Automated Printed Circuit Board Assembly Verification and Validation System

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***Abstract*—With the fast-paced evolution in the engineering field especially in electronics, the design of circuitry is becoming more and more complex. Hence, to make sure the Printed Circuit Board Assembly (PCBA) is designed correctly, the prototypes of the PCBA have to be tested and validated before moving on to manufacturing and production process. The In-Circuit Test (ICT) and flying probes are too expensive to be applied for a prototype stage. Hence, the verification and validation (V&V) test for the prototype of PCBA is done manually by the V&V engineers. However, it is a complex and time-consuming process. Therefore, there is a requirement to improve the current PCBA prototype verification and validation. This project is proposed to assist V&V engineers to perform a V&V test for PCBA prototype. This project basically consists of a CNC machine, which has total five degrees of freedom with measuring probe at the end effector. Three stepper motors were used to move the x, y and z coordinate of the probe. The stepper motors were controlled by controller myRIO with stepper motor driver A4988. Besides that, another two smaller stepper motors were used for the probing mechanism. The probing mechanism was designed and simulated by using SolidWorks software. For software, the data extraction from the PCB file was done by the algorithm built using LabVIEW. In addition, a graphical user interface (GUI) was also designed and built using LabVIEW. The system was tested in terms of accuracy and consistency by using samples of PCB. The results from the evaluation showed about 70.83% of accuracy in average. Overall, the performance of the system is acceptable and the accuracy of the system can be improved by the implementation of closed-loop control into the system.**

***Index Terms*—PCBA; Verification and Validation (V&V); CNC Machine; Data Extraction;**

I. Introduction

With the rapid improvement and development of consumer electronics industry, the requirement of the quality in printed circuit board (PCB) industry is increasing. Consequently, PCB industry is developing quickly to cope with the demand. The quality of PCBs determines the electronic products' stability and performance [1]. Therefore, defects detection is required to be precise and accurate by the electronic producers [2].

In PCB design, there are four main stages: part research and selection, schematic capture and simulation, board layout and verification and validation (V&V) [3]. In part research and selection, which is the most fundamental process of PCB design, evaluation of components is done so that each part or component is working well with each other. Next, the schematic is designed and constructed with computer-aided design software. Simulation is done after the schematic is completely constructed. After that, board layout of the PCBA is to be designed by using CAD software as well. Then, the prototype of PCB is built and to be tested through verification and validation, which is the main concern of this project.

In the industry, there are few types of PCBA testing and analysis methods. For example, In-Circuit Test (ICT) and flying probes are two common methods used by the industry currently. However, these two methods are too expensive and industries will not spend a huge amount of money just to test the prototype [4]. Hence, verification and validation process of PCBA currently is done by V&V engineers manually in the industries. This process is a tedious process and time-consuming as the circuitry design is complex.

The process of verification and validation of PCBA is a difficult stage as it requires V&V engineers to test it manually. This process is normally time-consuming for the V&V engineers to perform testing and troubleshooting. It is because there are thousands of pins on the PCBA to be tested. Besides that, due to the complex design of circuitry of PCBA, it is difficult for V&V engineers to find out the exact location of the points or pins which they would like to test. Moreover, the pins on the PCBA are very tiny as nowadays, the components are surface mount device (SMD), hence, there is a high possibility for the V&V engineers to make mistake while performing verification and validation [5]. From the statements above, it is obvious that the efficiency of industries is still not satisfying. Therefore, there is a need to come out with a solution which is able to help V&V engineers to speed up and improve the process of PCBA verification and validation.

To solve this, implementation of automation for PCBA verification and validation would be preferred. With the implementation of automation in PCBA verification and validation, the efficiency of performing PCBA verification and validation can be improved. Hence, the overall efficiency of the PCB manufacturing industries can be enhanced as well.

The remaining of the section will go as follow. The related works such as PCBA testing methods, PCB manufacturing data files, data extraction and CNC machine will be discussed. Then, the methodology employed in this project will be detailed out. It starts with software development on how data are extracted and the graphical user interface is built. The hardware development includes CNC machine setup and probing mechanism design. Results and discussion are shown as to support the findings. Finally, the conclusion is made to the carried out study.

II. RELATED WORKS

This section describes the work which has been done previously on the PCBA testing, data extraction and explains the elements involved in the project (e.g., GenCAD file, DXF file and CNC machine).

A. PCBA Testing Method

In industry, there are many different types of testing methods for PCBA for identification and testing of defects in PCBA. Testing is done to confirm that a PCBA is designed or manufactured correctly. If the result shows that the PCBA has a failure, it will undergo the troubleshooting process. On the other hands, the PCBA can move on to manufacturing process. The common methods which have been used are In-Circuit Test (ICT), flying probes, functional test, electric safety testing and more [6].

In-circuit test (ICT) is a type of automated test method which is used to test PCBAs in industry. ICT performs manufacturing defects analysis to PCBA which covers the majority of common process faults that can occur during production. ICT can be done at fast speed. However, ICT is expensive compared to other methods. It requires a “bed of nails” test fixture and dedicated test program for only one PCBA [6]. If there are any changes or modifications of PCBA, the whole test fixture needs to be replaced by a new one. Due to this, ICT is only suitable to examine the PCBAs which have been confirmed to be launched to the market and not prototype.

The flying probe is another PCBA test method which is commonly used in industry. Just like ICT, flying probe offers manufacturing defects analysis, measurements and limited analogue and digital measurements [6]. However, flying probe is slightly more time-consuming compared to ICT. It is because flying probe does not have the test fixture like ICT does; it has only a few probes which are constantly running over the PCBA [4]. The testing time of flying probes also depends on the trajectory of the probes [7]. A flying probe is also a high-cost approach for testing PCBA. However, it can be reused to test another PCBA by reprograming the flying probe.

Both methods are too expensive for just testing prototypes. Therefore, a low-cost version of the flying probes testing system is to be designed for testing the prototype of PCBA.

B. PCB Manufacturing Data Files

When a PCB is designed and ready to be manufactured, PCB data files (e.g., Gerber file, GenCAD file and Drawing Exchange Format file) are required for the manufacturing process. The detail of GenCAD file and Drawing Exchange Format file is discussed as followed.

GenCAD is the abbreviated form of generic Computer Aided Design (CAD) file. GenCAD file contains the physical design information for PCB. For instance, the board size, pads, components, test pins and even signals can be figured out in the GenCAD file. GenCAD file is made up of a group of text which contains keywords and parameters. The keywords identify the type of data while the parameters represent the data.

Drawing Exchange Format or DXF file is a file extension for graphics image format which specialized for Computer Assisted Drafting (CAD) software. It is developed by AutoDesk in 1982 with the purpose of allowing their AutoCAD product to corporate with other programs or software. DXF files can be in ASCII format or binary format. However, ASCII DXF files are more commonly used than binary as DXF files in ASCII format are more comprehensive.

C. Information Extraction from Unstructured Data

The database is built from an organized collection of data and information. However, these data and information are collected from the unorganized and unstructured source. Therefore, the method of extracting useful data from raw data or so-called data mining is very important. Data mining is a process of figuring out interest patterns from large resource [8]. Figure 1 shows the overview of information extraction-based text or data mining.

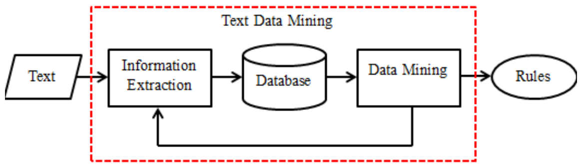

Figure 1: Overview of Information Extraction-based Text Mining [8]

According to the previous research done by Geetha and Mala, they stated that the process of information extraction from unstructured data begins with an analysis of unstructured data, followed by data extraction, syntactic and semantic analysis, data classification, inference rules and representation into a structured format, and ended with data relation [9]. The information extraction method and process that they proposed was reviewed and modified in this project for extracting information from GenCAD file. Lee and Kim also stated that keyword extraction technique which extracts main features and information is crucial in information retrieval, text categorization, topic detection, and document summarization [10].

D. CNC Machine

CNC is the abbreviated form of Computer Numerical Control, which is automated numerical control system. CNC machine includes a minicomputer control and operates based on the program instruction [11]. CNC machine has great flexibility, compatibility and computational capability. CNC machine involves several working axes and the most common CNC machine has three working axes (x, y and z-axis) with a fixed end-effector. According to Lei *et al.*, a five-axis CNC machine tool involves two additional rotary axes for controlling the position of tool orientation [12]. In their research, five-axis CNC machine was being investigated and the kinematic chain of five-axis CNC machine was analyzed. Figure 2 shows the coordinate systems of a five-axis milling machine.

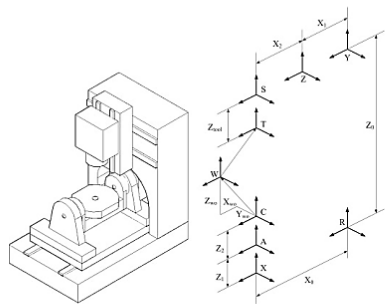

Figure 2: Coordinate Systems of a Five-axis Milling Machine [12]

III. METHODOLOGY

This section describes the method used to develop the system. It includes data extraction from GenCAD file, modification of DXF file, CNC machine and probing mechanism design, and stepper motor control.

A. Data Extraction from GenCAD

GenCAD file is the most important component of the system as almost all the data needed by the system is generated from there. However, without proper study and data extraction method, it is impossible to obtain any information needed for it. Therefore, in order to obtain useful information from GenCAD, there were three phases which need to be undergone with the implementation of LabVIEW, which were data identification, data extraction and data rearrangement. Figure 3 demonstrates the flow in data extraction from GenCAD.

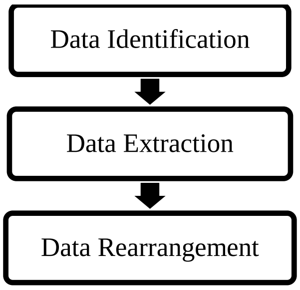

Figure 3: Flow in Data Extraction from GenCAD

GenCAD contains many sections, hence, only the sections which have the useful information are taken care. Therefore, sections which have the needed information were identified. The information that this system required is a component name with a pin number, x and y coordinate on PCB board, a layer of that component located, and netname of that pin. The only sections needed in GenCAD file are “SHAPES”, “COMPONENT”, and “SIGNALS”. The rest sections such as HEADER and BOARD were cut or ignored for computation efficiency. Then, these three sections were extracted out from the whole GenCAD file and stored in a variable.

However, the information in these three sections was not organized in the desired way and some excessive information which was not needed inside these sections had to be removed. Therefore, useful information in these three sections was extracted out through the keywords in each section. Figure 4 shows the technique used to extract information while Figure 5 demonstrates an example of part of the data that extracted from GenCAD file.

After extracting the information from the GenCAD file, the information still could not be used by the system as the information was not organized. In this phase, the data which had been extracted were rearranged and grouped accordingly. From data extraction, useful information such as component name with pin, layer and its netname were figured out. However, the x and y coordinate of the component pin was still missing. Therefore, the calculation was done from the central location, rotation and the difference of distance in order to obtain the x and y coordinate. Equation (1) and (2) determines the x and y coordinate of the component. The parameters x, y, Δy, and Δx were extracted from the GenCAD file as well.

$$Y\text{-}coordinate = y + \Delta y; \quad (1)$$
$$X\text{-}coordinate = x + \Delta x; \quad (2)$$

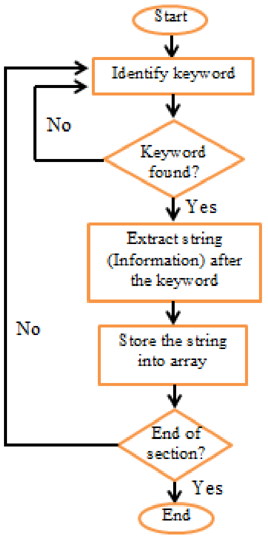

Figure 4: The Flow of Information Extraction Technique

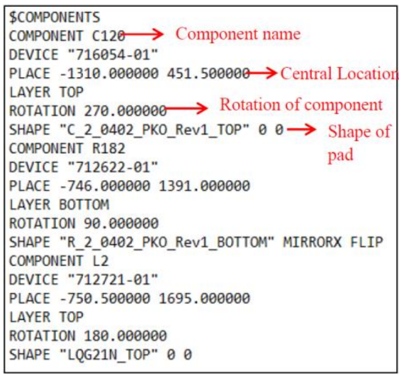
$COMPONENTS
COMPONENT C120 → Component name
DEVICE "716054-01"
PLACE -1310.000000 451.500000 → Central Location
LAYER TOP
ROTATION 270.000000 → Rotation of component
SHAPE "C_2_0402_PKO_Rev1_TOP" 0 0 → Shape of pad
COMPONENT R182
DEVICE "712622-01"
PLACE -746.000000 1391.000000
LAYER BOTTOM
ROTATION 90.000000
SHAPE "R_2_0402_PKO_Rev1_BOTTOM" MIRRORX FLIP
COMPONENT L2
DEVICE "712721-01"
PLACE -750.500000 1695.000000
LAYER TOP
ROTATION 180.000000
SHAPE "LQG21N_TOP" 0 0

Figure 5: Part of the Data Extracted from GenCAD

B. CNC Machine Setup and Probing Mechanism Design

CNC machine is the main hardware of the system. The end-effector of CNC machine or the probing mechanism was designed. The frame of the CNC machine was built from the parts (e.g., aluminium bars with different length, threaded rods, linear shaft, bolts and nuts with different dimension). Aluminium bar was chosen as aluminium has enough strength to withstand the weight of the stepper motors and the whole system. Figure 6 shows the frame of CNC machine built.

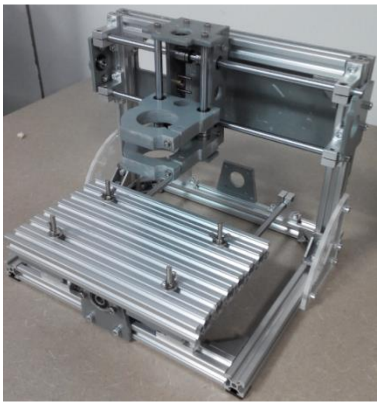

Figure 6: Frame of CNC Machine

Figure 7 demonstrates the design process of probing mechanism. If the result from the validation of prototype was not satisfying, the whole process had to be started over again until the satisfying result was obtained.

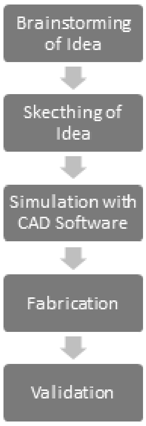

Figure 7: Block Diagram of Probing Mechanism Design Process

C. *Construction of Stepper Motor Circuit*

To control the stepper motor 42H27HM-0504A-18, which was used to control the movement of three main axes, stepper motor driver A4988 was required. The A4988 is a microstepping motor driver with a built-in translator which can be operated for full step, half step, quarter step, eighth step and sixteenth step microstep resolution [13]. In the proposed system, full-step stepping sequence was implemented to operate the stepper motors for three main axes. Figure 8 shows the circuit diagram constructed between myRIO, A4988 and stepper motor 42H27HM-0504A-18.

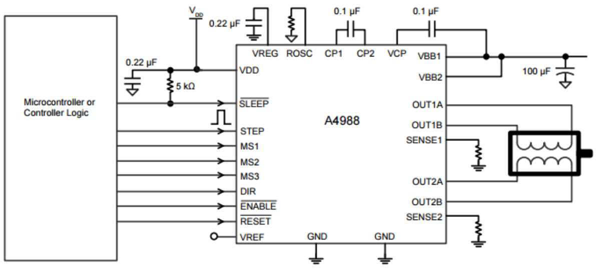

Figure 8: Circuit Diagram for Stepper Motor 42H27HM-0504-18

D. *Stepper Motor Control Algorithm*

The probes had to be moved to the exact location of the pin, hence, the stepper motors had to be controlled precisely and accurately. The algorithm for stepper motor control was created. The algorithm for stepper motor control was divided into two parts, which are unit control stepper motor or “steps”. After the unit was converted to “steps”, it was then sent to the controller, myRIO to operate the stepper motors accordingly.

The unit used in GenCAD file can be mm, inch or others and it depends on the designer. However, unit THOU, which is thousand of an inch, is commonly used in the industry. In order to convert THOU to steps, firstly, it was required to be converted to mm and then, from mm to steps. THOU were converted to mm by using the relationship as in Equation (3).

$$1 \text{ THOU} = 0.0254 \text{ mm} \tag{3}$$

Since the stepper motors used for controlling the movement of x, y and z direction were stepper motor 42H27HM-0504A-18, the conversion of unit for this stepper motor required to follow its specification, which is 1.8^{o} per step. The linear distance travelled by one revolution of threaded rod was 2 mm. Therefore:

$$1 \text{ mm} = 100 \text{ steps} \tag{4}$$

The number of steps was sent to the myRIO microcontroller to generate pulses. The pulses from myRIO were generated by the algorithm made by LabVIEW. The motor driver used for this stepper motor was A4988, the pulses required to be sent from the myRIO were just normal square waves. Figure 9 shows the process for stepper motor control algorithm. Table 1 shows the stepping sequence for stepper motor control.

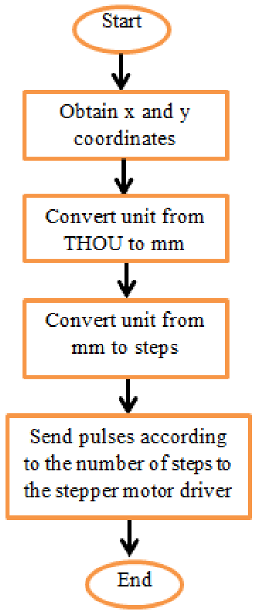

Figure 9: Flow Chart for Stepper Motor Control

Table 1
Stepping Sequence for Stepper Motor

Step	Phase			
	A	B	A’	B’
1	1	0	0	0
2	0	1	0	0
3	0	0	1	0
4	0	0	0	1

E. *Design of Graphical User Interface*

Simplicity, user-friendliness, robustness and the efficiency of the GUI were the main concerns while designing. The GUI integrated the algorithms for data extraction from GenCAD, and stepper motor control. The GUI was created by using LabVIEW programming. Figure 10 demonstrates the flow chart of the GUI developed for the system.

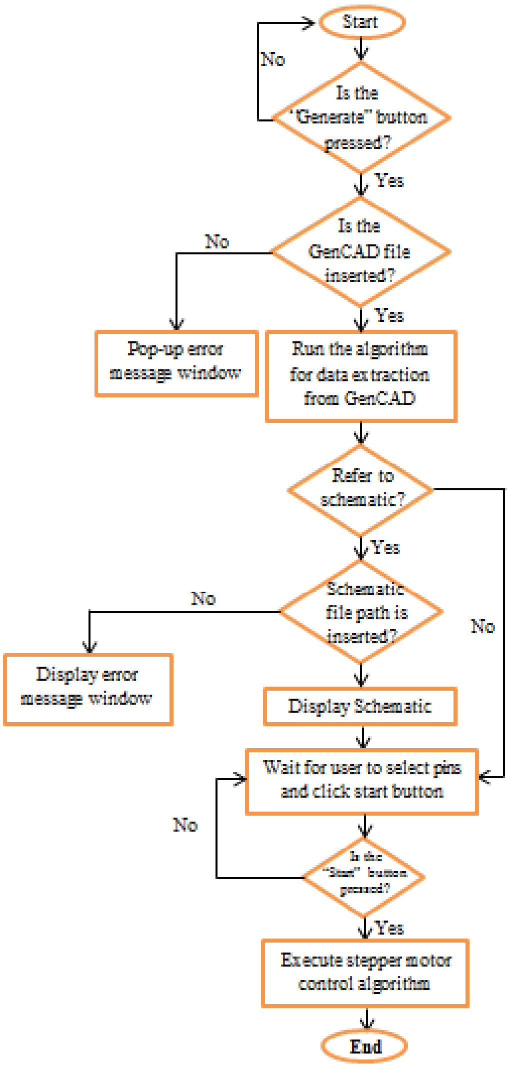

Figure 10: Flow Chart of the GUI of the System

IV. Results and Discussion

A. Results for Hardware Development

Hardware development includes the development of probing mechanism and assembly of the Automated PCBA V&V System. Probing mechanism was designed and most of the parts were printed by using a 3D printer. The parts printed were examined to ensure the dimension of the parts were correct. From the results, there was no misprint or mistake during the printing process. The printed parts of probing mechanism were assembled together and tested to ensure the movement of the probing mechanism was smooth before installing it to the system.

However, the movement of the probing mechanism was not smooth and too loose. It was because of the improper tolerance set while designing. The tolerance was modified and the parts were reprinted and tested. Nevertheless, the rotation of the probing mechanism was not smooth even after the modification of the design. It is because sometimes the drive gear from stepper motor was not always in contact with the driven gear and sometimes too tight and caused the stepper motor did not have enough torque to rotate the mechanism.

The problem was solved by adding springs as the suspension at the stepper motor of the drive gear. As a result, the rotation of the probing mechanism was smooth. Figure 11 shows the implementation of spring as a suspension at drive gear of probing mechanism. Figure 12 demonstrates the final appearance of PCBA V&V System.

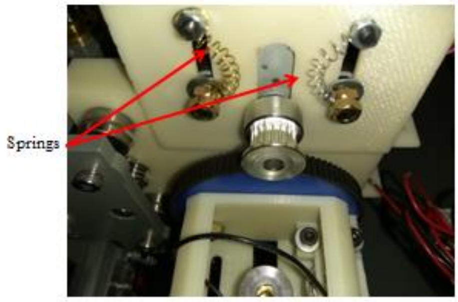

Figure 11: Implementation of Spring as Suspension

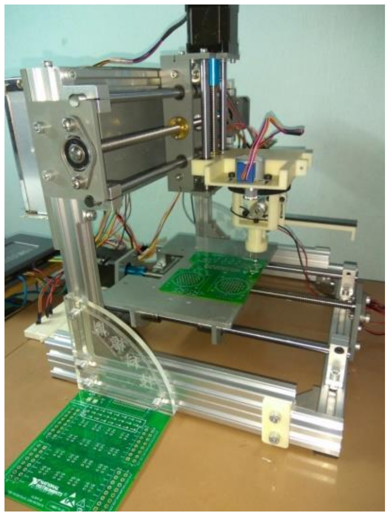

Figure 12: The Developed Automated PCBA V&V System

B. Results for Evaluation of Automated PCBA V&V System

The whole system was evaluated in terms of accuracy and consistency. The accuracy of the system means the accuracy of probing at the pin on PCBA and consistency is the ability the system to provide the desired result constantly. To test the system, samples of PCB were used to be probed by the system. Figure 13 shows the experimental setup for evaluating the accuracy of the system.

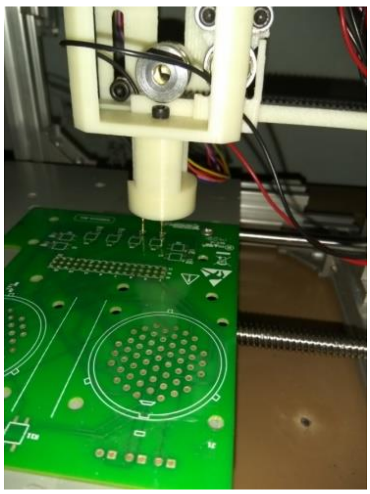

Figure 13: Experiment setup for evaluating the accuracy of the system

Two samples of PCB were used and twenty pairs of the pins were probed to test the accuracy of the system. Samples of PCB were placed on the testing platform of the system with the correct orientation. Each sample of PCB was tested three times. Twenty pairs of the pins on each sample of PCB were picked randomly to be probed by the system and the results were tabulated in Table 2. The average accuracy of the system is 70.83%.

Table 2
Results for Probing Test of the System

		Sample PCB	
		PCB A	PCB B
Trial 1	Number of Correctly Probed Pairs	15	14
	Accuracy	75%	70%
Trial 2	Number of Correctly Probed Pairs	14	13
	Accuracy	70%	65%
Trial 3	Number of Correctly Probed Pairs	14	15
	Accuracy	70%	75%

From the results, it can be observed that some of the pins were not successfully probed. It was mainly because of the weakness of open-loop control system of the system. Besides that, load effect to the stepper motor caused the loss of steps and consequently, the accuracy of the system dropped. The friction of the thread is another concern which causes inaccuracy.

The system was also compared to the current PCBA prototype V&V practice. Twenty pairs of pins from the PCB A were randomly picked and the time required for probing these pairs of pins by using the system and current method was recorded in Table 3.

Table 3
Time Required for Completing Probing 20 Pairs of Pins

	Current PCBA Prototype V&V Practice	Automated PCBA V&V System
Time Required for Completing the Probing of 20 Pairs of Pins	≈ 40 mins	≈ 15 mins

From Table 3, it can be observed that Automated PCBA V&V System was faster compared to the current PCBA prototype V&V practice. Current PCBA prototype V&V practice required a long time to complete because it was done manually by the engineer. In addition, the engineer required time for referring to the schematic diagram and PCB layout file for figuring out the exact location of the pairs of pins. As a result, the performance of Automated PCBA V&V was acceptable by engineers in National Instruments.

V. Conclusion

As a conclusion, the objectives of this proposed project has been achieved. Automated PCBA Verification and Validation System was successfully designed and built with the capability of performing PCBA V&V test automatically. It was compared to the current PCBA prototype verification and validation practice and the result from the comparison showed that the proposed project has the potential to be implemented in the industry to replace the current practice.

For further development, the closed-loop control system is suggested to be implemented in the system instead of the open-loop control system. It is because with the feedback of the position of the probe to the control system, the error on the probing can be minimized and as a result, the overall accuracy of the system can be improved. For instance, PID control system is a solution which can be used to eliminate the error on the position of the probes. In order to implement closed-loop control system, the encoder is a recommended component which is able to give feedback, which is the current position of the probe, to the system.

As a nutshell, it can be deduced that the system developed is able to replace the current PCBA prototype V&V practice as it can overcome the weakness of current method, which is time-consuming and high chance of making mistake. Automated PCBA Verification and Validation System can be implemented in the industry to improve the PCB design process and then, increase the efficiency of PCB design industry.

Acknowledgment

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References

[1] Z. Li and Q. Yang, "System design for PCB defects detection based on AOI technology", *4th International Congress on Image and Signal Processing, CISP 2011*, vol. 4, pp. 1988-1991, 2011.

[2] Y. Hu, "State and Development of Automatic Optical Inspection Applications in China", *Control and Automation*, vol. 155, p. 143, 2006.

[3] National Instruments, "Best Practices in Printed Circuit Board Design", Best Practices in Printed Circuit Board Design - National Instruments, 23-Dec-2015. http://www.ni.com/tutorial/6894/en

[4] JJS Electronics, "The definitive guide to test within electronics manufacturing", 1st ed. Lutterworth: JJS Electronics Ltd, 2017.

[5] Y. Aruga, K. Hirasawa, H. Aoki, Y. Ohashi, T. Hatakeyama, S. Nakagawa, et al., "Study of relationship between copper patterns and temperature rise of printed circuit board for small surface mount electronic devices using constriction thermal resistance", *2016 International Conference on Electronics Packaging (ICEP)*, pp. 190-194, 2016.

[6] R. Poppe, "Electronic PCB assembly testing: In-Circuit Test or Flying Probe?", *Electronic Manufacturing Services Blog*, 10-Jul-2014.

[7] Y. Hiratsuka, F. Katoh, K. Konishi, and S. Shin, "A design method for minimum cost path of flying probe in-circuit testers", in *Proc. of SICE Annual Conf. 2010*, pp. 2933-2936, 2010.

[8] V. Gupta and G. S. Lehal, "A survey of text mining techniques and applications", *Journal of Emerging Technologies in Web Intelligence*, vol. 1, pp. 60-76, 2009.

[9] S. Geetha and G. A. Mala, "Effectual extraction of Data Relations from unstructured data", *IET Chennai 3rd International Conf. on Sustainable Energy and Intelligent Systems (SEISCON 2012)*, pp. 1-4, 2012.

[10] S. Lee and H.-j. Kim, "News keyword extraction for topic tracking", *Fourth International Conference on Networked Computing and Advanced Information Management (NCM'08)*, pp. 554-559, 2008.

[11] J. Valentino and J. Goldenberg, *Introduction to computer numerical control (CNC)*, Prentice Hall Englewood Cliffs, 2003.

[12] W.-T. Lei, W.-C. Wang, and T.-C. Fang, "Ballbar dynamic tests for rotary axes of five-axis CNC machine tools", *International Journal of Machine Tools and Manufacture*, vol. 82–83, pp. 29-41, 2014.

[13] Pololu, "A4988 Stepper Motor Driver Carrier", Pololu Robotics & Electronics. https://www.pololu.com/product/1182. [Accessed: 26-Feb-2017].