Thesis for the Degree of Master of Engineering

Development of Robotic Laser Scanner system for collecting profile in weld defect detection

By

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Department of Industry 4.0 Convergence Bionics Engineering

The Graduate School

Pukyong National University

August, 2022

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(용접부 결함 검출용 3D 프로파일 수집을 위한 로봇 응용 레이저 스캐너 시스템 개발)

Advisor: Prof. Junghwan Oh

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A dissertation

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Development of Robotic Laser Scanner system for collecting profile in weld defect detection.

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Abstract

In the era of technology, especially with the current 4.0 revolution, scientists strongly developed the Internet of Things (IoT) field. We admit that the field of robot development is one of the core foundations of IoT. In the world, robots are increasingly interested in research; many scientific reports and practical products are on the market. Along with the development of other technology fields, robotics plays an essential role in the research and development of science and technology worldwide. One of the robotics problems scientists are studying is robotic systems applied in industry. These systems bring many practical elements to humans as they have the potential to solve many problems such as surveillance, rescue, transportation in industrial warehouses, and so on. Industrial robots offer performance and reliability in tasks that are difficult for humans to perform. Thesis "Development of a Robotic Laser Scanner system for collecting profile in weld defect detection" research methods to build and develop a scanner system that can support humans in problems of weld defect detection.

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Chapter 1. INTRODUCTION

Welding is essential for joining metals and repairing metal products in manufacturing industries [1, 2]. Robotic and automation systems are also gradually being applied to this job to replace workers to improve production efficiency [3]. For industrial products, the quality requirements between welds are very high. Unfortunately, sometimes the product appraisal after welding is completed encounters problems such as the weld defect being too small, not being seen with the naked eye, and exposure to metal can also cause problems related to health [4]. Mike Louie Enriquez et al. [5] used artificial intelligence and computer vision technology to detect defects and evaluate the quality through images of welds. By collecting and processing sensor data, R.S.Barot et al. [6] investigated a system for real-time monitoring and evaluating weld quality. Weld quality assessment is obviously essential . These studies, however, focused only on one stage of product evaluation, without providing a comprehensive system, including hardware and software, for data collection and data analysis.

In recent years, the significant development of laser technology has gradually replaced traditional technologies in general. There are many applications for lasers, including biomedical, industrial, high-tech, and so on. Mobile and industrial robotics applications widely utilize lasers for scanning and collecting sample data [7]. C.Almansa et al. [8] used the laser scanning method to estimate the fish biomass from the single fish weight in a tank. As in this study [9], Jakub Sandak et al. used a laser sensor to determine surface roughness in an industrial environment that is non-contact with reconstructions of the profiles. For the measurements, the authors used 15 species of wood with varying densities and colors, based on specific triangular profiles were prepared. Several studies have reported lasers being effective in scanning and reconstructing surfaces. Obviously, applying laser sensors to monitor and detect weld defects is a new direction with high efficiency .

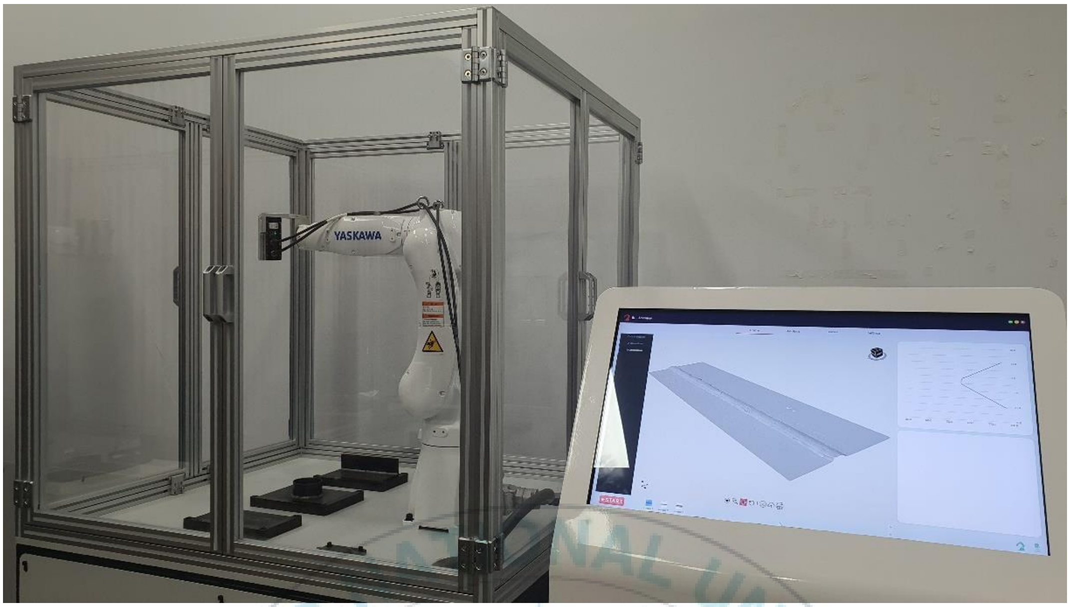


Figure 1 The proposed robotic laser scanner system in Nano Bio Medicine lab

This thesis presents a robotic laser scanner system consisting of mechanical hardware, data collection, and control software to measure and calculate weld defect detection. By collecting raw data from a laser sensor mounted on the probe of a robotic arm, profiles are sent back and processed on a computer with software written in C#. Two- and three-dimensional images are collected with a resolution of 256 pixels to 2048 pixels to provide the analyst with multiple viewing angles. Besides, weld defects are then also detected and analyzed by optimization algorithms. The robotic laser scanner system has been operating stably, and the data collected and extracted is of good quality, actively supporting the detection of product defects and improving product quality.

Chapter 2. ROBOTICS LASER SCANNER SYSTEM ARCHITECTURE

1. Overview of System Architecture

The robotic laser scanner is a system developed at Nano Bio Medicine laboratory, Department of Industry 4.0 Convergence Bionics Engineering. The object of the present system is to provide a robotic laser scanner system that can get profiles of weld samples or others. In the proposed method, a robotic laser scanner system is provided that consists of:

- A robot arm Yaskawa-GP8
- A robot controller YRC1000micro
- A laser profile sensor Micro-Epsilon 30x2
- A trigger board
- A computer

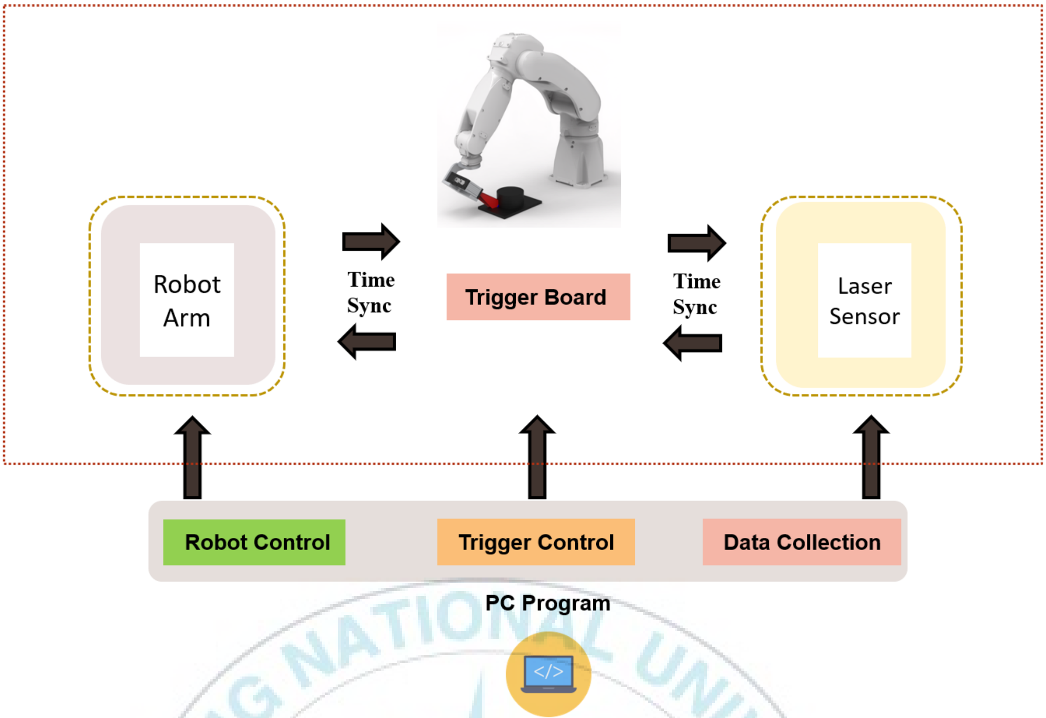


Figure 2 The block diagram of the robotic laser scanner

As the robot arm moves, raw data is collected by a sensor from the probe, which is controlled by the YRC1000micro robot controller. It is necessary to synchronize the robot system and laser sensor with the help of a pulse generator circuit called a trigger board. The settings parameters and raw data are transmitted and received to the PC via UART and Ethernet protocols.

2. Motion Control Module

2.1. Yaskawa Motoman GP8 Robot Arm

GP8 robot is a new robot model of Yaskawa, officially released on the world market in August 2016. GP8 is a six-axis robot that performs well in applications such as assembling electronic components, dispensing, material picking, tending machines, and other industrial applications.

Figure 3 Robot Motoman Yaskawa-GP8 [1]

This robot model has outstanding improvements compared to the current corresponding robot line, MH5SII. All-axis motor speed is 15% faster than MH5SII, and R-axis turning radius is reduced by 8%, helping the working arm to save space and reduce the possibility of robot arm collision with the workpiece and die, improving access to difficult locations. GP8 has an optimal configuration and is versatile in many applications of picking up electronic components, assembling, grinding, etc. Yaskawa's GP8 has the fastest movement speed compared to other Robots in the 5-8kg mass grab series. Especially with high axes speed in acceleration and deceleration, which reduces the dead time of a cycle working process and maximize production efficiency. The superiority in the rate of GP8 comes from the upgrade of the servo motor from Sigma 5 to Sigma 7, which is Yaskawa's most advanced servo line with the advantages of small size, high speed, and torque, using a 24-bit encoder. ~16,777,216 pulses/rev for absolute precision and state-of-the-art ARM (Advanced Robot Motion) microprocessor technology.

[1] Image source: GP8 (yaskawa.eu.com)

The cables are inserted into the arm, which should increase the rope's life, reduce the risk of wire breakage, and improve the operating reliability of the robot.

This GP8 has a reach of 727 mm, allowing the robot to have a wide operating range, and rotate to the back of the robot. The GP8 robot can pick up a mass of 8 kg, but in cases of high moment and inertia, it can be flexible for installation by floor-standing, wall-mounting, or ceiling-mounting.

2.2. YRC1000micro Robot Controller

Figure 4 Robot controller YRC1000micro [2]

The MOTOMAN YRC1000micro is an ultra-compact, precise, powerful robot controller for small robots up to 12 kg (GP Series, HC Series, MotoMini, and SG-Series Scara, most of them support power supply). 230V/3 phase), capable of controlling robots with up to 2 additional external axes. This one is small in size, and lightweight housing is ideal for a space-saving stand-alone installation or can be installed horizontally or vertically in a 19" rack or machine control cabinet.

MOTOMAN robots with YRC1000micro controllers are open to a variety of programming methods, including hand guiding, standard teach pendants

[2] Image source: YRC1000micro (yaskawa.eu.com)

(Touchscreens), motologix function blocks, software pendants, offline simulation tools, ROS (Robot Operating System), and customer-developed apps written using our SDKs (e.g. Motoplus C/C++, MotoCom32 SDKs).

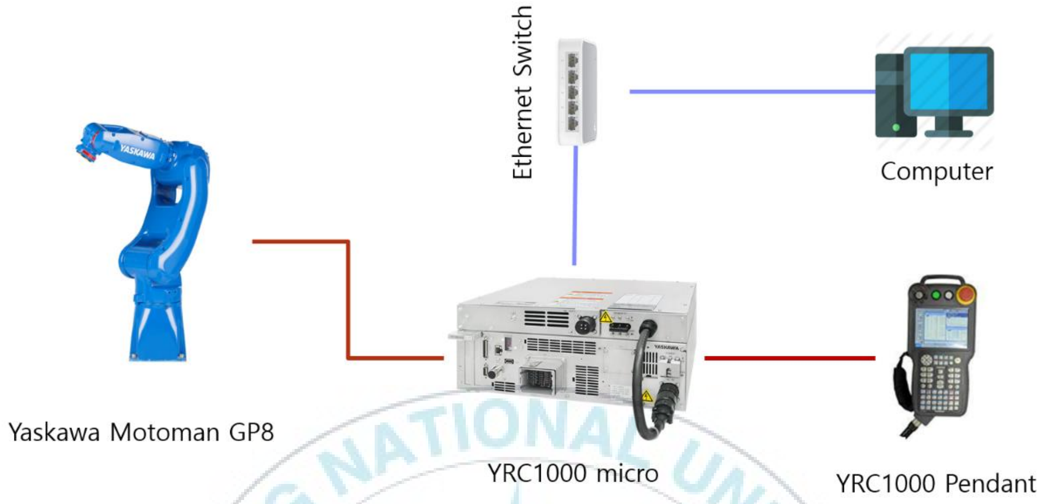


Figure 5 Block diagram of the motion control module

In the robotic laser scanner system, the user can operate the robot with two solutions through a YRC1000 pendant or PC program that control by a high-speed ethernet server function.

3. Data Collection Module

3.1. Micro Epsilon 30x2-50 Laser Profile Sensor

The laser profile sensor collects height data along the path of the laser beam instead of a single point. Using a single sensor, this one provides two-dimensional and three-dimensional measurements, such as height, width, and angle differences. In addition to height data, the profile sensor also collects reflected light intensity data to provide a stable solution for inline measurement and inspection. Many laser profile sensors are available on the market for a wide range of applications.

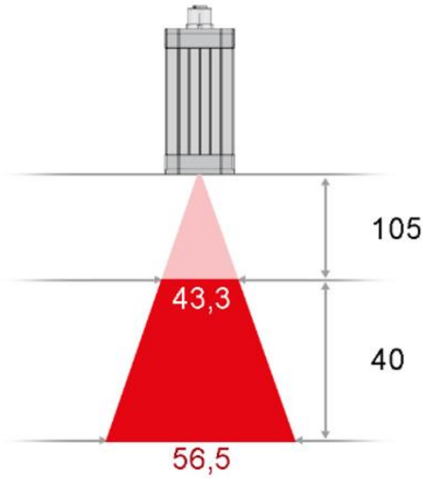


Figure 6 Laser profile sensor Micro-Epsilon 30x2 and Measuring range [3]

The robotic laser scanner system uses a Micro-Epsilon 30x2-50 laser profile sensor fixedly mounted on the robot probe to collect raw data from samples. The new LLT30x2 laser profile sensor provides scanning frequency up to 5 kHz and resolutions up to 1024 points. Due to their high accuracy and versatility, this sensor type is particularly suitable for static and dynamic robotic applications, which need to measure and evaluate angles, steps, gaps, distances, circles, etc.

3.2. Principle of optical triangulation

Like conventional laser distance sensors, Micro-Epsilon 30x2-50 laser profile sensors work based on the principle of optical triangulation. This principle is often applied to laser sensors that detect at short ranges (about 1.5 - 60cm), using CMOS technology and for high accuracy. For this type, the sensor will emit a diffused triangular laser beam that passes through the lens and reaches the target. Upon reaching the target, the light beam is reflected and returned to the CMOS sensor, focusing on a single point. We will calculate the distance to the target object based on the change in reflection angle. In addition, Micro-Epsilon 30x2-50 has a

[3] Image source: https://www.micro-epsilon.com/2D_3D/laser-scanner/scanCONTROL-3002/

bandpass filter to eliminate invalid light. This filter allows only light that correlates to the laser diode's wavelength to pass.

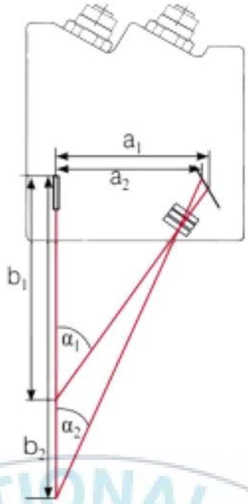


Figure 7 Laser sensor structure [4]

To calculate distances between the sensor and the measuring point, we use triangulation based on a laser beam detected within a column of the sensor matrix. In most cases, producers use the bottom of the sensor as a point of reference. The calculation follows the formula [10]:

$$b_1 = \frac{\alpha 1}{\tan \alpha 1}$$

The sensor can measure position, distance, intensity, reflection width, moment 0, moment 1, and threshold. The meanings of these parameters are described in the table below.

Table 1 The meanings of parameters

Distance	The CMOS sensor will detect the center point of the reflection to get the distance (i.e. z value) of a measuring point. Based on mapped values, these one is converted to coordinates in reality. The variable is transmitted as a 16-bit

[4] Image Source: Micro Epsilon Interface Documentation

	unsigned integer field which has to be scaled by the sensor-specific scaling factors.
Position	The position (i.e. x value) corresponds to a pixel row on the CMOS sensor. It is similar to the z value. For every column, a position value is detected, and this value is converted to coordinates in reality. A 16-bit unsigned integer field is transmitted, which has to be scaled.
Intensity	The transmitted value is the difference between the detected intensity maximum and the currently used threshold. Intensity correlates to how much light one pixel of the matrix has detected while the shutter was open. A prerequisite for detecting a reflection is that the power is above the threshold. A 10-bit unsigned integer field is transmitted.
Reflection width	The reflection width correlates to the number of contiguous pixels corresponding to the points that have an intensity of the current reflection above the threshold. A 10-bit unsigned integer field is transmitted.
Moment 0	Corresponds to the current reflection's integral intensity ("area of reflection"). The moment is thus defined by the integral of the power over the reflection width. The value is transmitted as a 32-bit unsigned integer field.
Moment 1	It corresponds to the center of gravity of the reflection, which is used as a foundation for calculating position and distance according to the calibration table. It is transmitted as a 32-bit unsigned integer.
Threshold	The threshold used for the single measuring point consists of the absolute or dynamically calculated threshold and the

	determined backlight suppression. A 10-bit unsigned integer field is transmitted.

3.3. Data Transmission between Laser Profile Sensor and Control PC

We can use both ethernet and serial protocols for data transmission. In this research, the author transfers data according to the ethernet protocol because of its high processing speed.

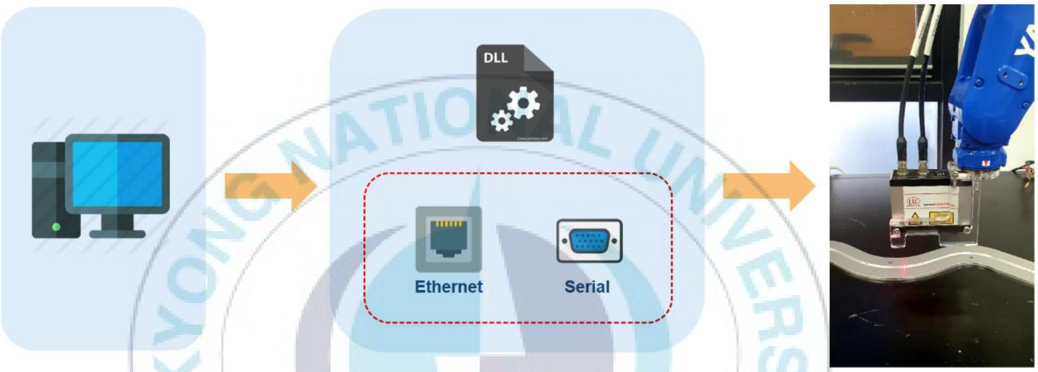


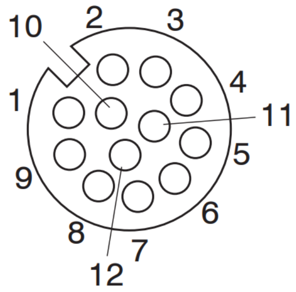
Figure 8 Block diagram of data transmission method

Ethernet protocol

Ethernet is a network protocol that allows networked devices to send and receive data to other devices on the same network. The Institute of Electrical and Electronics Engineers (IEEE) defines ethernet as the 802.3 protocol [11]. Systems that use ethernet technology in local area networks (LANs) where computers/devices are connected in a primary physical space. The outstanding features of ethernet include high-speed data transmission, guaranteed security, and reliability [12].

Table 2 Assignment of the multifunction socket on scanCONTROL 30x2-50

Pin	**Designation**	**Cable color**	**Connection view**
9	+ Ub	red	

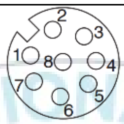
2	GND	blue	
3	+on/off	white	
1	-on/off	brown	
12	RS422	red-blue	
11	/RS422	gray-pink	
10	GND RS422	purple	
4	In1	green	
	In2	yellow	
	In3	gray	
In4	5	pink	
GND-In	7	black	
Screen	Housing	black	

Data transmission

To perform data transmission between the laser profile sensor, the author uses two socket ports, which are multifunction sockets to supply power and receive pulses from trigger circuits and ethernet sockets to transmit raw data collected from samples to the computer. Table 2 and Table 3 describes the function of these socket pins.

Table 3 Pin assignment Ethernet connection

8-pin connector		
Pin no.	**100BaseTX**	**1000BaseT**
5	Tx+	D1+

6	Tx-	D1-
8	Rx+	D2+
1		D3+
2		D3+
7	Rx-	D2-
3		D4+
4		D4-
		

4. Synchronization Module

In sections 2 and 3, the author discussed controlling the robot arm's motion and getting raw data from the laser profile sensor. However, to merge these data into a complete 2D/3D image, the system needs to synchronize these two modules perfectly. In this section, the author will present the trigger board of the system, which works as the synchronization module. Figure 9 shows the block diagram of the trigger board connection.

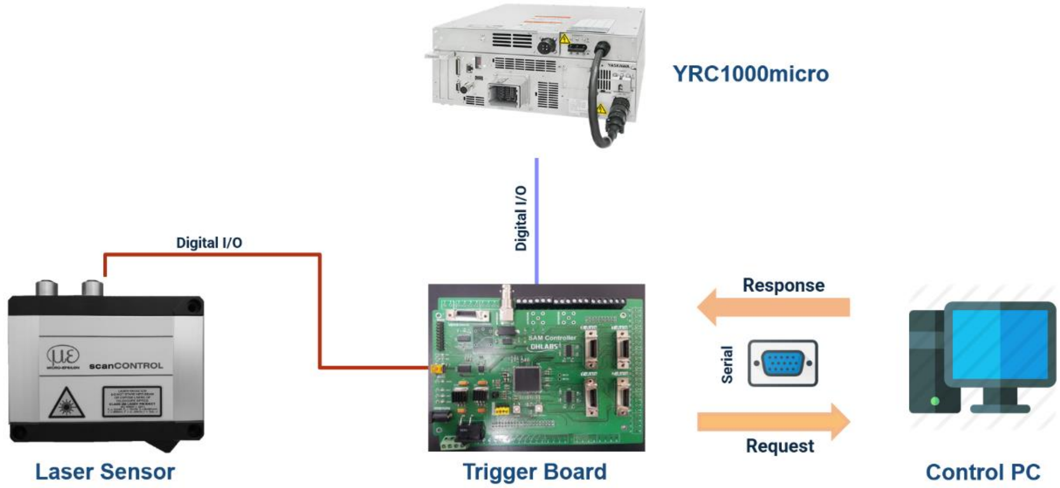


Figure 9 Block diagram of the synchronization module

To synchronize the YRC1000micro driver and the Micro-Epsilon 30x2-50 laser sensor, the author uses the digital IO pins on these two devices and connects them to the trigger board. The trigger circuit is responsible for receiving movement information from the controller, including speed, step resolution, and signals to start and stop the scanning process. This information is then calculated and converted into pulse frequency, fed to the laser sensor. The laser sensor with an external trigger setting will perform a sample scan with this received frequency. Table 4 describes these connections between devices.

Table 4 The connections between devices

Micro-Epsilon 30x2-50	Trigger Board	YRC1000micro
+Ub	24V	
GND	GND	GND
In2	XA	
In3	XB	
GND-In	GND-Out	
	IN7	A9 – Alarm/Error Occurred
	IN8	A13 – OUT08

Chapter 3. DEVELOPMENT OF ROBOTICS LASER SCANNER SYSTEM SOFTWARE

1. Overview of Software Architecture

RL-Scanner developed by the author is software written in C# (programming language). The main functions of this application include rendering Heightmap/2D/3D images using data collected from lasers, measuring weld defects, etc. Similar to the hardware architecture, the software architecture of RL-Scanner also includes modules such as motion control to control the robot's movements, the setting module to set laser and trigger parameters, scanning module to control the system and render 2D/3D images of samples. Figure 10 describe the function map of software architecture.

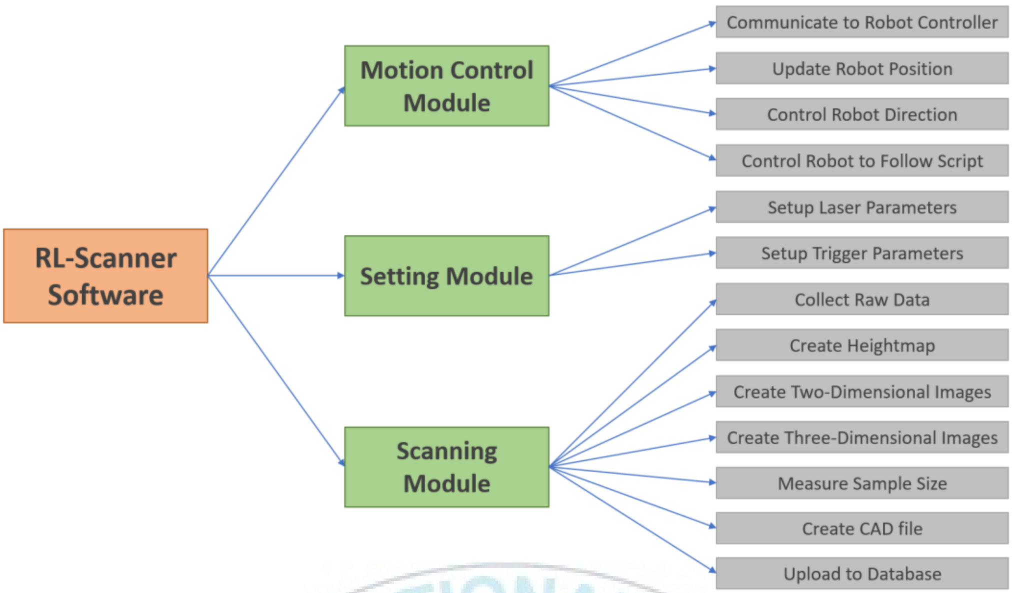


Figure 10 The function map of RL-Scanner

2. Motion Control Module

User Datagram Protocol

UDP stands for User Datagram Protocol. It is a section of the Internet protocol used for programs running on different devices on the network. Unlike TCP/IP, UDP sends short frames called datagrams, allowing faster data transmission [13].

Motion Control Module using UDP protocol

The motion control module performs the primary function of controlling and correcting the movement of the robot arm by sending and receiving control packets to the robot controller using UDP protocol based on pre-existing robot control standards. Figure 11 shows the layout design of this module. The layout of the motion table displays movement buttons and robot coordinates updating in real-time. When the user presses the move button, the program will send a request to check whether the Hold Robot status is on or off; it is necessary to ensure that the Hold Robot status is enabled before the robot moves.

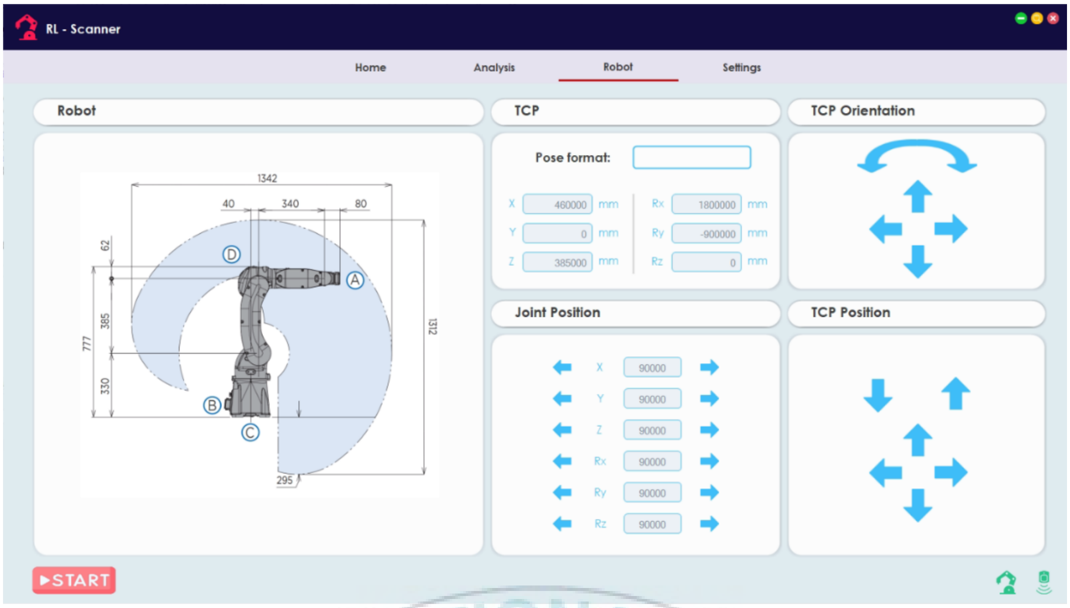


Figure 11 Motion control layout

Besides, a continuous update of the robot coordinates will be performed during movement. Movement progress will be stopped immediately whenever the program receives an error alarm from the controller. The pseudocode below describes the RL-Scanner's process of controlling a moving robot.

Algorithm 1 Algorithm for Robot Control

Update current setting

if (servo off)

    Turn on servo

Start thread of updating robot coordinates

Start movement progress

if (received packet is warning alarm)

    Stop movement progress

---

3. Setting Module

LLT.dll

The LLT.dll is a Dynamic Link Library (DLL) for simply integrating scanCONTROL sensors into own applications. It provides an abstraction level above the direct responses of the scanCONTROL by Ethernet or the serial interface. The focus of the design of the DLL has been set on the simplicity of the interface and high performance.

The functionality includes the complete parametrization and control of the sensor, the transmission, saving, and converting of measurement data in all different transmission modes. Additionally, the connection monitoring between PC and scanCONTROL can be done via the DLL. Furthermore, the integration of several sensors into one application is possible.

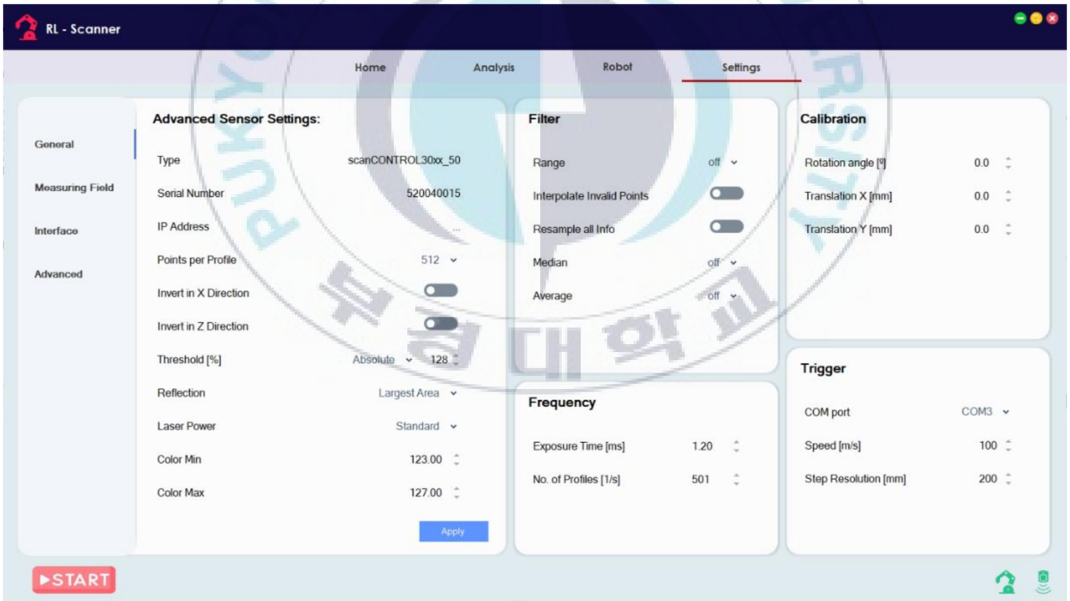


Figure 12 Settings layout

Setting laser sensor parameters using Dynamic Link Library

The parameters of the Micro-Epsilon 30x2-50 need to be calibrated accordingly to collect a complete set of raw data from the laser sensor. Micro-Epsilon provides users with pre-built software to do that job. However, using many different tools during scanning can be difficult for users. Therefore, based on the C# SDK that Micro-Epsilon provides, the author has integrated the setting module into RL-Scanner, helping users set up sensor parameters, select filters, and customize frequency and trigger parameters easily. Figure 12 shows the layout design of this module.

4. Scanning Module

The most essential and core part of RL-Scanner is controlling the scanning and rendering of 2D/3D images. Figure 13 shows the layout design of the scanning module.

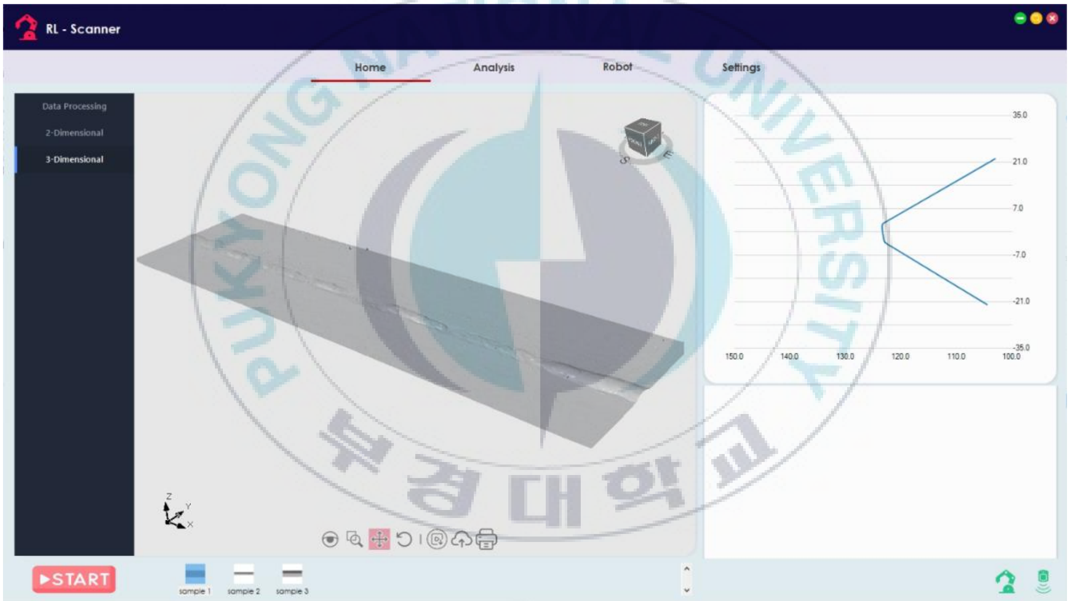


Figure 13 Home layout

To create two-dimensional images, first, the author gets raw data from the laser sensor through a call-back function. This call-back function will be called whenever the sensor collects a new data set. Then, the data consisting of 2 values according to the x-axis and z-axis is saved into two-dimensional arrays. The bitmap matrix is initialized from this collected raw data set. The algorithm for Rendering 2D Images is described as pseudocode below.

Algorithm 1 Algorithm for Rendering 2D Images

```
Clear 2D image table
Get raw data from sensor
Get min color value and max color value from setting
for all raw data list
    rgb  = (max_color – raw_data_value) * 767 / (max_color - min_color)
if (rgb < 256)
     r = rgb & 0xFF; g = 0; b = 0;
if (rgb < 512)
     r = 255; g = rgb & 0xFF; b = 0;
if (rgb < 512)
     r = 255; g = 255; b = rgb & 0xFF;
Create bitmap from r, g, b data
View bitmap on 2D image table
```

To render three-dimensional images, the author uses Eyeshot API. This API support software developer to build, analyze geometry from scratch, and generate tool paths. Geometries can also be imported or exported in CAD file formats. The algorithm for Rendering 3D Images is described as pseudocode below.

Algorithm 2 Algorithm for Rendering 3D Images

```
Clear 3D image table
Get raw data from sensor
```

```
for all raw data array
        create a 3D point
        add a 3D point to a 3D point list
for all 3D point list
        remove invalid point
Create triangles
Create a mesh surface from a 3D point list and triangles
View the surface in eyeshot environment
```

Chapter 4. EXPERIMENT AND RESULT

In the current experimental design, the author expects the system to be able to scan samples with a maximum speed of 100 mm/s and a step resolution of 0.5 mm. The settings of the laser sensor are set by the author as follows:

Table 5 The settings of the laser sensor in the experiment

Parameters	**Status**
Reflection	Largest Area
Laser Power	Standard
Color Min	123
Color Max	127
Suppress Backlight	Enable
Video Filter	Enable
High Resolution	Enable

Calibration	Enable
Data Format	Compressed

Figure 14 A collected profile during the scanning process

Experiment 1,

For testing the maximum resolution that the system can scan, the author uses a sample with holes with sizes of 0.5 mm, 1 mm, 2 mm, 4 mm. The laser scanner system is specified to scan with a resolution of 256 pixels and 1024 pixels, respectively. The results of the experiment are depicted in figures below.

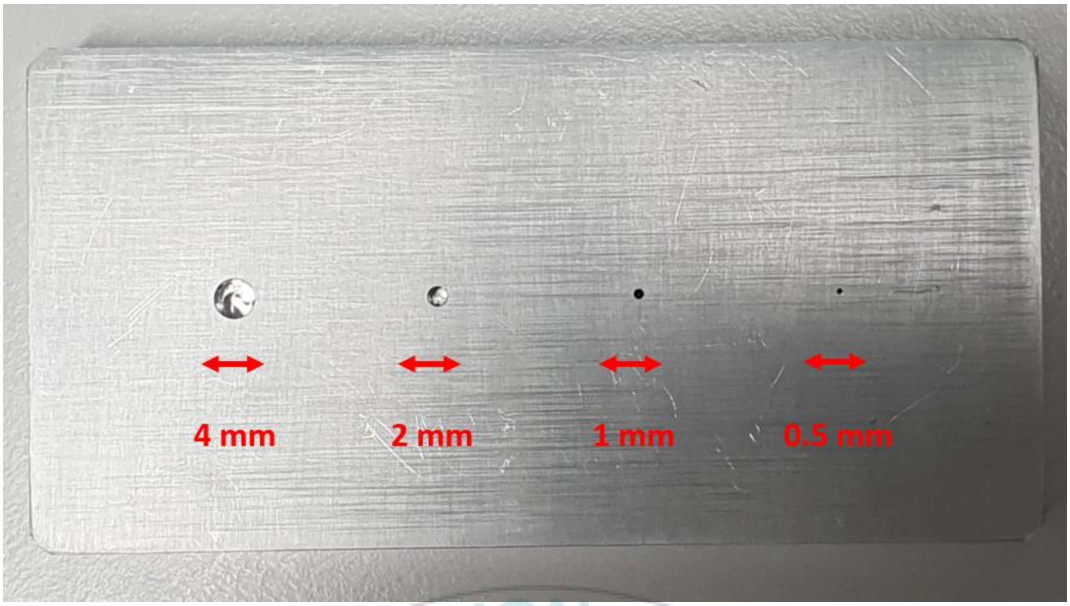


Figure 15 The sample for testing resolution

The figure below shows the sample heightmap.

Figure 16 The sample heightmap with low-resolution

Figure 17 The sample heightmap with high-resolution

The figures below show the two-dimensional of two samples.

Figure 18 The two-dimensional image of the sample with low-resolution

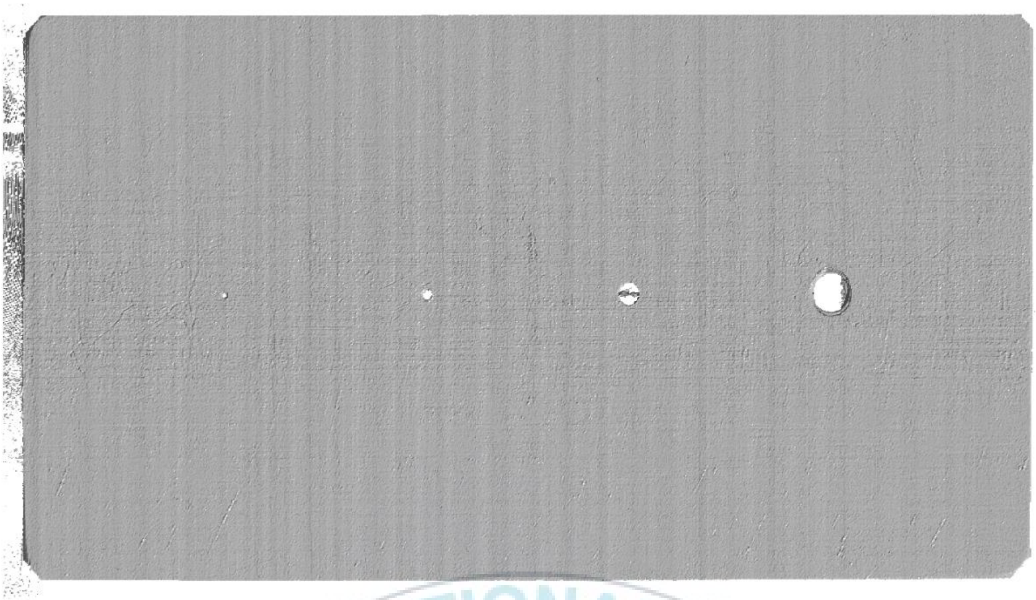


Figure 19 The two-dimensional image of the sample with high-resolution

The figures below show the three-dimensional of two samples.

Figure 20 The three-dimensional image of the sample with low-resolution

Figure 21 The three-dimensional image of the sample with high-resolution

Experiment 2

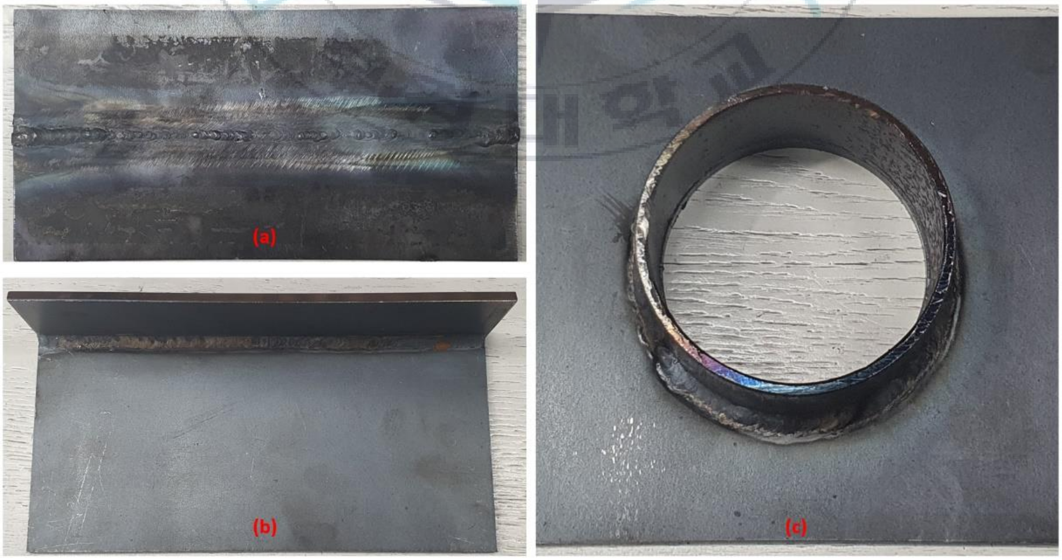


Figure 22 The sample for testing image quality

In order to assess the quality of images obtained with weld samples, the author uses three samples with different shapes, consisting of a normal sample, a round sample, and a square sample. The speed of 100 mm/second is used to scan these samples in turn at the highest resolution. A description of the experimental results can be found in the figures below.

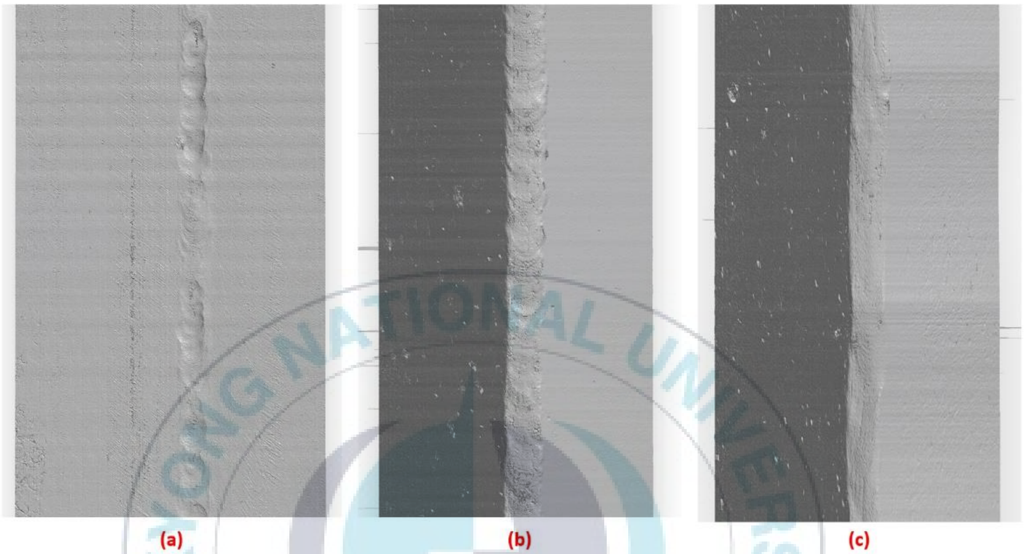


Figure 23 The two-dimensional image of three samples

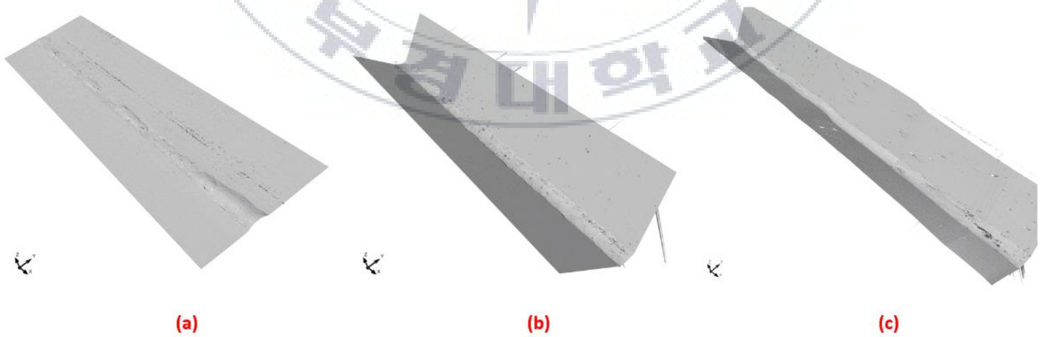


Figure 24 The three-dimensional image of three samples

Chapter 5. DISCUSS AND CONCLUSION

This paper proposed and evaluated the development of a robotic laser scanner system for profile collection applied in weld defect detection.

As part of the first experiment, the system scanned and rendered samples with holes of 0.5 mm to 4 mm in both low-resolution and high-resolution modes. The results show that the low-resolution mode can clearly display 1 mm, 2 mm, and 4 mm holes; holes with a diameter of 0.5 mm are almost impossible to detect in heightmaps, two-dimensional and three-dimensional images. Conversely, the high-resolution mode allows all samples and holes to be detected and reproduced perfectly. The two- and three-dimensional reconstructions of weld samples were successfully performed in the second experiment also. Image and signal quality is almost sharp and noiseless when using high-resolution mode. These images provide more perspective to users during product evaluation. It is also possible to detect weld defects on rendered images. Furthermore, users can use extensions like distance measurement, zoom in, zoom out, and synchronize images with a cloud server in the two-dimensional and three-dimensional viewer modes. Scan speed is an essential parameter in evaluating the performance of the scanning process. As a result of our experiment, the scan speed of the system reaches 100 mm/s. The image will be reproduced sharper and with less noise when the user slowed down the scan speed. Overall, the author concludes that the designed system meets the stated requirements.

A problem that creates noise during the scanning process is the shadowing effects. In this case, the laser line may disappear behind steep edges entirely or partially. This is why these areas are not visible to the receiver [14]. As a general rule, the laser triangulation method cannot measure objects with steep edges one hundred percent. Therefore, intricately textured samples may not reproduce rendered images perfectly. As a future solution, the author intends to write software to resolve this issue.

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용접부 결함 검출용 3D 프로파일 수집을 위한 로봇 응용 레이저 스캐너 시스템 개발

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요약

근래에 빠른 속도로 발전하는 기술시대에서, 4 차 산업 혁명과 함께 과학자들은 사물 인터넷(IoT) 분야에서 큰 발전을 이루어 냈다. 특히 로봇 개발 분야에서 IoT 가 핵심 기반 중 하나로 알려져 있으며, 세계에서 로봇 연구에 대한 관심이 커짐에 따라 많은 논문과 실용적인 제품이 시장에 나오고 있다. 다른 기술 분야의 발전과 함께 로봇은 현재 과학 기술분야에서 필수적인 역할을 수행한다. 현재 연구중인 로봇 공학의 문제 중 하나는 현대 산업에 적용되는 로봇 시스템이다. 이러한 시스템에 대한 보완은 감시, 구조, 물류 창고내에서의 운송과정 등과 같은 문제들을 해결할 가능성이 있어 실용적인 이득에 대한 기대가 크다. 또한 산업용 로봇은 인간이 수행하기 어려운 작업에서 보다 효율적인 성능과 신뢰도를 제공한다. 본 "용접부 결함 검출용 3D 프로파일 수집을 위한 로봇 응용레이저 스캐너 시스템 개발" 논문은 용접 결함 검사를 향상시킬 수 있는 스캐너 시스템을 구축 및 개발하기 위한 방법을 연구한다.