Thesis for the Degree of Master of Engineering

Automatic sample tracking in ultrasonic testing system utilizing deep learning

By

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Department of Interdisciplinary Program of Biomedical

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The Graduate School

Pukyong National University

August 2020

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（딥러닝을 활용한 초음파 검사 시스템의 자동 샘플 추적）

Advisor: Prof. Junghwan Oh

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Ly Cao Duong

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A dissertation

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Abstract

Ultrasonic testing (UT) system is a family of non-destructive testing techniques has been developed to conduct examinations and make measurements of material, part or component without causing destruction. Recently, in almost UT system, in order to determine the coordinate dimension of a sample, it is manually operated. However, it took a long time and difficult to finish doing an operation. Furthermore, the system operator had to be trained, learning skill or getting qualification before use the machine or equipment. As the result of this inconvenience, a based-lab system for automatically detect sample is in needed. In this thesis, by combine image processing and YOLOv3 deep learning with the UT system, we introduce the vision solution can help identify, determine and track coordinate, size or shape of the sample. In addition, the combination of vision and motion control are used to optimize the scanning process, procedure and operation.

Keywords: Ultrasonic testing system, non-destructive testing techniques, image processing, YOLOv3, deep learning, vision, motion control

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Chapter 1. Introduction

According to a recently technology industry, non-destructive testing (NDT) system has been used widely to get and evaluate the structure, quality of a material without causing damage. This technology is called by many definitions, the three commonly name are nondestructive inspection (NDI), nondestructive examination (NDE) and nondestructive evaluation (NDE). Ultrasonic, radiographic, eddy-current, magnetic-particle, visual testing, … are the most frequently method used for NDT system. [1]

As the family of NDT system, the ultrasound testing (UT) system can measure the parts of a sample in micrometer by acoustic signal. The ultrasound wave is highly sensitive to a difference in acoustic impedances (Z) between two materials which is suitable for having microstructural properties of material placed inside water.

Figure 1: The ultrasound testing system [2]

The UT system provides A-scan, B-scan, C-scan and 3D (three-dimensional) image. A-scan image, also known as amplitude mode display the data when accurate distance measurements are required. B-scan image is a brightness pixel display screen proportional to the echo signal amplitude. C-scan image provide a 2D (two-dimensional) section to examine defects inside a material.

In order to get the data, the UT system has to be took by 2 rotary motors and 1 linear motor along Y, Z and X axis. The operator has to control the UT system by our software to move the transducer to the sample position.

It took a long time and manually for industry. To be automation and faster, combined vision with UT system was applied in our system. By using the camera keep on the Z axis, we can develop the vision system for automation tracking, moving and detecting sample. Furthermore, vision system can provide efficient solutions to measurement of dimension and shape of sample.

Besides that, the automatic guild imaging has been applied as automation system for tracking object such as coin, steal or copper with multi-layer structure. It is widely used for others sample which can place inside our water tank. Vision system is especially suitable for this application. Because of many kinds of sample, the demands for object tracking is a big problem to be achieved. Currently, there are many deep learning platforms can solve this problem, in one of them, you only look one (YOLO) is a clever convolutional neural network (CNN) for fast and accurate tracking object in real-time.

In our system, the camera can increase the scanning speed significantly. Not only reduce the scanning time but also can measure, detect object real-time. It can be called pre-treatment stage for measure ultrasound image after scanning. In this study, we concentrate on real-time tracking and motion controlling for UT system. In addition, we apply deep learning to predict the object after short time training by YOLOv3, our machine can learn, trial and predict any kind of sample quickly and easily with high accuracy.

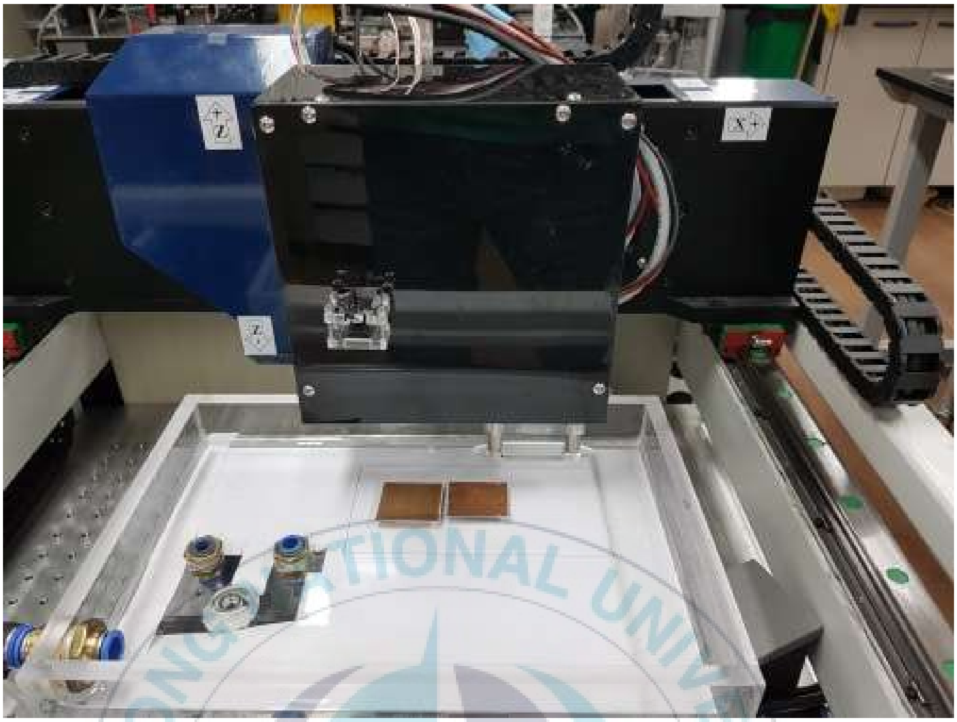


Figure 2: UT system with Camera

Chapter 2. Materials and methods

1. Motion control

For the motion control, the UT system using 3 AC servo motors, 2 rotary motors for Y and Z axis and 1 linear motor for X axis. In order to control the motor, we use the AC servo driver form Mitsubishi and Panasonic.

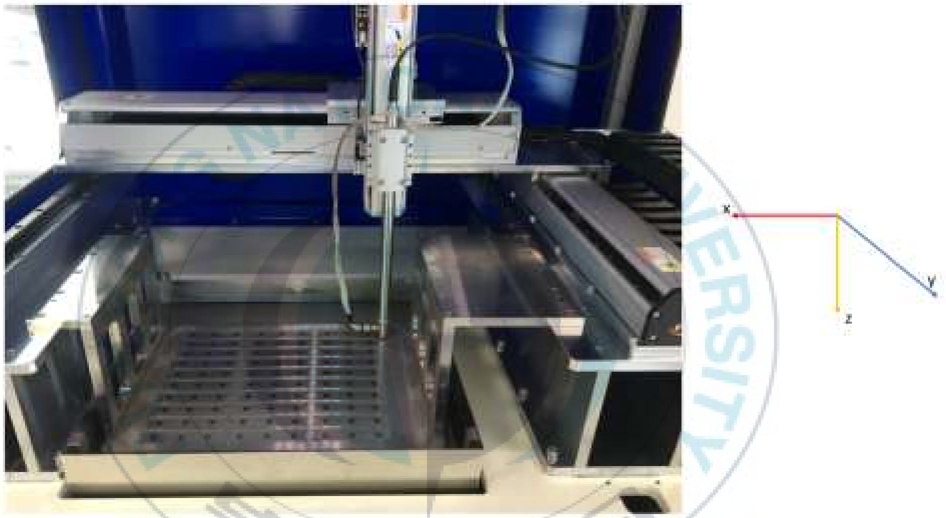


Figure 3: 3-Axis UT system [2]

1.1. Basic information servo packs

Depend on the required parameters of the UT system, the AC servo driver Mitsubishi (MR-J4) and Panasonic (MINAS A6) were picked up. The MR-J4 driver is rotary motor driver which was chosen to control the Y and Z axis. The MINAS A6 was used for linear servo motor (X axis) which can couple the load directly with smooth motion and high positioning accuracy. The UT system parameters are mentioned on the Table 1 below.

Table 1: Parameters of UT system

	Motion type	Range (mm)	Max velocity (mm/s)	Step size (µm)
X axis	Linear	350	750	1
Y Axis	Ball screw	350	100	1
Z Axis	Ball screw	170	100	1

The MINAS A6 and MR-J4 servo driver are shown in Figure 4 and specifications are show in Table 2 and Table 3.

Figure 4: Panasonic MINAS A6 and Mitsubishi MR-J4 servo driver

Table 2: Mitsubishi MR-J4 servo driver specifications [3]

Type	Power supply	Interface	Rated output (W)
Rotary servo amplifier	3-phase 200VAC or 1-phase 200 V AC	General-purpose	400

Table 3: Panasonic MINAS A6 servo driver specifications [4]

Type	Power supply	Interface	Rated output (W)
Linear servo amplifier	3-phase 200VAC or 1-phase 200 V AC	General-purpose	1600

1.2. Pulse train references control

Servo amplifier is a powerful driver to control the servo motor. They provide many ways to control the motion. In our system, we chose pulse and direction mode using a differential signal.

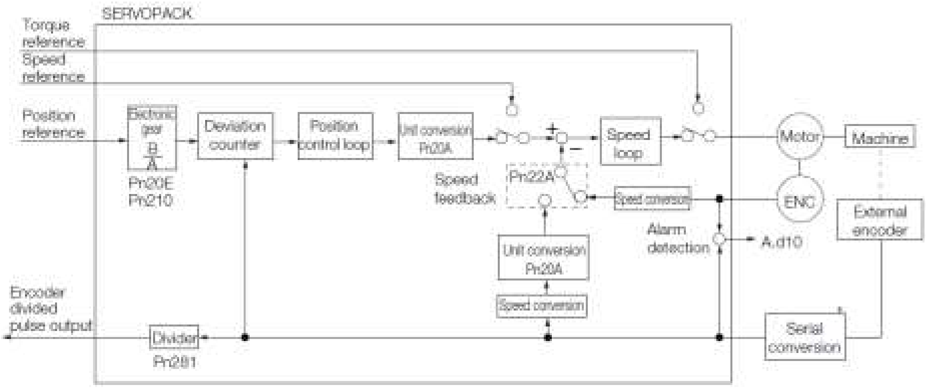


Figure 5: Pulse and direction position fully-closed loop control [5]

In order to input the reference to the driver, the input from the host controller must follow the specify which are shown on Table 4.

Table 4: Sign and Pulse train reference

Forward Reference	Reverse Reference
	

The line-driver IC SN75ALS174 from Texas Instrument is also used for the reference pulses and sign signal. The differential signal from line-driver to prevent the appearance of noise. The following diagrams show below on Figure 6.

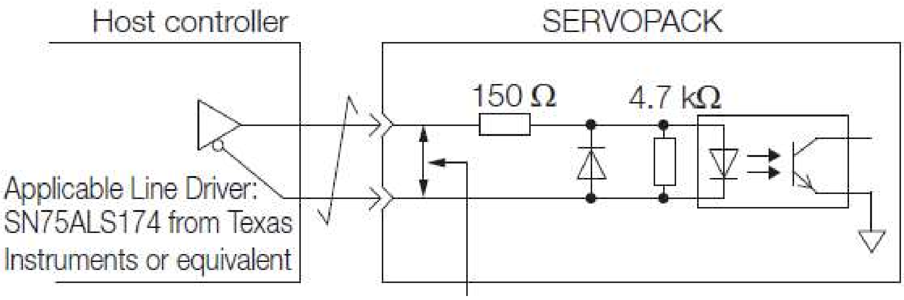


Figure 6: Line-driver output diagram [5]

2. YOLOv3

After finishing the motion control, the main goal is real-time sample detection. In our system, we use YOLO version 3 for sample detection. YOLO is one of deep learning model in order to detect the object on the image fast and accurately. YOLO can run on difference environments and it only needs to apply the model to each image once (You Only Look Once).

Currently, to perform detection the systems take a classifier for that object and evaluate it at various locations and scales in a test image. Systems like deformable parts models (DPM) use a sliding window approach where the classifier is run at evenly locations over the entire image. [6]

The YOLO detection system has 3 steps. Firstly, resizes the input image to 448 x 448. Secondly, runs a single convolutional network on the image. Finally, thresholds the resulting detections by model's confidence. [7]

This system divides the input image into an *S x S* grid. If the center of an object falls into a grid cell, that grid cell is responsible for detecting that object. [7]

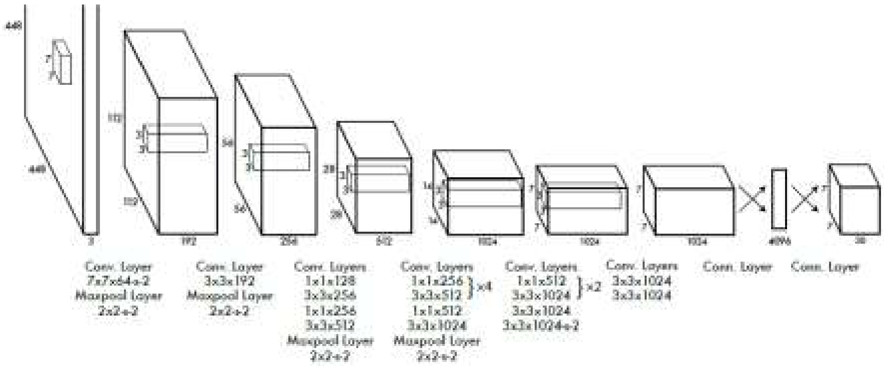


Figure 7: The YOLO Architecture [7]

In this technique, a coin or a PCB (printed circuit board) is chosen to train the data which results in class of the object and can be real-time detected by camera to provide information of the object such as: class, shape, size and coordinate dimensioning.

For the first training, the coin was chosen for training process. To demonstrate the result, we use 1000 images from internet with difference size, type, color and from difference country for training data.

Figure 8: Coin image dataset

In order to label a data, we labeled them manually with LabelImg. LabelImg is a software that is built in Python and Qt designer. The software can run on Linux and strongly support for labeling the data.

Figure 9: Labeling sample images

After labeling all the sample images, we separated sample image dataset in to train data and validate data. The train data with 80% random images from the dataset and 20% remain for validate data.

After 12 hours training with 60000 epochs, the average loss is 0.06. In order to verify the result, we take a picture of 3 types of coin sample in our lab and get the result on Figure 9 below.

Figure 10: Result of YOLO trained with coin sample

3. Coordinate dimensioning and contour determination

As mentioned in previous part, after classify the sample by YOLO and apply to the camera, it would identify and classify the sample on camera viewer. The main goal of our system which get coordinate dimensioning of each sample. In this technique, several image processing algorithms were applied which result in coordinate dimensioning to provide information of sample.

In the study, position “Left”, “Right”, “Top” and “Bottom” of sample is put on the top-left area of the camera viewer for visual identification. On figure 10 below, each color red, green, blue and turquoise defines left, right, top and bottom coordinate of the coin, and the value in side “[]” is x-coordinate and y-coordinate base on camera resolution and position [0,0] is extreme top-left point on camera viewer.

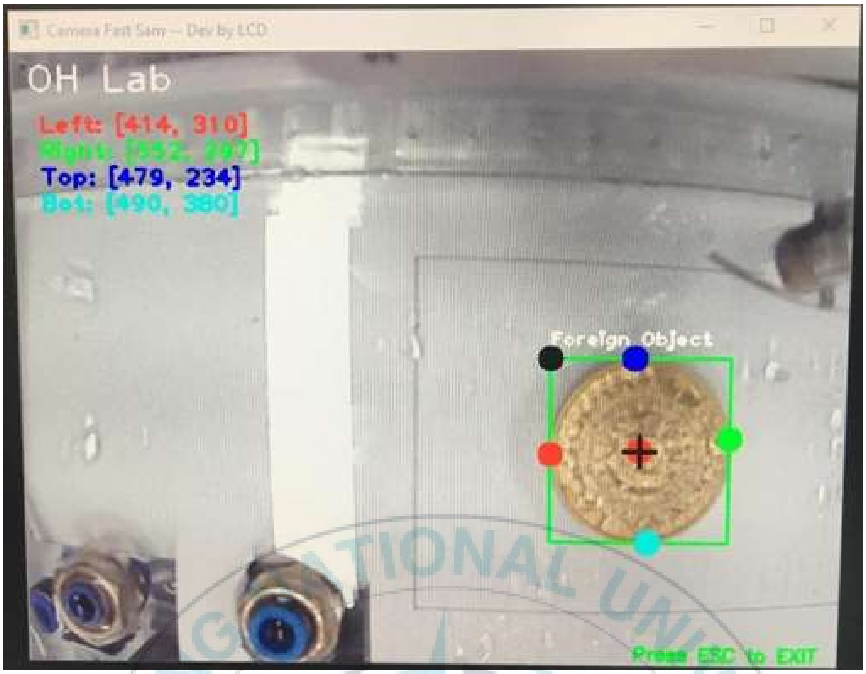


Figure 11: Demonstrate the coordinate dimensioning

In term of automatic motion control, in order to get a scan image, a single-element transducer will move to top-left point of sample (black point on Figure 10) and the camera will get rectangular bounding box to calculate dimensions and can be transferred to motion control board to provide information of sample.

The information of sample include class, start-point, shape, dimension, distance between transducer and start-point. In order to calculate distance between start-point and transducer, camera and transducer were fixed on Z-axis. As shown in Figure 11, center of camera was chosen zero-point (0,0) and the distance X and Y already known before by fix on Z-axis. There is no difficulty to calculate the distance between Transducer and start-point (purple line) by the Pythagorean algorithm.

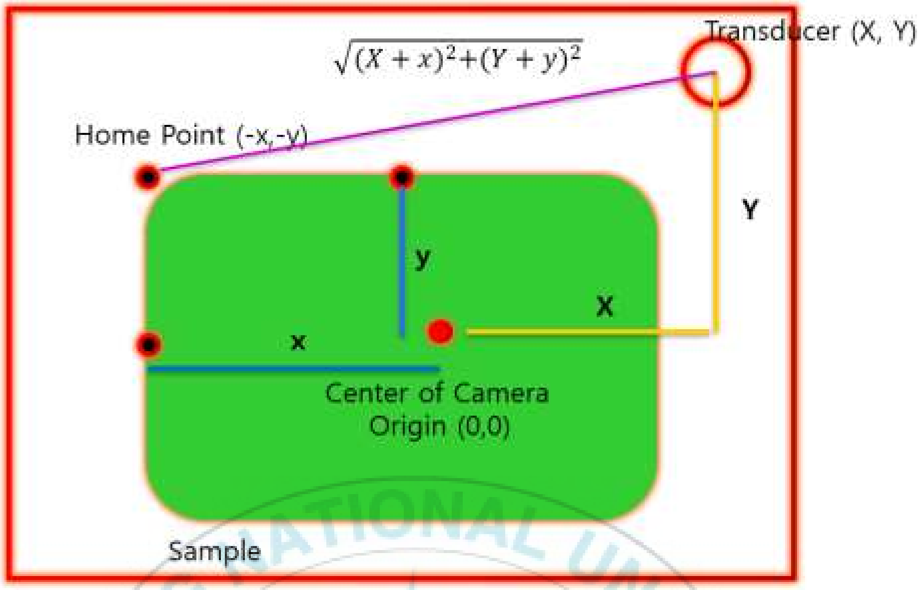


Figure 12: Demonstrate algorithm in calculating distance

In original scanning method, we have to scan all rectangular area as shown in Figure 12. In term of boosting scanning performance with advanced feature, the transducer will scan over the sample area in zigzags. This feature can help reduce the time scanning and memory data significantly. The difference between original and extend feature as shown in Figure 12 and Figure 13.

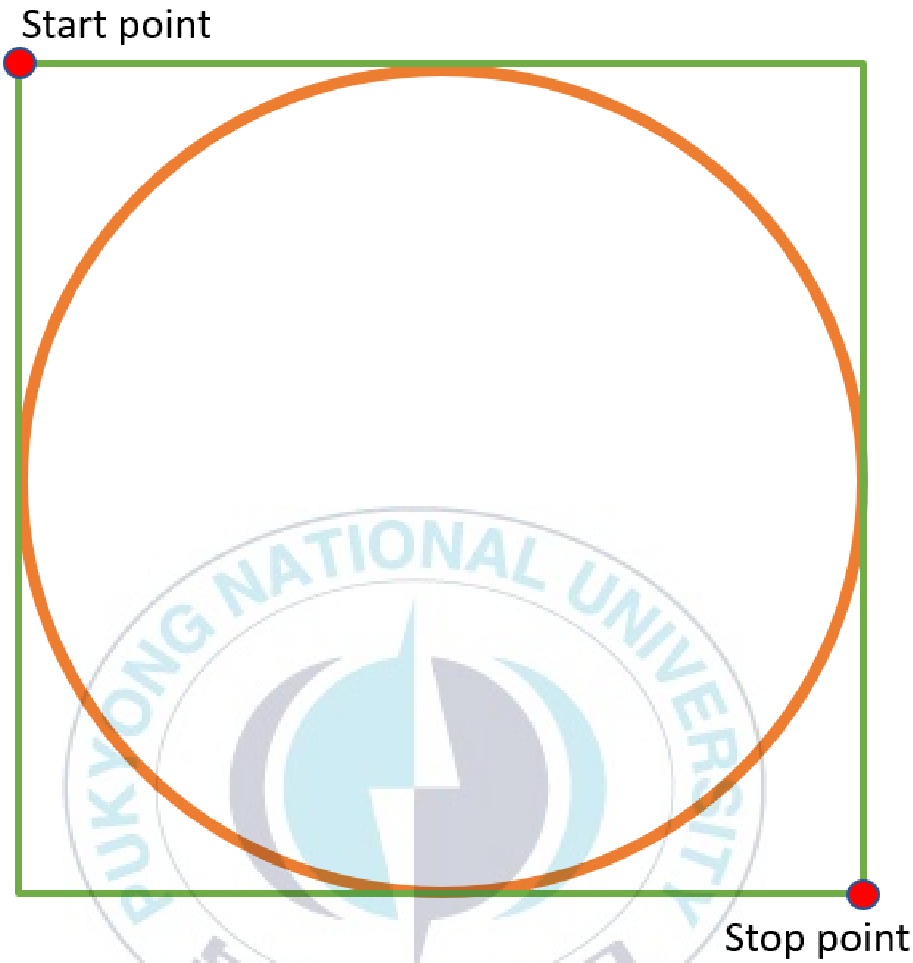


Figure 13: Original scanning method

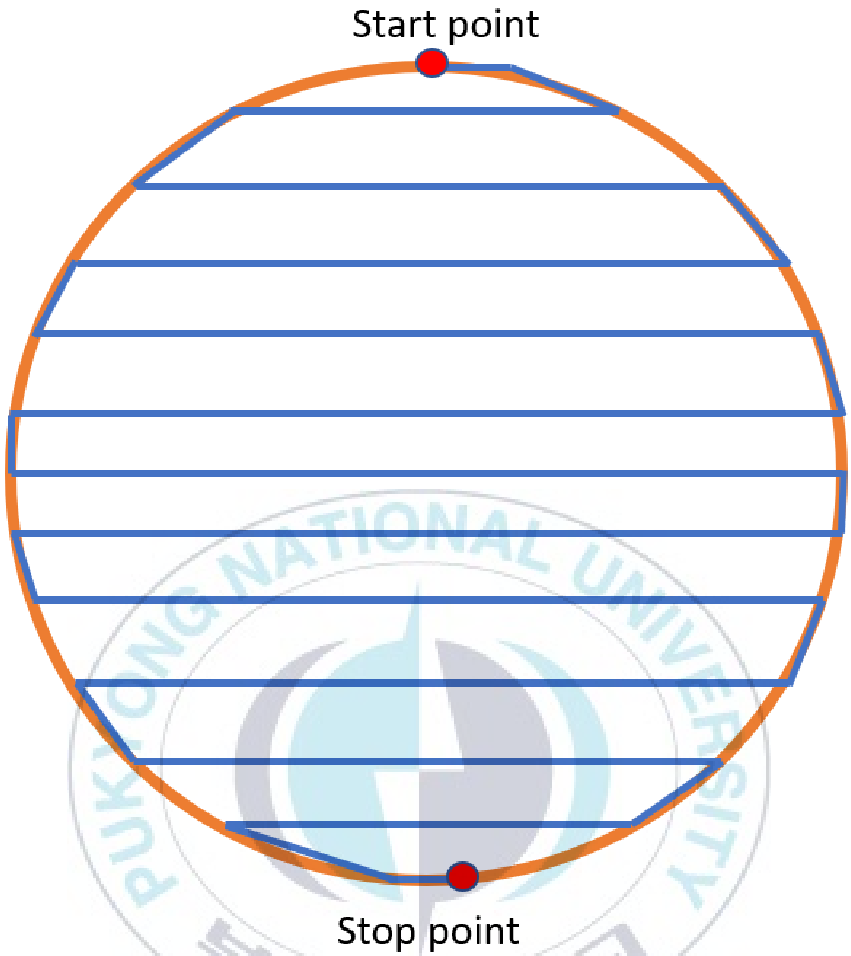


Figure 14: Advanced scanning method

The contours of sample are determined by contour features in OpenCV (Open source computer vision) library. After get all the contours point, the camera saves it to 1D array data. Because of the outer contours return oriented counter-clockwise, in order to move the transducer in zigzags, a data pre-processing was applied which is sort the data into zigzag pattern. Finally, all data was reconstructed into a standard and send to motion control board.

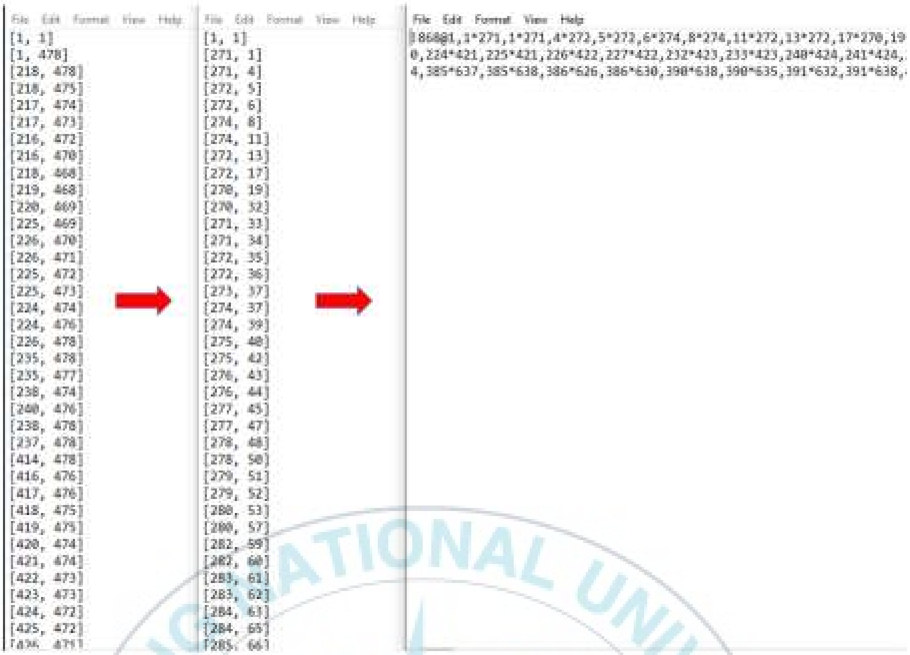
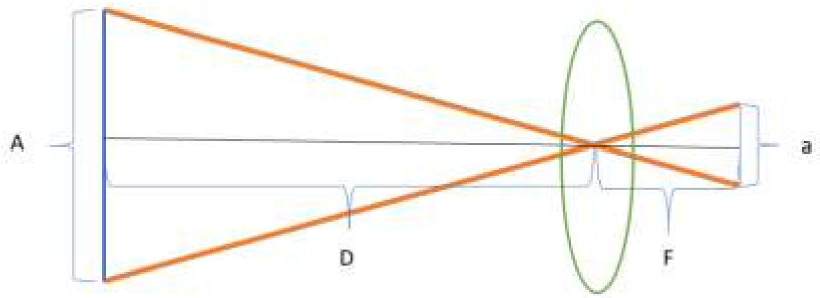


Figure 15: Demonstrate data processing and reconstructing

In order to measure the real distance or size of sample in µm, the calibration process was prepared. By choosing object we know height and fix the distance between focal point and image plane, beside know the focal length and real size of pixel in µm. The value of ratio is calculated by f = F/D where f is ratio value, F is focal length in µm and D is distance between focal point and image plane in µm.



$$f = \frac{a}{A} = \frac{F}{D}$$

- f: ratio
- F: focal length (m)
- D: distance between focal point and image plane (m)
- a: object's height (m)
- A: know height (m)

Figure 16: Demonstrate measuring the size of an object

After calibration, the real size of the sample or distance can measure by A = a/f where A is a real size or real distance in µm, a is object's height in camera sensor convert from pixel to µm and f is ratio as shown in Figure 15 above.

Chapter 3. System designs

1. Motion control system

In this study, after convert camera data to real size and distance, the controller for motion control in need. STM32 microcontroller was chosen as the heart of motion control system. This is type of 32-bit microcontrollers based on the Arm Cortex-M processor combining high performance signal processing and low-power operation.

Figure 17: STM32F407VGT6 discovery board [8]

Table 5: STM32F407VGT6 characteristics [8]

Model	Core	Supply and I/O	Oscillator	Fast I/O
STM32F407	32-bit Cortex M4	1.8 V to 3.6V	8 MHz	84 MHz
A/D converters	I/O ports	UART	Timer	DMA
3x12-bit	140	4 USARTs	17 timers	16-stream DMA

1.1. Motion control block diagram

Depend on UT system parameters, the main board control was designed based on STM32F4 microcontroller discovery board. The main board include 4-Axis motion control ports utilizing high performance pulse generation.

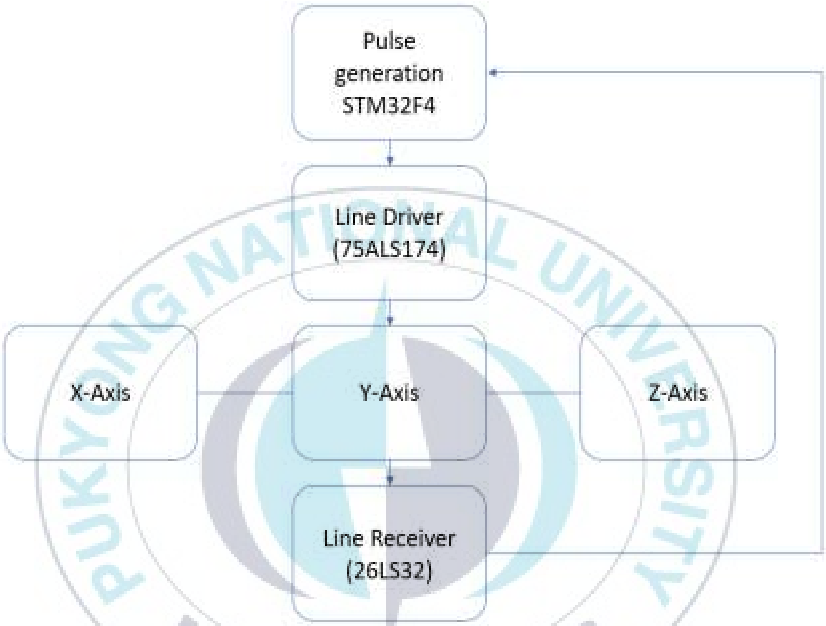


Figure 18: Motion control block diagram

The microcontroller generates the pulse signal which have range from 1 Hz to 1 MHz to control the motor speed. The microcontroller control number of pulses with duty cycle 50% in order to determines position of motor which is respective to AC Servo Amplifier standard.

The line driver IC (integrated circuit) creates the differential signal 5V TTL follow the input signal from microcontroller. This is a particular way to transfer electrically information using two different pair of signals which can resists noise from EMI (electromagnetic interference) noise and increases the transmission distances between pulser and receiver IC.

In order to optimizes timing control by decrease delay time between two times control after reached the desired position. The line receiver IC was applied to read encoder feedback signals from AC servo amplifier. Microcontroller started activated counters and compared with number of pulses generated from microcontroller ware created before.

Three main parts of motion control system: microcontroller, line driver, line receiver IC is combined together in to a motion control board circuit. We included 9 sensor ports which is isolated by optocoupler for home and proximity sensors, each axis content 2 proximity sensors and 1 home sensor. Furthermore, 4 general purpose I/O 24V pins were added into control board for extension.

1.2. Schematic Diagram

In this study, Altium Designer was used to design the circuit principle of motion control system. The schematic can help manage and understand the block diagram in previous part more easily.

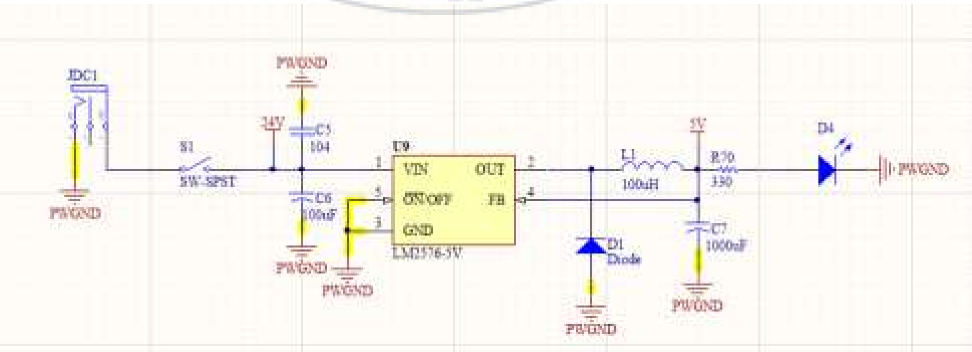


Figure 19: Control board power supply schematic

All main parts of motion control circuit use 5V DC power supply input, there for the power switcher IC LM2576-5V form Texas Instrument is used to convert unregulated DC input to 5V DC.

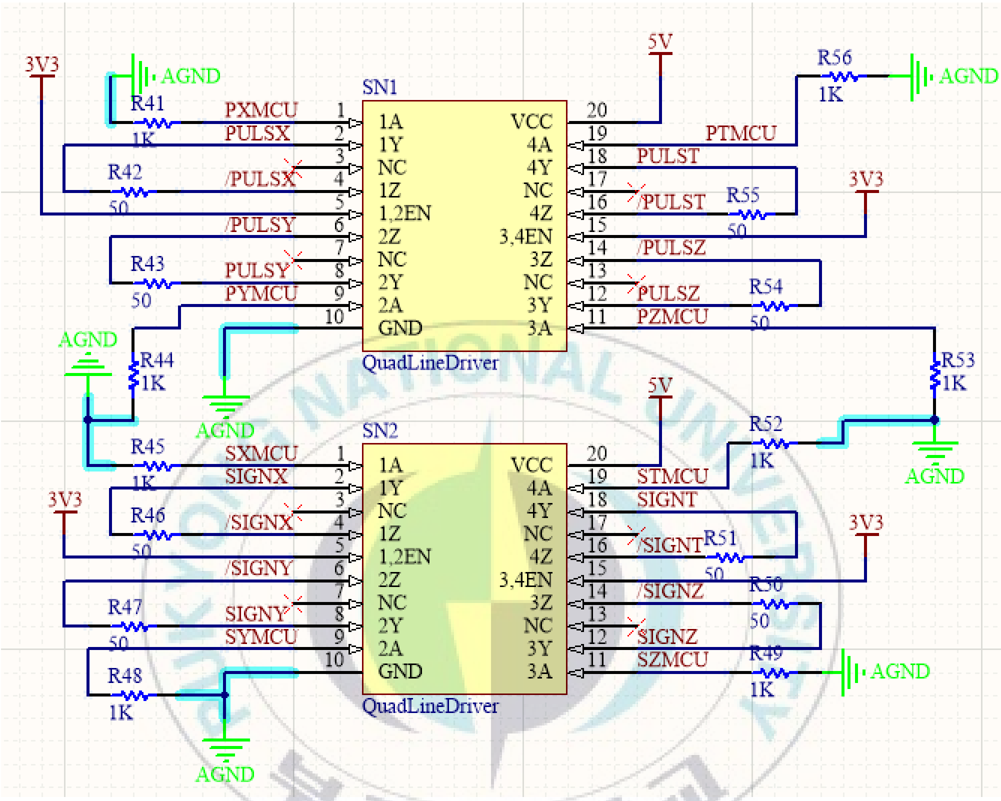


Figure 20: Line driver 75ALS174 schematic

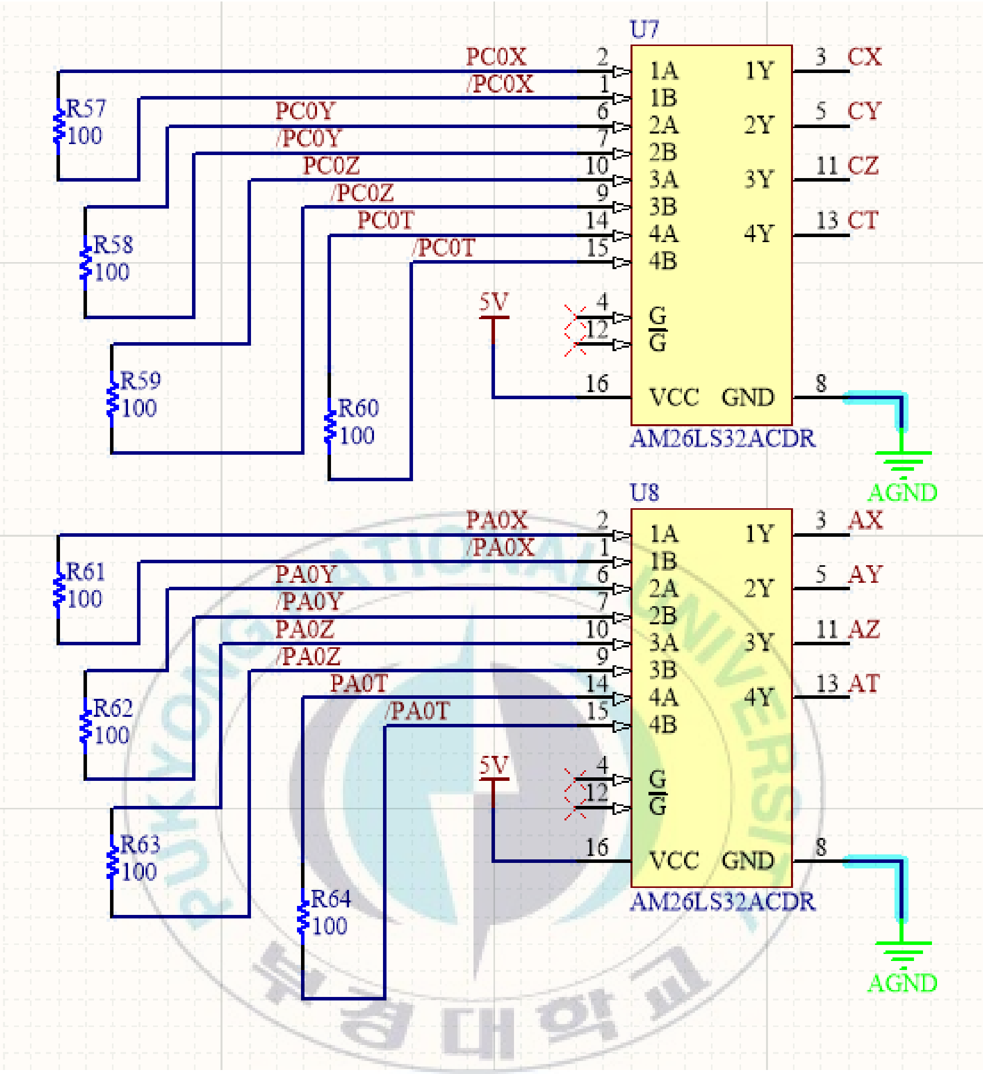


Figure 21: Line receiver 26LS32 schematic

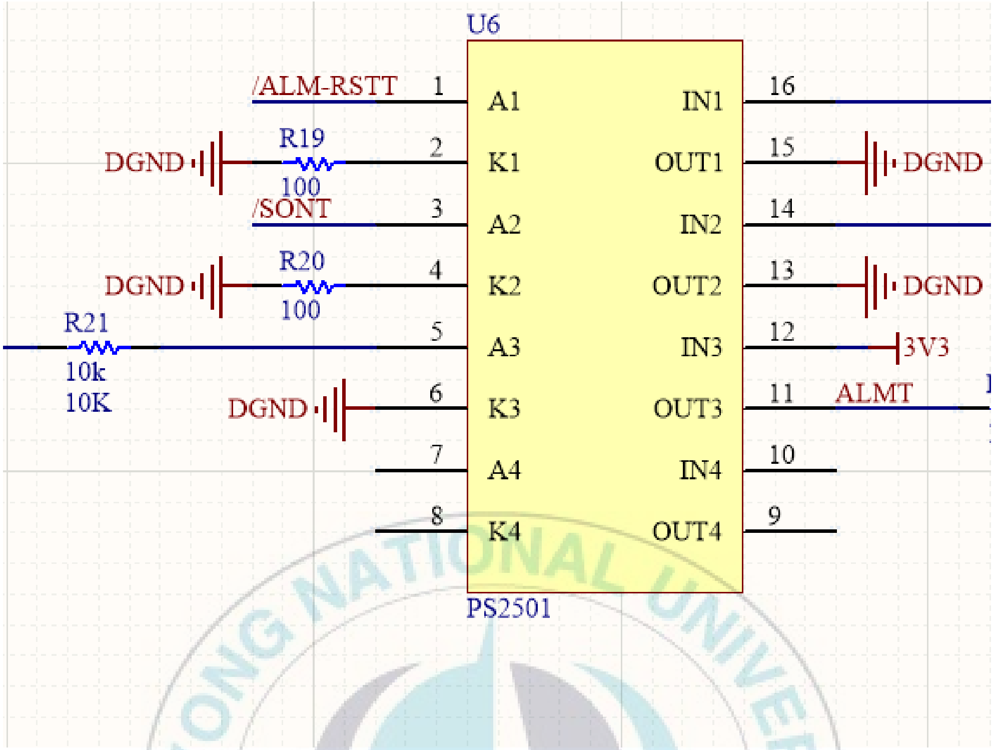


Figure 22: Isolated optocoupler PS2501 schematic

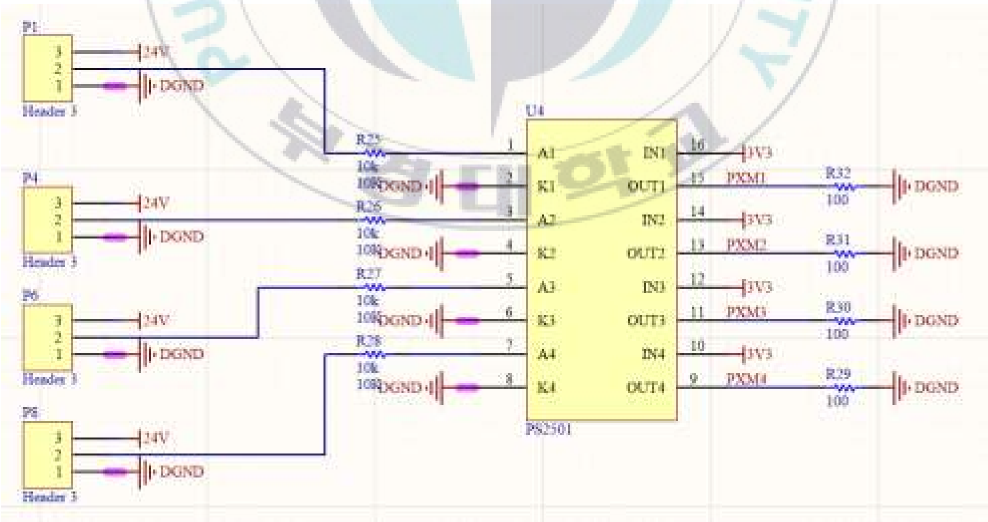


Figure 23: 24V general purpose input schematic

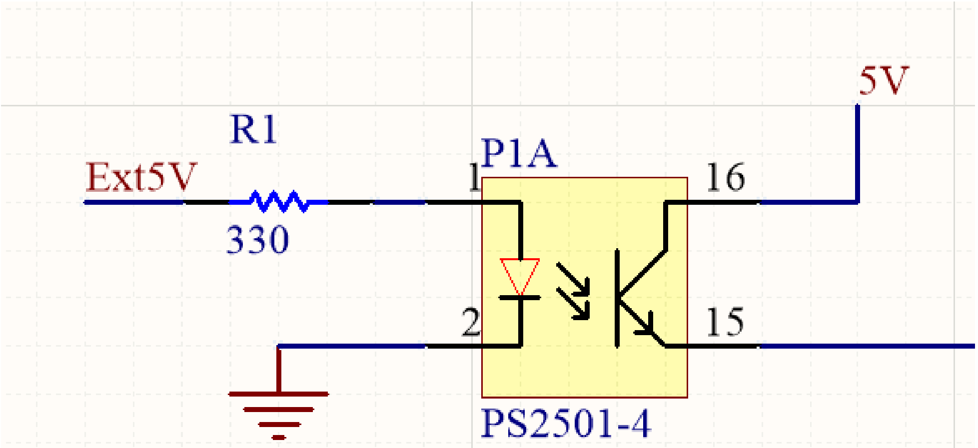


Figure 24: 5V general purpose output schematic

1.3. Printed Circuit Board (PCB) and 3D viewer

The motion control board was designed in 2 layers with SMD (surface mount devices) and THD (through hole devices) mounted on surface. The PCB was devised to 3 parts: power supply, microcontroller and driver signal.

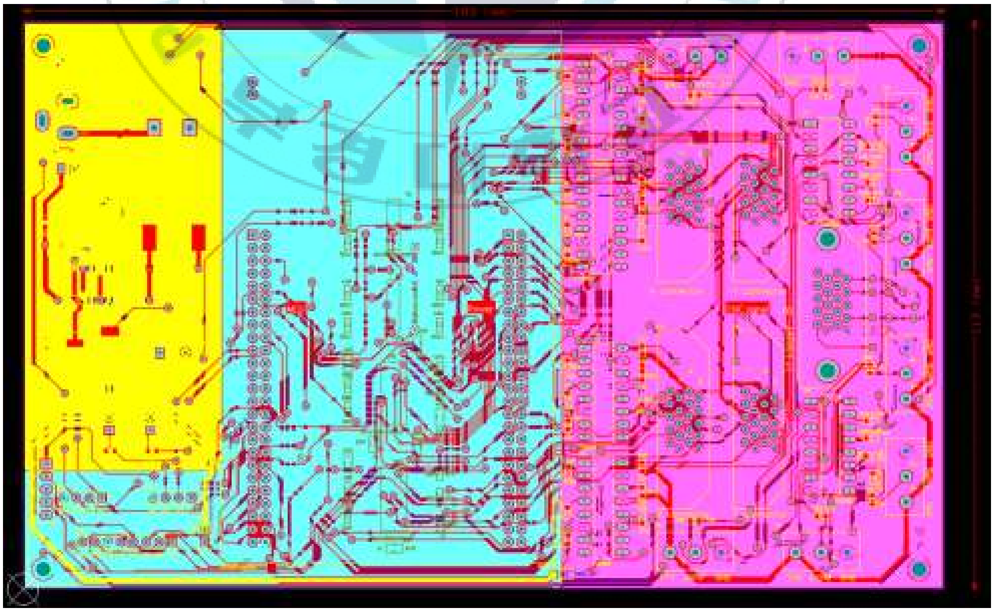


Figure 25: Motion control board Top layer

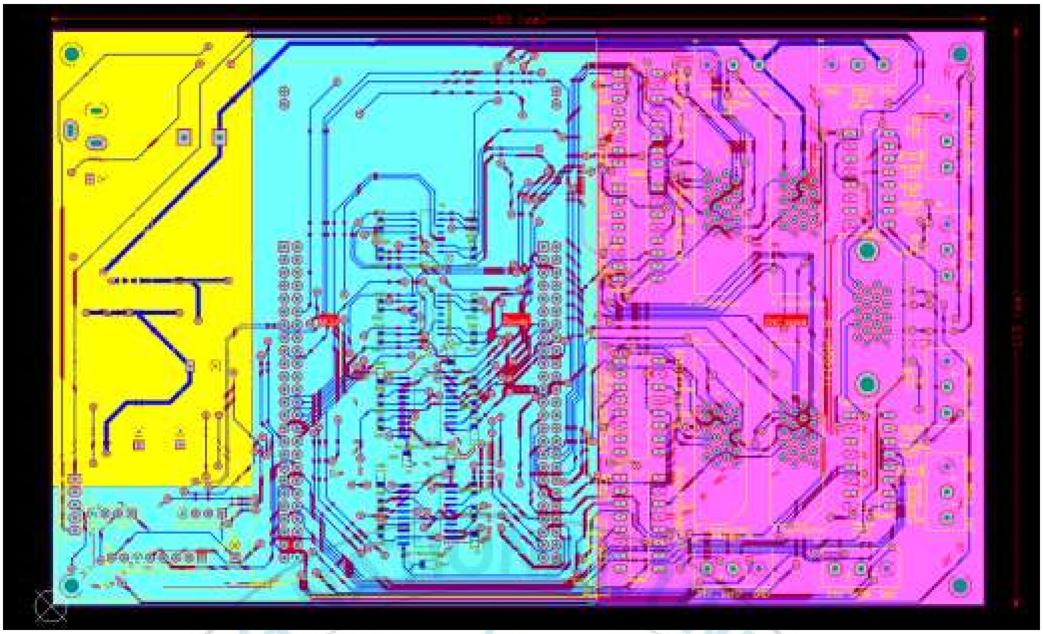


Figure 26: Motion control board Bottom layer

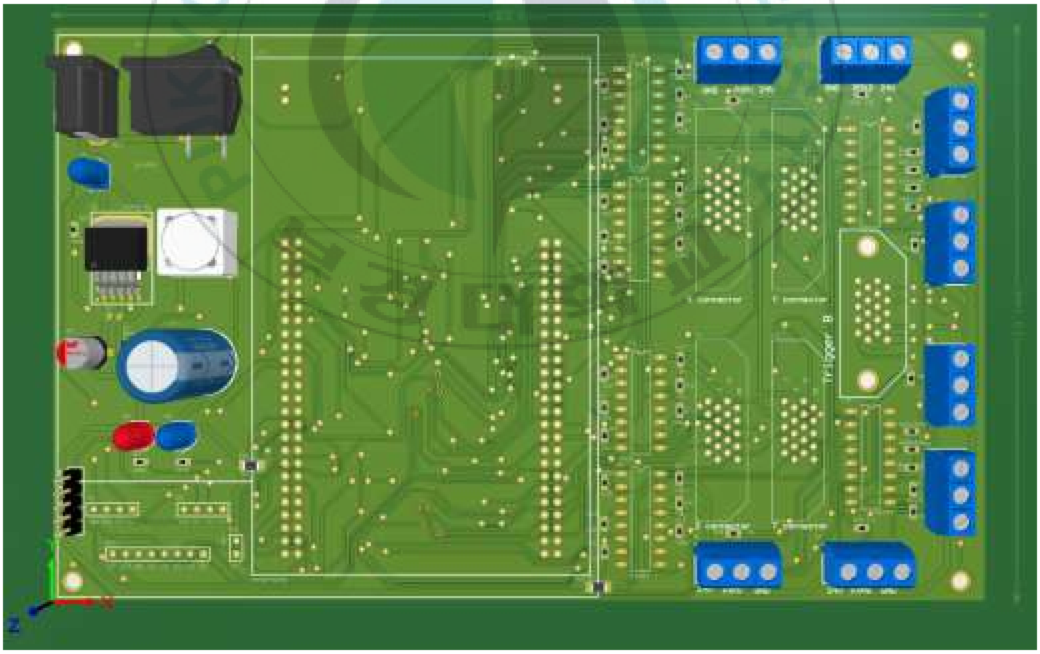


Figure 27: Motion control board 3D top view

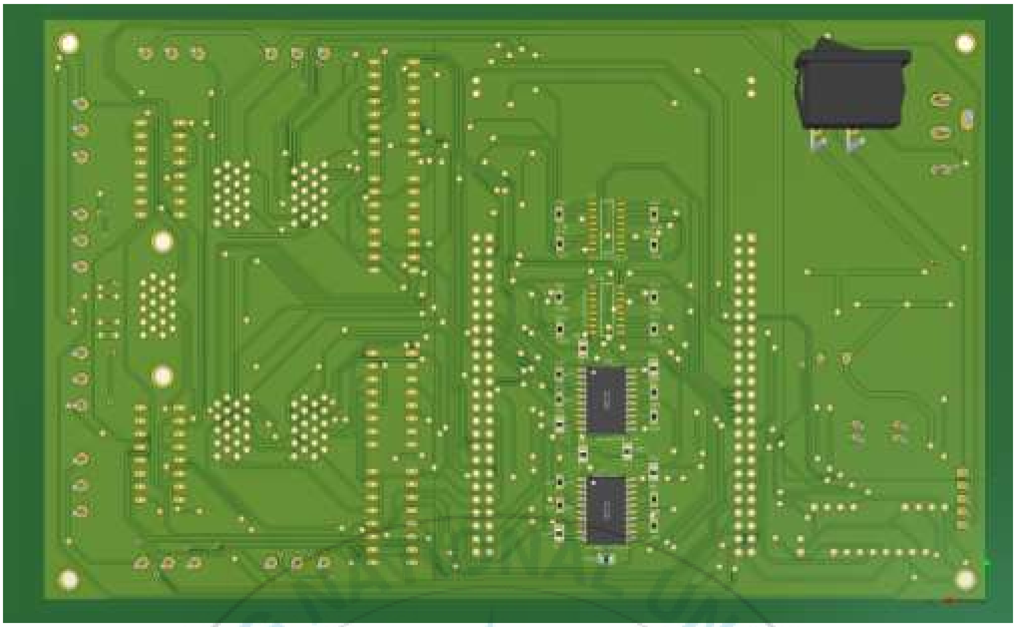


Figure 28: Motion control board 3D bottom view

2. Vision System

The most important part to the system is a vision application which is used camera and OpenCV library. OmniVision OV7725 has been used to get data. According to datasheet document, the sensor is a high-performance ¼ inch, single chip VGA and image processor in package, resolution is 640x480 and capable of operating at 60 frame per second.

Table 6: Camera Specifications [9]

Array size	Lens size	Angle	Pixel size	Image area
640x480	1/4’’	25º linear	6 µm x 6 µm	3984 µm x 2952 µm

2.1. Vision system block diagram

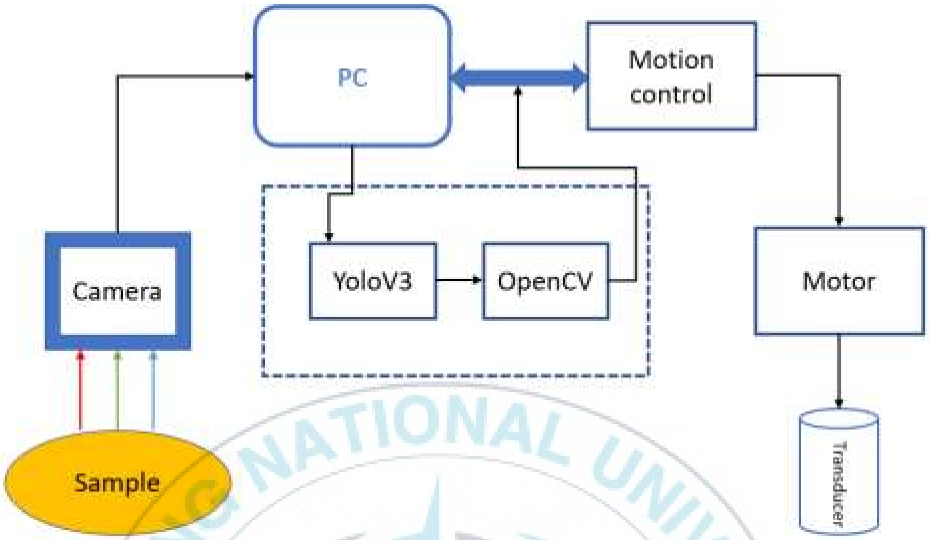


Figure 29: Vision system block diagram

Image of sample is collected by camera in RGB (Red Green Blue) 24-bit raw data. The PC (Personal Computer) receive raw data via USB 2.0 port under OpenCV (open source computer vision) library. Raw data is applied to YoloV3 model and return object prediction. The OpenCV access to an object to count the number of objects, get type, shape, coordinate and structure of an object.

In order to move the transducer to a sample place, the coordinate and structure of sample has to be changed to a new unit which is common unit with motion control system. In this case, the camera unit in pixel is changed to the motion control unit in µm. The way to change the unit was mentioned in previous chapter.

2.2. User interface design

In this study, in order to have a visual display user, Qt designer was used which having a lot of strength to build a graphical user interfaces (GUIs) with Qt Widgets.

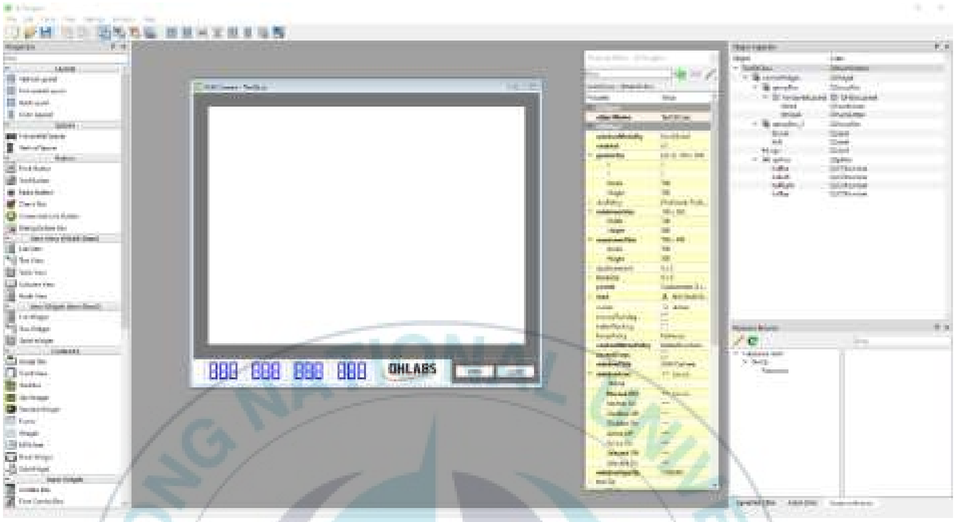


Figure 30: Qt designer viewer

Due to the demand for user experience, some controls and indicators attached to the user interface. This leads user to observe the operation process of camera. Moreover, the user can intervene to improve the operation process or to have manually control in need.

In the bottom left corner, there are 4 indicators number in order to display the extreme coordinate point of the sample in left to right order and top to bottom order. In the bottom right corner, 2 control buttons to open and close the camera were added which label is “open” and “close”. The white area in the middle is camera display as shown in Figure 30.

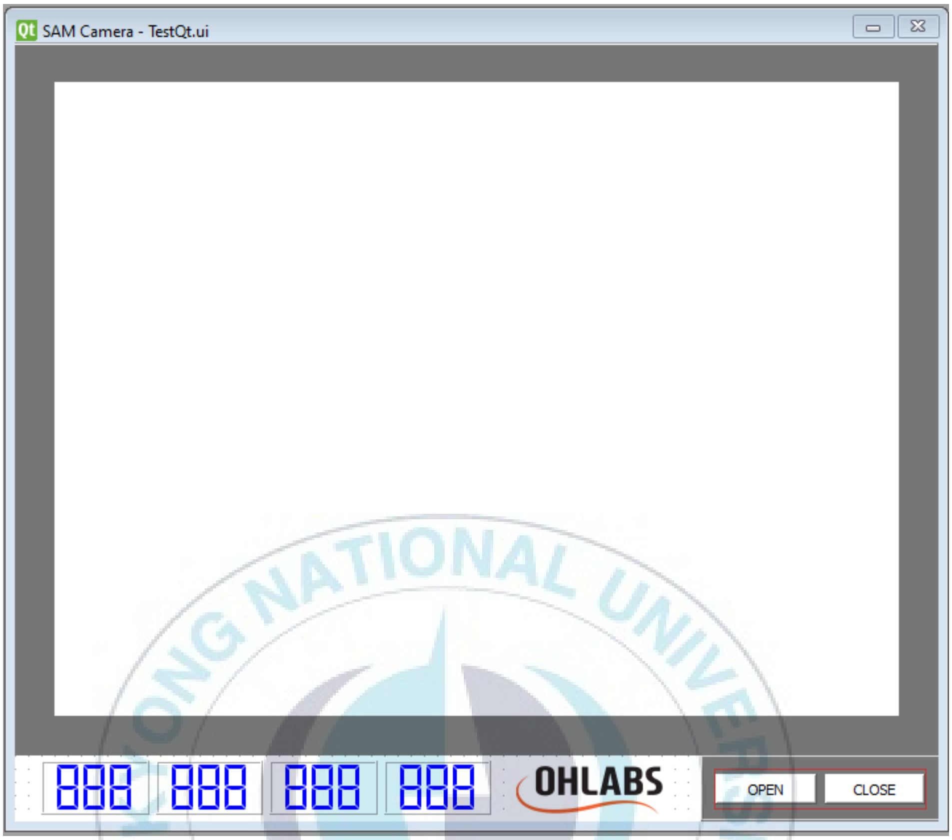


Figure 31: Camera user interface

Chapter 4. Results

1. Automatic sample tracking user interface

In this topic, there are two functions have been made. The main function is sample detection and image processing. The real-time camera program is primarily detection sample position and synchronize it with motion control system. Before synchronization, the raw data form camera was applied into Yolo model which is a deep learning model for object detection at high FPS (frame per second). The second function is motion control system, the main of motion control is used as robot to enforce value of coordination from the camera.

Figure 32: Camera Interface of real-time sample detection

The raw data was acquired by camera sensor would be transferred immediately to Yolo model and image processing program before display on user interface. Algorithms of Yolo forward to the frame of image only once through the network. First, the image was divided into a 13x13 grid of cells, the size of each cell depends on the size of frame input.

For coordination, the network predicts the sample and returns the bounding box actually encloses a sample and particular class of sample. The program is not only return bounding box and particular class but also checking the position, size and shape at every sample. Furthermore, it showing the values of coordination of sample on 3 digits 7 segments LED.

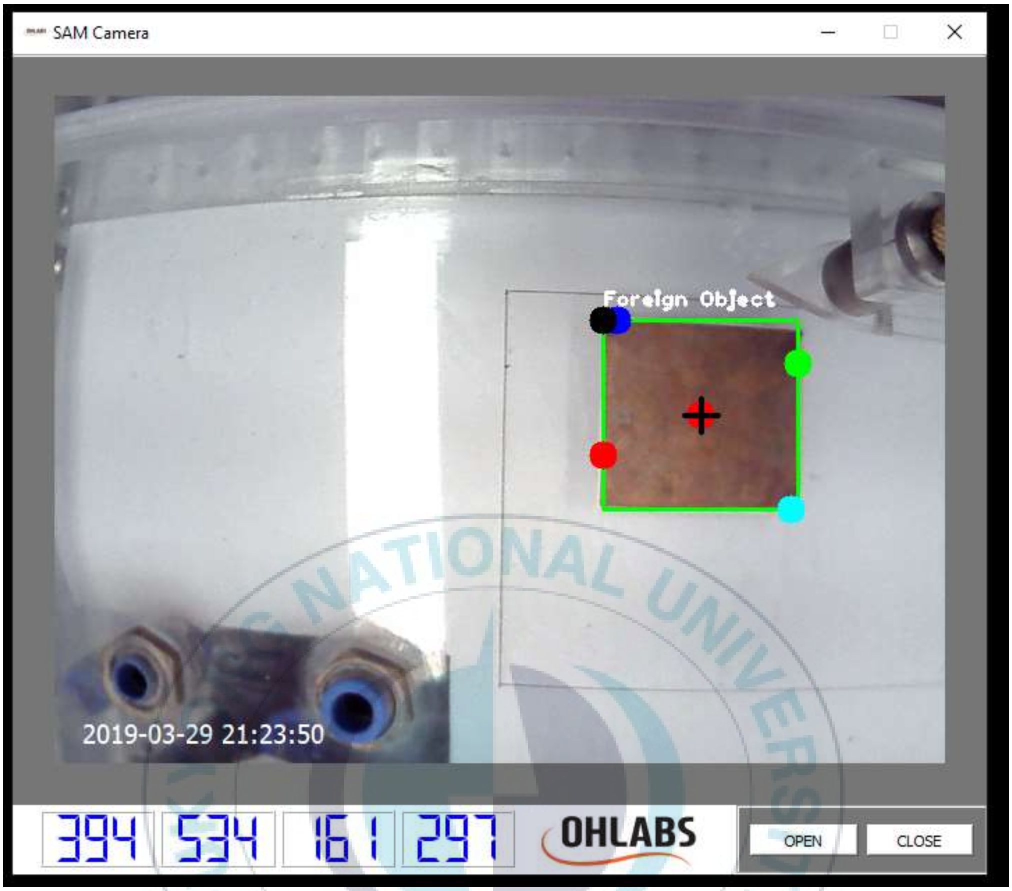


Figure 33: Demonstration with KCC sample

Figure 34: Demonstration with IC/Chip sample

Figure 35: Demonstration with PCB (printed circuit board) sample

In order to start scanning the sample, transducer (on right-top corner) have to move to start point (home point) which was marked black color on display screen. The home point is combined by y-coordinate of Top point and x-coordinate of Left point. The Top point was marked blue color and Left point was marked red color on the screen in Figure 34. Three figures above show results for three type of sample. Four values data show on the screen provide the information of four extreme coordinates.

2. 4-Axis motion controller

The 4-axis motion controller board (Figure 35) was customized to control the external AC servo motor driver. The board include four SCSI-20pins connectors provide 20 general purpose I/O pins for create pulse control output and receive input signal from servo driver. The motion controller has 8 channels general purpose 24V input. Each channel can receive 24 voltage input signals from sensors or actuators. Channel 1, 2, 3 also be used as an external proximity sensor for intrinsically safe during scanning process.

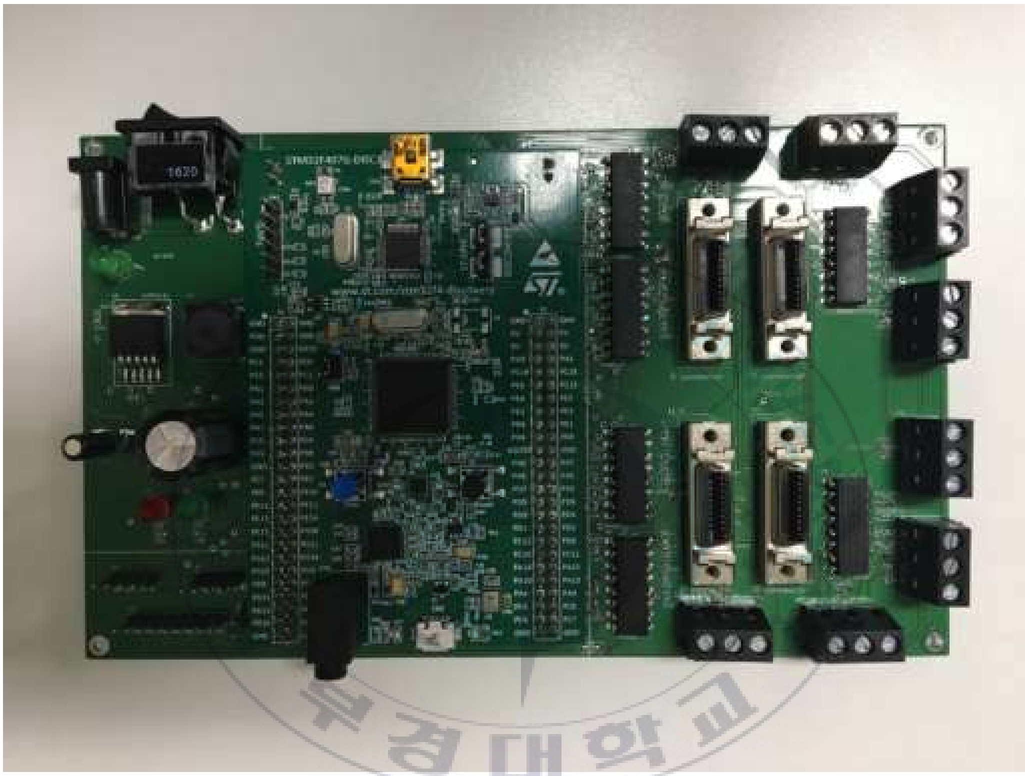


Figure 36: 4-Axis motion controller board

The motion controller board was set up for scanning mode and motion mode with selectable mode include jog, auto, home. In jog mode, user can set speed from 1 millimeter per second to 100 millimeter per second independently. In auto mode, we provide 10 levels of speed from 10 to 100 millimeter, when user input the speed and desired position, the microcontroller will apply the speed to axis which changes maximum difference between three axes. The fourth connector use for external motor in needed.

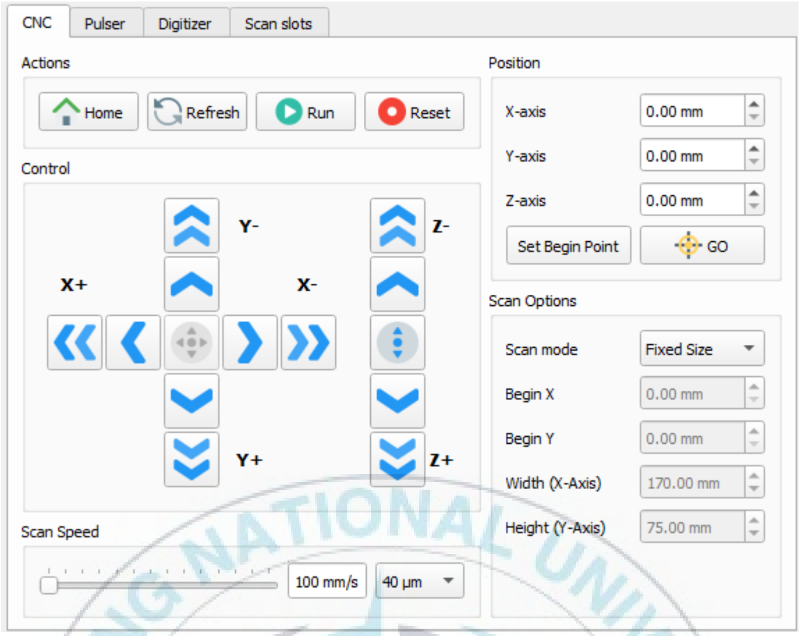


Figure 37: Motion control user interface

3. Trigger output controller

As used most often, the X-axis motor that carry on the Z-axis and transducer would pulse the trigger by an encoder built in the motor. This means triggers frequency would correspond to the direction and velocity with the same total amount and frequency between two pulses. In order to manage the trigger when the motor change direction, another STM32 microcontroller was used, this microcontroller control the total pulse input from encoder per cycle direction by define the lead channel between channel A and channel B. If the motor run forward, channel A leads channel B, else channel B leads channel A.

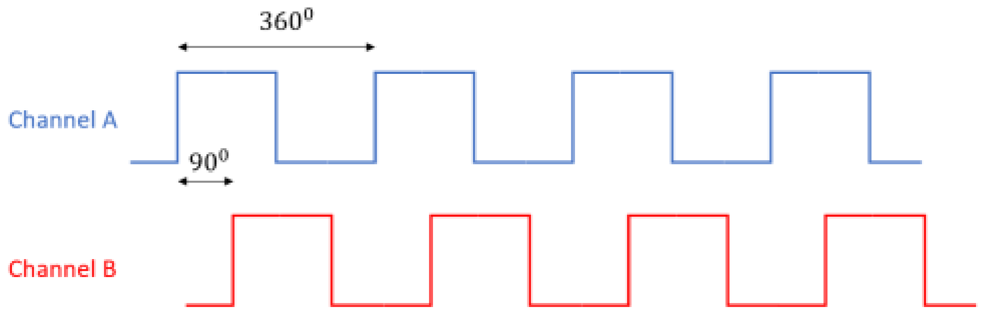


Figure 38: Channels A, B, phase shift of encoder

When motor change direction with high acceleration (from 500 mm/s to 0 mm/s), the motor will cause vibration which cause miscount the output pulse. In order to cancel the wrong pulse by combining both phase A and phase B with addition and subtraction counter.

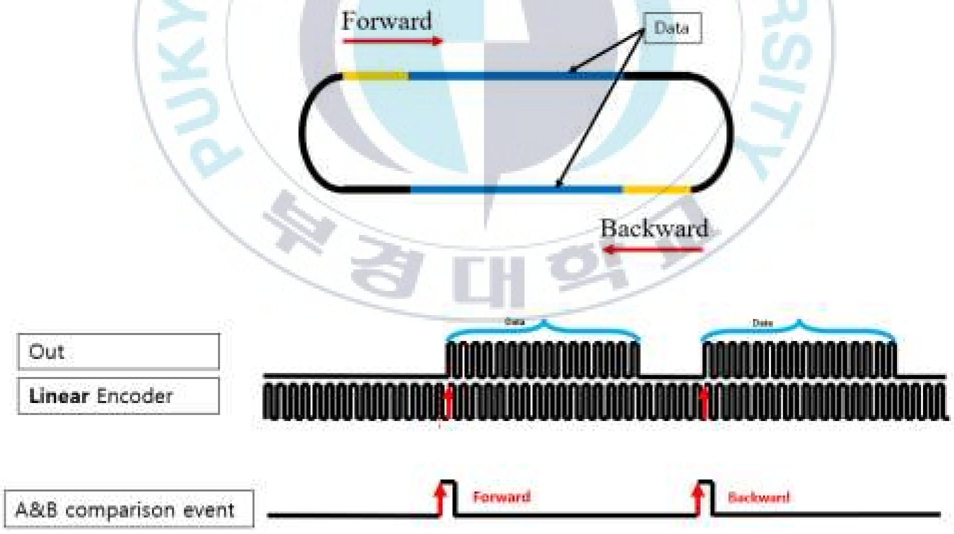


Figure 39: Trigger management algorithm

Furthermore, to increase the degree of accuracy, the virtual signal (definition by virtual Z) was created to ignore the wrong pulse. When the motor change direction, all the pulse signal was counted up to the Z value which input by user or optimized value based on several calibration. When the counter value equals to Z value, the pulse copy process is activated. In this study, 10 times calibration would be performed by synchronizing pulse signal between run forward and backward direction.

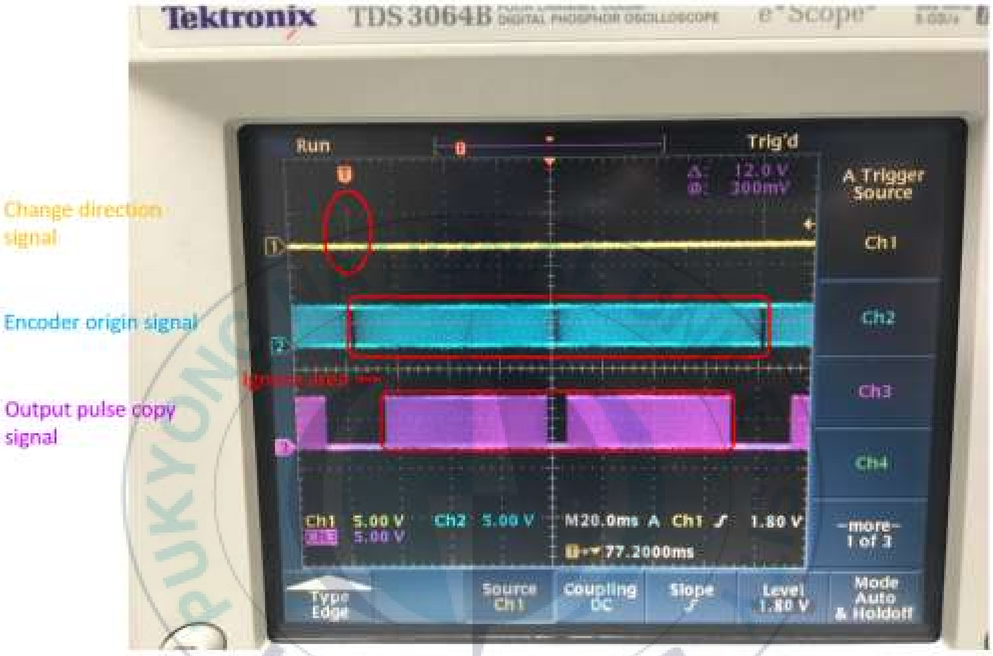


Figure 40: Demonstrate trigger management

In some of cases, in order to decrease the scanning time by increase the step size pulse trigger. This make challenge to mechanical system when the encoder output pulse is constant. To increase the trigger step size, a method called divided pulse trigger is applied. By the method, for each the desired divide value, the microcontroller creates one pulse trigger. This means if the divide value is 3, the pulse trigger signal is created correspond with 3 pulses input from A channel encoder.

Figure 41: Demonstrate output pulse trigger divide by 2

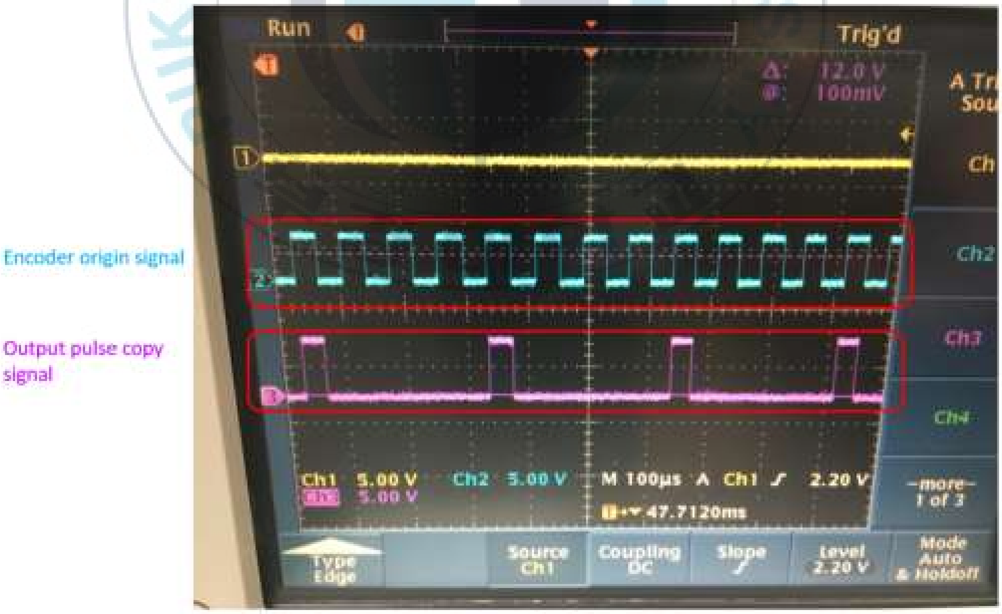


Figure 42: Demonstrate output pulse trigger divide by 5

Chapter 5. Conclusion and Discussion

In this study, the system could detect the sample and get coordination automatically. To access possibility as well as able to be trusted well, more and more different kind of sample need to be performed.

The system has been self-controlled based on STM32 microcontroller. All printed circuit board has been designed and welded to increase long life stable. Furthermore, this makes optimize the cost that could be used in study or be optimized for mass production.

The customized motion control board with 1-4 axes can be integrated with camera module to apply in manually or automatically control the UT, NDT, SAM system. This design can also extend I/O pins, sensors and actuators in need.

At the moment, due to the small number of data, the system did the low sample detection rate. Furthermore, the limit of camera quality and polarization of light in water can make noise and bad result in direct light sources. For the better experiment, the system needs to be improved the image quality with high-performance camera hardware and polarized filter.

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