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Design of Automated Needle Placement Machine with a Printed Circuit Board Composite Board Fixture

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In this study, we aim to develop an automated needle placement machine using a printed circuit board (PCB) composite board fixture for electrical testing purposes. The machine consists of hardware development and software control system design. The machine is equipped with an *XY* platform placed on an aluminum extrusion base. Above the *XY* platform, two tilted testing platforms (A and B) and an industrial CCD camera are installed. The industrial camera primarily monitors and prevents human errors while observing the needle placement coordinates. The software development involves reading the original drill hole needle pattern files and converting them into editable coordinate files. These files are then imported into the Raspberry Pi operating system and processed using the Python programming language. The program reads the absolute coordinate points of the needle placement machine center and plans the path between the needle points and the absolute coordinate points. The proportional-integral-derivative (PID) controller drives the *X*, *Y*, *A*, and *B* four-axis motors, and the position data from the four-axis motor encoders is read to obtain the target coordinates. After performing position fine-tuning compensation, the probe is inserted into the fixture until the needle placement is completed. The electrical testing of the next program on the fixture is then carried out. The advantage of this research lies in using the automated machine to assist human operators, ensuring accurate probe insertion into the needle fixture. This reduces the defect rate in PCB electrical testing processes and improves work efficiency, leading to automated production realization.

1. Introduction

The rapid development of high-tech industries has significantly increased the demand for dimensions in the micro- and nanometer scales.(1) In the field of international IC processing,

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advances in wafer size and linewidth can be observed. Very-large-scale integration (VLSI) circuits have linewidths smaller than 50 nm, and the wafer size has reached 300 mm.(2) Packaging technology is also evolving towards goals such as high power, high strength, low energy consumption, and miniaturization, such as 2.5D-IC and 3D-IC. The downsizing of IC components indirectly poses challenges for needle placement in packaging test carriers for printed circuit boards (PCBs),(3) and difficulties are encountered. Under the continuous reduction in pitch and increase in density between layers of sockets, the difficulty in maintaining stability, manufacturing, testing, calibration, visibility, and yield also increases. The multilayer structure of the test carrier board, combined with the need to maintain high precision and varying socket positions and heights, results in complex preoperations.(4) To overcome the aforementioned issues, we propose the development of a PCB composite needle placement fixture and an automated needle placement machine. This machine assists in the manual needle placement process. In this paper, we introduce a four-axis mechanism that enables horizontal and tilting motions, allowing the needle placer to vertically insert the needle into the target pinhole. This design was aimed at making the needle placement process more convenient and effortless. To meet the high precision requirements in the semiconductor industry for measuring PCB substrates, the traditional design of the positioning platform with ball screws has been replaced with a magnetic drive to reduce issues such as friction, sliding, and vibration caused by gears.(5) High precision is achieved by using a linear encoder in combination with an optical scale.(6) However, this approach has limitations in terms of a limited range of motion and high cost. To address the challenges of achieving a large travel range, precision, stability, and cost-effectiveness, a stacked configuration is adopted for the platform design.

Moreover, unlike most existing positioning platforms, ours has the capability to tilt owing to the addition of an axial component.(7) Therefore, AutoCAD, Solidworks, and other drawing software are used for mechanism design and simulation analysis. The structure mainly consists of an *XY* platform composed of linear slides,(8) combined with a positioning mechanism (PM) consisting of a pitch axis.(9) The motion equations are derived on the basis of the Cartesian coordinate system(10) to calculate the motion mode. Proportional-integral-derivative (PID) control is employed to drive the mechanism, and CCD imaging is used to ensure accurate needle positioning(11) and achieve the required mechanism orientation for needle insertion. In terms of software, Python programming language, which has gained popularity in recent years, is utilized for program design and development. Python's built-in Thonny IDE or MobaXterm is used for remote connection to Raspberry Pi, via which the fine-tuning of hardware control, monitoring, and data acquisition is possible.

Integrated with various technologies, PCBs or printed wiring boards (PWBs) have replaced the traditional copper wiring and distribution methods, leading to mass production. The development of PCBs advanced rapidly after the birth of transistors in 1950, and in the late 1990s, breakthrough discoveries by IBM, Panasonic, Toshiba, and others contributed to the practical application of additive PCBs,(12) which continues to this day. In the current PCB industry, different types of material are used to produce PCBs in accordance with to various industrial requirements, resulting in variations in material properties, flexibility, size, and manufacturing processes.(13–14) As technology advances and electronic devices become more sophisticated, the demand for lightweight, slim, short, and small devices increases. PCBs need to accommodate a growing number of electronic components within a limited space while improving computational efficiency. Consequently, the early single-sided PCBs have evolved into double-sided and multilayered boards to meet these demands. Presently, PCBs are heading towards high-density and high-efficiency technologies, making the inspection of multilayered boards more challenging.(15) Although the production line for multilayered PCBs has established comprehensive processes, many manual operations still exist, including PCB testing. PCB testing primarily involves visual inspection, reliability testing, and electrical testing. Visual inspection is commonly used for examining the appearance of PCBs, focusing on dimensions, circuits, coatings, substrates, and metallic components to identify any defects. This type of testing is often conducted through manual visual inspection or automated optical inspection.(16) Reliability testing, on the other hand, is aimed at assessing the PCB's resistance to heat, humidity, and flexural strength to ensure its functionality under specific environmental conditions. Various testing methods are employed for reliability testing, such as high-temperature and high-humidity tests, surface insulation resistance tests, accelerated aging tests, and thermal shock tests.

Electrical testing involves both noncontact and contact methods. Noncontact methods include the use of conductive films, conductive probes, and arc testing. Owing to the greater variety and higher technical difficulty of noncontact testing methods, the mainstream market still focuses on traditional contact-based testing, which primarily involves probing the test points.(17,18) In-circuit test (ICT) is a type of contact-based test primarily used for assessing the overall functionality of packaged PCBs. ICT involves testing the functionality of various individual ICs and conducting open-circuit tests on the assembled circuits to verify if the PCBs meet the design expectations. Within ICT, there is a simplified circuit testing method known as manufacturing defect analysis (MDA) testing. MDA testing involves testing circuit boards for defects by performing open-circuit tests on components such as resistors, capacitors, transistors, and diodes. Its purpose is to prevent the use of defective PCBs in the manufacturing process, thereby saving resources and labor that would otherwise be invested in manufacturing unusable circuit boards.(19) Both types of electrical test mentioned above can be performed using methods such as flying probe testing and fixture testing, with fixtures further categorized into dedicated fixtures and universal fixtures.(20) Flying probe testing utilizes four to eight independently controlled probes, similar to a robotic arm, to move the probes to the test points on the device being tested, which are identified using industrial cameras. By rapidly raising and lowering the probes, the test probes make contact with the test points to perform high-voltage insulation and low-resistance continuity (open and short circuit) tests.(21) In terms of operation, flying probe testing requires the CAD files to be converted and tested beforehand, generating .IGE and .SPC files that are placed in the execution folder. Test functions, probe limits, and contact positions are set in the files. Improper settings may cause the probe to leave indentations at the test points during testing. Fixture testing, specifically ICT, consists of two main components: the testing fixture and the automatic testing equipment. The testing fixture requires the production of a customized template to securely hold the test panel on the platform for testing. Prior to operation, the probes are manually inserted into the test holes of the PCB or fixture. The fixture is then placed into the automatic testing equipment, which sends the test signals through the probes on the device, confirming whether the circuitry between various components meets the expected specifications.(22) Next, we will compare the advantages and disadvantages of flying probe testing and dedicated fixture testing. Flying probe testing primarily relies on controlling the probe's position through coordinate settings to touch the test points, eliminating the need for fixtures. However, owing to testing one unit at a time, it is not suitable for high-volume testing. Both dedicated fixture testing and universal fixture testing require the production of fixtures in advance and the insertion of probes into the test holes. They are placed in the testing equipment to simultaneously test multiple circuits, significantly improving testing efficiency. The main difference between the two lies in the fixtures. Dedicated fixtures have probes placed on the fixture for testing, whereas universal fixtures have variations in the mounting method to accommodate different fixture configurations, but the probes are embedded in the PCB. On the basis of the requirements for future high-density and high-efficiency testing, we will adopt dedicated fixtures to implement ICT testing as the research goal for PCB testing. As mentioned earlier, the testing fixture is a necessary component for conducting electrical testing, especially for dedicated fixtures. Different PCB boards require corresponding fixtures, and the production of fixtures involves processes such as computer-aided design (CAD files), hole sizing, NC programming, drilling on the fixture board surface, fixture assembly, probe installation, wiring, fixture installation, and inspection, as well as management.(23) Despite the labor-intensive and expensive production process, fixtures are still widely used for testing purposes, such as the structural analysis of semiconductor PCB board systems,(24) design and characterization of embedded Low-Temperature Cofired Ceramics (LTCC) balun measurement fixtures,(25) and custom fixture debugging for tests.(26)

As the world enters the era of high technology, there is a significant increase in the demand for circuit boards, which has led to longer working hours. At the same time, the global workforce is facing increasing labor costs. The previous manual inspection methods are unable to cope with the growing demand.(27) However, the process of probe insertion into fixtures has traditionally been done manually. To meet the future industry's requirements, it is necessary to develop an automated approach for probe insertion.(28,29) Therefore, the development of this dedicated fixture probe insertion machine is aimed at assisting manual labor in performing probe insertion and achieving automation in the process.

2. System Architecture

Owing to the immobility and lack of adjustability of the fixture itself, but the need for movements such as displacement and tilting during the probe insertion process, we propose an architecture for a dedicated probe insertion and testing machine system using a four-axis machine, Raspberry Pi, and an industrial camera (CCD). In machine operation, on the basis of the drilling process of PCB circuit boards during the manufacturing process, similar to CNC machining, the PCB circuit boards are drilled. Therefore, in this work, the CAD file used in the machining process is converted into an Excel file. Through MobaXterm, the IP address is configured to establish a remote connection to Raspberry Pi. (MobaXterm provides all-in-one functionality for remote tasks. When we use secure shell protocol (SSH) to connect to a remote server, a graphical secret file transfer protocol (SFTP) browser will automatically pop up for editing remote files directly. Remote applications will also be displayed seamlessly on our Microsoft windows desktop using the embedded server. By reading the Excel file located in a specified path, the next position coordinates of the probe platform are received. The encoder data are read and transmitted back to Raspberry Pi, which calculates the movement distances along each axis. The platform motors are then driven to the specified positions. The industrial camera (CCD) is used in conjunction with the CCDs on the top and bottom to confirm the corresponding holes in the fixture. This comparison allows users to verify the actual status of the platform and achieve automated probe insertion.

The testing objective of the PCB hybrid probe fixture for the line-needle probe machine is to insert the line needle into the holes of the fixture during PCB testing. To achieve this functionality, we developed the testing hardware, which is primarily divided into three major parts: the *XY* platform (black ball), the rotating platform, and the CCD camera. The structure utilizes the *XY* platform as the bottom position-moving platform to bring the holes to the coordinate origin (0, 0). The platform is equipped with the A and B axes (orange rectangles), allowing the rotation of the upper and lower plates to form a through-hole (white square) for probe insertion, as shown in Fig. 1, where the red dotted line is the centerline, and the blue line is regarded as threading the needle.

The design of this mechanism originates from the Micro Adjustable Testing Tool,[30] which is an electrical testing fixture. The commonly available fixtures in the market are mostly vertical in orientation with limited lateral movement and no adjustable angles.[31] Therefore, the idea is to replace the bottom fine-tuning mechanism with a linear motor stack, forming an *XY* platform with improved speed and precision of movement, thus achieving rapid positioning functionality. In addition, by combining the servo motor to rotate the upper platform, multi-angle rotation can be achieved. To meet the design requirements and maintain control precision while performing multidirectional movements, forward and inverse kinematic analysis of the machine's motion is carried out using the Cartesian coordinate system. The system is developed using the Visual

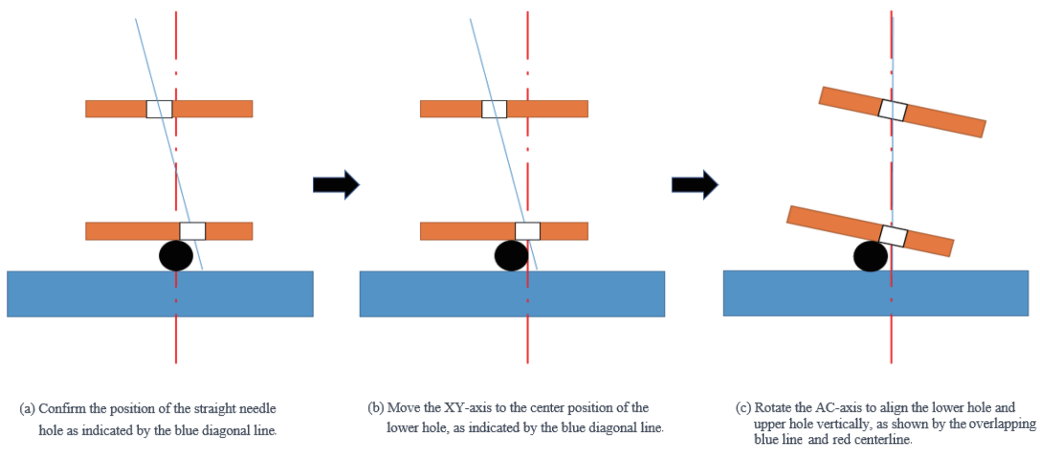

Fig. 1. (Color online) Needle placement process.

Studio editor to write Python programs for image recognition and image processing. The first step is to convert the AutoCAD files of PCB drilling into Excel-readable files. The thickness of the needle fixture board is then inputted, and on the basis of that, the tilt angle of the needle is calculated and the needling operation is performed. The process is defined as one cycle, and each cycle of needling is performed in a row-by-row manner according to the order of the needle fixture holes. Since Python cannot directly read Excel file data, the built-in Pandas library is used to read the Excel file data. Initially, the Excel file data are scanned to identify any blank fields, which are then modified or deleted. The remaining data are transformed into a matrix. By using Pandas library functions, the matrix data are programmatically read line by line from top to bottom, allowing for the calculation of the needle hole coordinates. The independent single-axis motors are driven by PID control and pulse-width modulation (PWM) modulation for precise position movement. The motors move from the bottom axis to the top axis, with each axis being positioned before the machine performs lateral movement and rotation to align the needle holes and the needle in a straight line. Additionally, CCD cameras are utilized for image detection and verification of the hole positions before needling is carried out. The flow of the entire system is illustrated in Fig. 2.

3. Experimental Analysis

The needle fixture machine is constructed by integrating the design of a four-axis platform, forward and inverse kinematic derivations, and machine vision CCD. The base of this needle fixture machine is assembled using extruded aluminum, and it is equipped with an *XY* platform composed of stacked linear motors and a rotating platform consisting of A and B axes, which are driven by servo motors. The workpiece fixture is secured using a locking fixture block, and multiple fixed holes are set on the platform for adjusting the fixture block, facilitating the fixation of the fixture. Dual CCD cameras are used for aligning the needle insertion and confirming the needling process. To ensure clear and focused images from the CCD cameras, the visible range of the CCD is considered, and the needle fixture on the panel is elevated above the design of the rotating platform. This panel mainly serves to secure the needle fixture. The system diagram is depicted in Fig. 3.

The structural analysis of the four-axis platform is illustrated in Figs. 4 and 5, depicting the strain and stress analysis, respectively. On the basis of the diverse requirements of numerous clients, AutoCAD is used to read the 2D original drawings of the needle placement fixture. The coordinates of the fixture holes are then converted and exported as an Excel-readable file. Subsequently, the thickness of the fixture material is inputted, and the tilt angle for needle placement is calculated and implemented. The process is defined as one cycle, with the needle placement performed sequentially following the order of the fixture holes. Since Python cannot directly read Excel files, the built-in Pandas function is employed to read the data from the Excel file. Initially, the Excel data are scanned for empty cells, which are corrected or deleted. The remaining data are then transformed into a matrix, and the Pandas function is utilized to set up a program that reads the matrix data line by line from top to bottom, thereby obtaining the coordinates of the needle placement holes. Simultaneously, position commands are sent to the

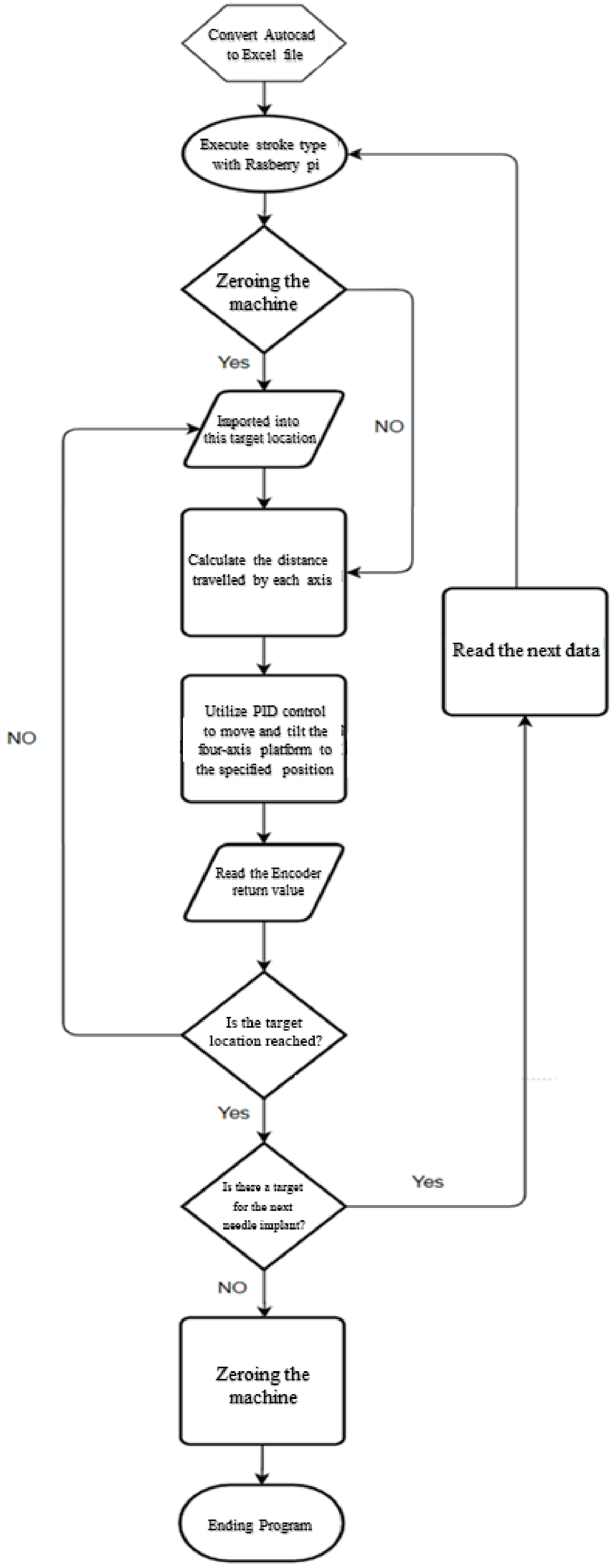

Fig. 2. System operation process.

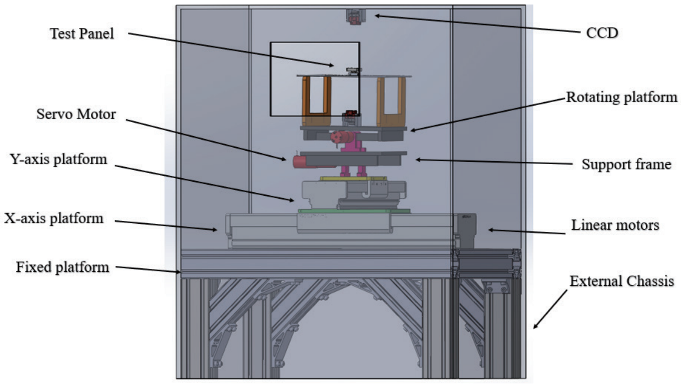

Fig. 3. (Color online) Structure of dedicated machine system for needle placement.

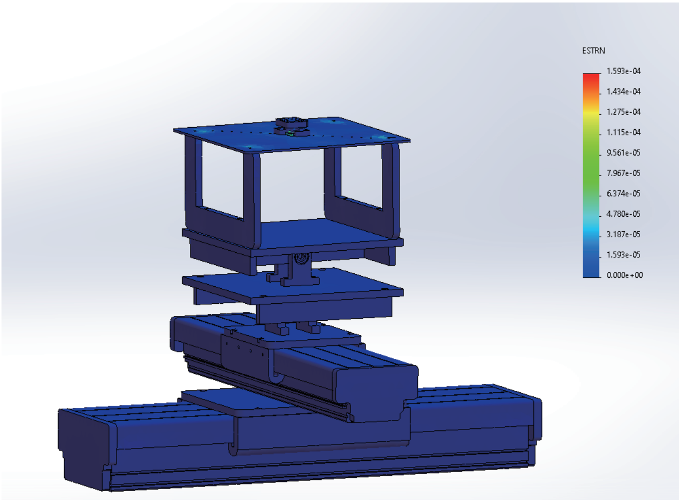

Fig. 4. (Color online) Strain analysis.

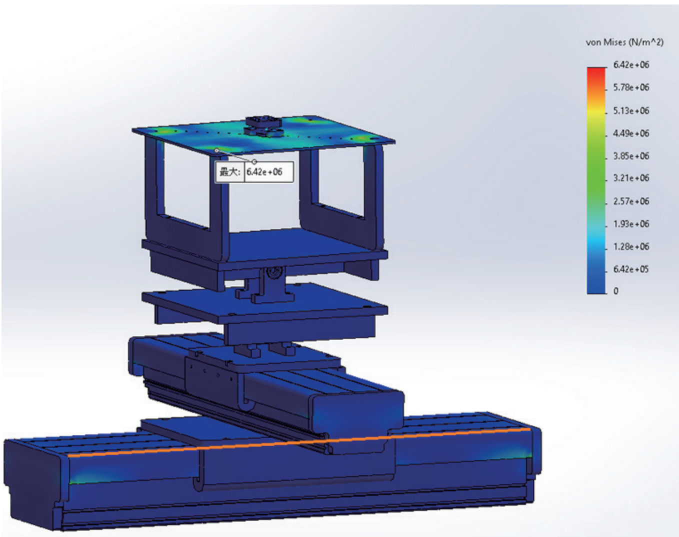

Fig. 5. (Color online) Stress analysis.

respective axis motors to drive them to the designated needle placement positions. CCD cameras are employed for image detection and confirmation of the hole positions prior to needle placement.

The control of this system primarily via a PID controller combined with PWM for position control of the linear motors. In the current stage, the angle control is performed using MG90S servo motors. Through repeated testing, the PID parameters are adjusted and fine-tuned. In terms of control commands, the internal data from Excel are read and the absolute coordinates (with the origin as the reference point) are used. After completing a cycle of needle placement, the distance of the PCB movement is calculated. Control commands are then issued, and motor axis control is achieved through PID-optimized PWM output.

Figure 6 presents the actual dimensions of the fixture needle holder in a front view, with a 2.7-cm-diameter 50-cent coin for scale reference. Meanwhile, Fig. 7 displays a side view, along with a scale reference provided by a 2.5-cm-diameter 10-cent coin.

We employed Python and an industrial CCD camera for image capture, allowing us to magnify the captured images. Figure 8 illustrates the original magnified view of the needle placement holes.

By performing binarization, we separate the board from the hole positions. However, owing to the uneven distribution of the projected light source, unnecessary light source point noise, known as false features, is generated. Figure 9 illustrates the enlarged needle hole positions after undergoing binarization analysis.

Next, we apply Gaussian blur filtering to eliminate false features generated after binarization analysis. By adjusting the threshold of the RGB channels and enhancing the edge detection of the hole positions, the appearance of the objects is rendered, as shown in Fig. 10, which depicts the restored color image after Gaussian blur filtering. The accurate boundary hole positions are outlined using Canny edge detection, as shown in Fig. 11, which illustrates the boundary hole positions detected by the Canny edge detection technique.

In the experiment, we utilized Solidworks to design a four-axis needle placement fixture machine. The machine simulated the inclination caused by the variation in hole positions between the upper and lower boards. Control was applied to the motors along each axis to ensure

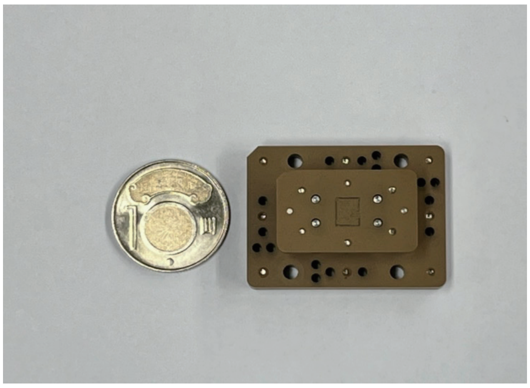

Fig. 6. (Color online) Top view of the needle placement fixture.

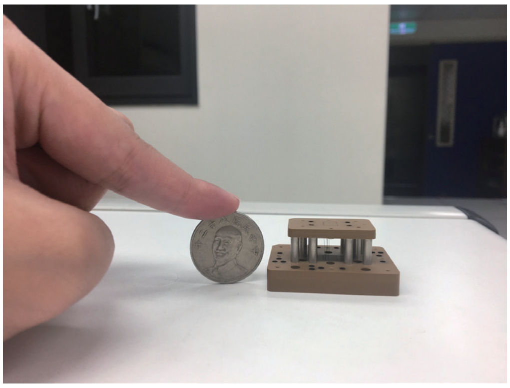

Fig. 7. (Color online) Side view of the needle placement fixture.

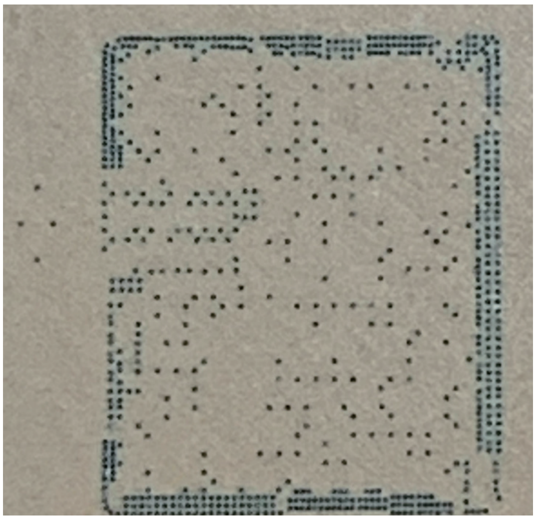

Fig. 8. (Color online) Original magnified view of needle holes.

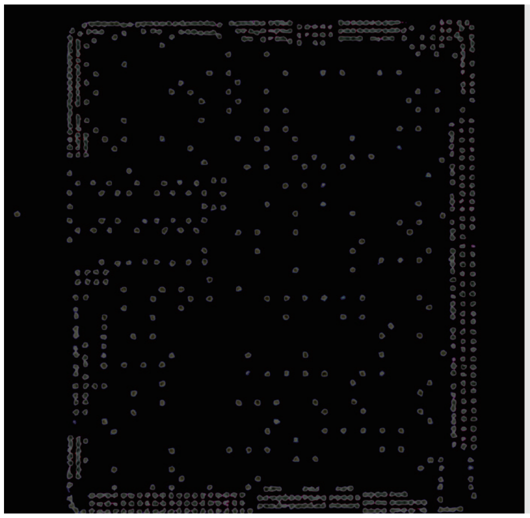

Fig. 9. (Color online) Binarization analysis results of enlarged needle holes.

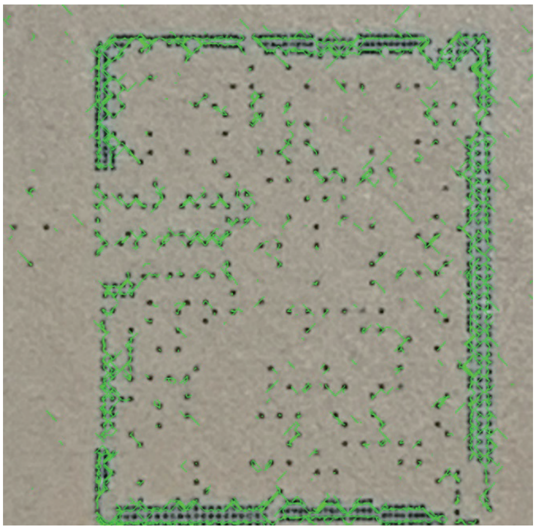

Fig. 10. (Color online) Restored color image after Gaussian blur filtering.

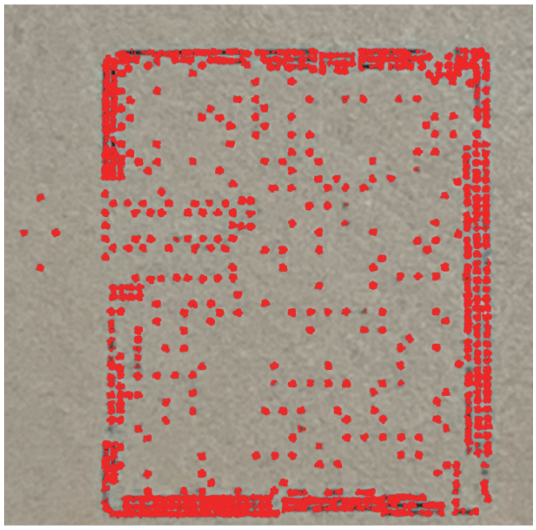

Fig. 11. (Color online) Canny edge detection of boundary hole positions.

alignment of the upper and lower holes with the needle, facilitating needle placement. CCD image recognition technology was integrated to accurately locate the holes and allow operators to monitor the hole positions for convenient needle placement. The Python programming language was employed to integrate PID control, CCD image recognition, and machine control. This integration resulted in the realization of the tilted top view of the needle placement machine shown in Fig. 12, the motion diagram of the tilted needle placement machine depicted in Fig. 13, and the schematic of actual needle placement shown in Fig. 14.

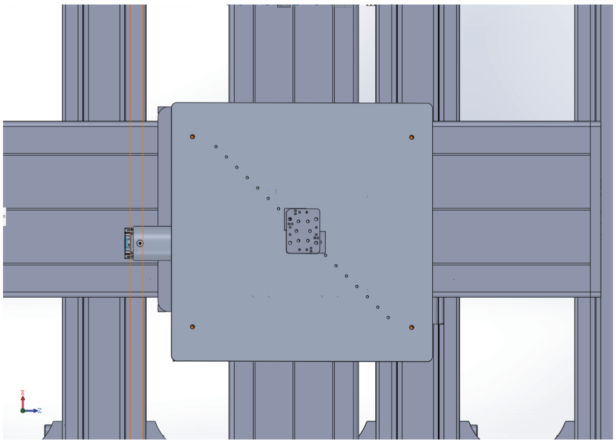

Fig. 12. (Color online) Inclined top view of the needle placement machine.

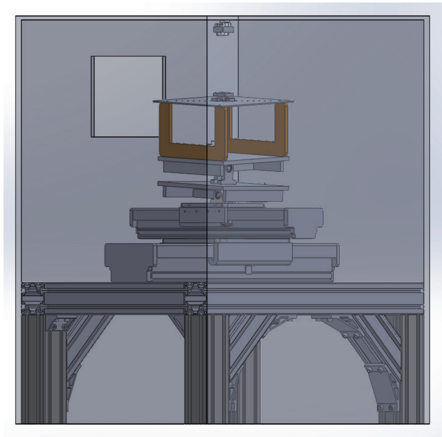

Fig. 13. (Color online) Inclined view of the action of the needle placement machine.

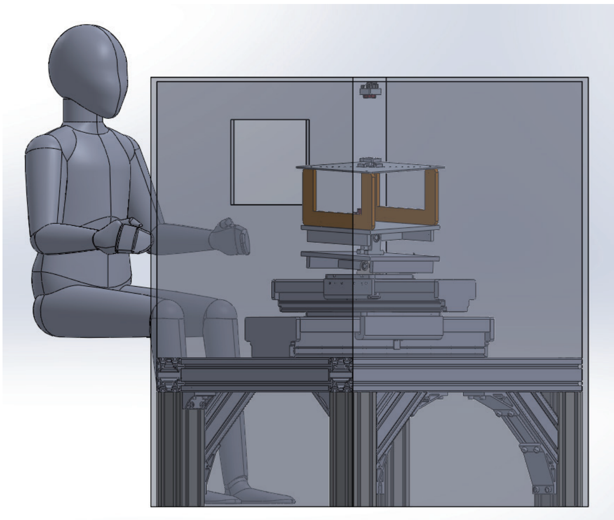

Fig. 14. (Color online) Schematic of actual needle placement.

4. Conclusion

In this study, we proposed the development of a PCB hybrid needle placement fixture and machine for high-density multilayer boards. A four-axis needle placement mechanism was designed, and stress and strain analyses were conducted on this mechanism. By using a Raspberry Pi control board and writing Python programs to read Excel file data, the coordinates of the needle placement holes could be calculated. Position control commands were then issued to drive the *XY* platform for positional movement and the AB rotating platform to rotate to the specified angle for needle placement at the coordinates of the holes on the needle placement fixture. By completing a single-hole needle placement cycle, the needle placement was carried out in a row-wise manner from top to bottom, although columnwise sorting can also be implemented using this method. In addition, Python and OpenCV were used to process the images, allowing users and the machine to have a clearer view of the needle placement holes. This integration of functionalities enabled needle placement. By utilizing the Raspberry Pi control board and running the built-in OpenCV program in Python, the camera was activated to observe and record the needle placement holes, thus completing the fixture needle placement process. In the PCB industry, there are still many processes that have not been fully automated. The difficulties primarily arise from factors such as precision requirements, product inconsistency, and high unit costs. The line-needle PCB composite fixture needle placement machine developed in this study was aimed at addressing these challenges. In the future, with sufficient funding, it is expected that either the A or B axis can be replaced with an additional rotational axis, namely, the C axis. Furthermore, the stacked *XY* platform can be transformed into a gantry-type *XY* platform with aligned axes. This modification not only enhances the overall stability of the machine but also facilitates more precise positioning at the origin.

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