 저자는 보다 발전되고 정확한 결과를 위해서는 더 많은 연구와 상세한 연구가 필요하다고 생각한다.