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Automatic lab system for optical, electrical, and thermal inspection of PCBs.

Carlos Vega
Instituto Universitario de Microelectrónica Aplicada (IUMA)
Universidad de Las Palmas de Gran Canaria (ULPGC)
Las Palmas de Gran Canaria, Spain
ORCID: 0000-0002-5629-1471

Aurelio Vega
Instituto Universitario de Microelectrónica Aplicada (IUMA)
Universidad de Las Palmas de Gran Canaria (ULPGC)
Las Palmas de Gran Canaria, Spain
ORCID: 0000-0002-4154-8799

Irene Merino
Instituto Universitario de Microelectrónica Aplicada (IUMA)
Universidad de Las Palmas de Gran Canaria (ULPGC)
Las Palmas de Gran Canaria, Spain
ORCID: 0000-0003-4380-6402

Oscar Pérez
Instituto Universitario de Microelectrónica Aplicada (IUMA)
Universidad de Las Palmas de Gran Canaria (ULPGC)
Las Palmas de Gran Canaria, Spain
operez@iuma.ulpgc.es

Abstract—**A cost-effective machine is presented to automatically carry out PCBs' optical, electrical, and thermal inspection. It can generate high-resolution composite images and perform automated voltage and temperature measurements at any point in the work area. Its use is designed for teaching and research environments, although it is also helpful in a repair workshop for troubleshooting.**

Keywords— optical inspection, electrical test, thermal analysis

I. Introduction

The testing and reparation of electronics systems is a complex and time-consuming task. In the labs, this process is mainly made by hand with the help of standard equipment like oscilloscopes. It exists equipment to automatise the test of the circuits, the flying probing testers. Those machines have one or more heads with test probes that touch the board in the test points for measuring the electrical characteristics between them. The main problem is that, due to their high price and complexity, they are out of reach of most labs and do not adapt adequately to this environment.

This publication presents a new cost-effective machine developed for PCBs' (Printed Circuit Board) automatic optical, electrical and thermal tests for research and educational environments. The initial objective with the design of this equipment was to introduce to the research group a new tool for the reparation of industrial PCBs from wind turbines.

The main task in the reparation process is the circuits' fault detection. The failures can be discovered in three ways: visually inspecting to find any visible damage, checking for short circuits by variations in the temperature, or testing the design electrically [1]. With the proposed machine, it can be checked automatically for faults on the PCBs. Also, this equipment is not only helpful in repairing goals but it can also be used to test new boards and evaluate their performance.

II. Machine Structure

A. General Design

One of the first challenges that were faced in introducing an electronic test solution in the labs was the cost and lack of flexibility of current solutions. The test systems on the market are targeting production lines, which creates high-cost solutions that do not adapt to the environment of the labs [2].

The mechanical solution proposed looks for a robust and straightforward design that can be easily replicated in other labs. The machine consist of a Gantry robot that controls the XYZ movement of the head unit. The head unit includes the machines' sensors, composed of a camera with a led illumination system, a point thermal sensor, an 8x8 pixel thermal camera, and a test probe.

The machine's structure has been developed to use commercial components and controllers. The core is based on extruded aluminium profiles connected with custom pieces, designed for fast additive manufacturing. It uses standardised Nema motors that connect with the moving parts by a belt for the motion. Thanks to the spread of affordable commercial 3D printers, these parts are widely available, which makes them ideal for this purpose.

B. Tray load strategy

The first step for extracting any information from the PCB is locking the board to the machine. There are multiple alternatives for locking the boards, but in an industrial environment, the most common are the ones based on conveyors. Industrial testing and pick and place machines use the conveyor to move the boards from the input area into the machine. There is usually a platform that lifts and blocks the board while operating. Then, when the board's operation is finished, the platform unlocks, and the conveyor pushes the board into the next step. This design forces the board's exterior dimensions to keep constant, because the width between the conveyors must be the same as the PCB. This width could be changed but forces to the configuration and calibration of the system.

For the application, it was decided to avoid the inconvenience of belt systems and their complexity and was opted to lock the PCB to an external frame that attaches to the machine (Fig. 1). This is fixed by employing two adjustable upper and lower rails, which have several positions to exert pressure on the PCB. With this solution, the board can be conveniently placed outside the machine and only inserted when the system is ready. It also allows us to increase the machine's operating time by having two trays, so while one is used in the machine, the PCB can be placed in the other.

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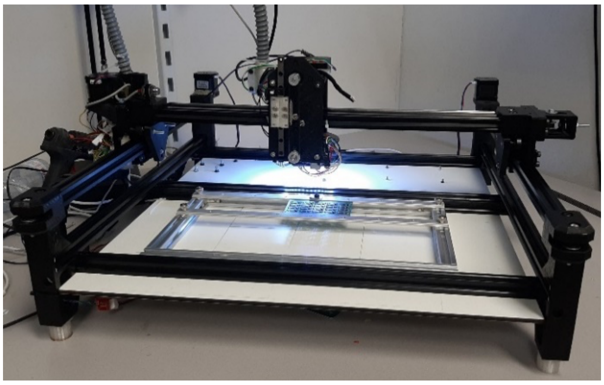

Fig. 1. Machine with the board placement frame.

III. Motion Control

A. *Controller Board*

The machine's motion system is controlled by a controller board designed for a 3D printer, specifically an SKR V1.4. This board was chosen because it offers a high amount of outputs, which are able to control six steppers, while keeping a competitive cost.

The machine follows the scheme in Fig. 2. There are two stepper motors for the y-axis, each in its line. Then there is one motor x-axis placed on the central arm. Finally, the motor controlling the z-axis is located at the top of the head unit. Additionally, the machine allows upgrading the functionality by placing two independent axes of rotation on the head for allowing tasks of pick and place for manufacturing or repairing.

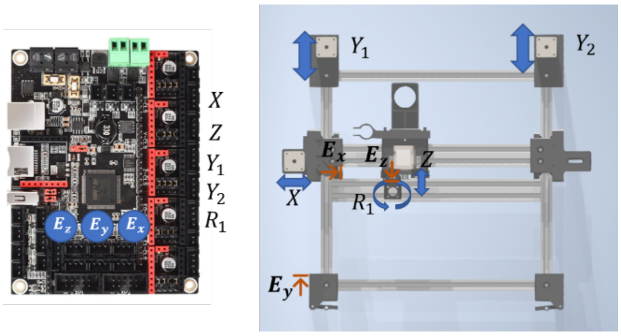

Fig. 2. Schema of the kinematics in the machine.

The movement on the axes is constrained by three end-stops that are used in the first homing process. For the x-axis and y-axis, hall sensors are used, which are more precise and reliable. For the z-axis, switch end-stop is used because it has a lower footprint, which allows to attach it quickly to the rail system.

B. *LabPCB Controller*

To control this system, it was needed of a driver solution able to handle the GCODE commands and let the system work remotely in the future. For this, a custom controller called LPController was designed. The software has been designed to control different machines by being able to handle different protocols, but in this case, we will use Marlin GCODE.

The controller is a C# application developed on Visual Studio. It has a TCP socket on the computer, where the user interface can connect and send the control commands. Internally the LP Controller has one driver to control each type of machine. Every type of driver handles the connection with the machine and translates the received commands to the protocol needed.

For this machine the control system is configured with two drivers simultaneously. As shown in Fig. 3, the first driver is responsible for controlling the motion system, while the second handles the communication with the head control unit. This combination is done thanks to the possibility of dividing the commands by their type.

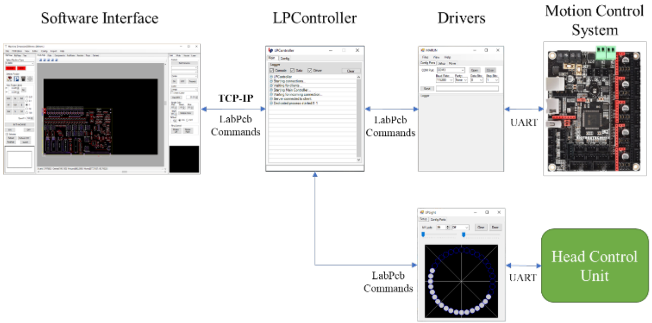

Fig. 3. Graph of the data flow in the machine.

In this project, it has been developed a custom general protocol to allow LPController to control different types of machines. The communication between the software interface and controller happens by a TCP-IP link, where the software is the client and responsible for always beginning the communication. In this protocol, the server must do the action and respond with an ACK (ACKnowledgment) if there is no specific response to the command. In TABLE 1, there are all the available commands implemented in the protocol.

TABLE 1. LPController available commands.

LABPCB MOTION CONTROL COMMANDS		
COMMAND	***PARAMETERS***	***DESCRIPTION***
HOMING		Force Homing machine
OFFSET	Offset	Define tool offset
XY	Xmm Ymm	Goto Xpos Ypos mm
Z	Zmm	Goto Z position
GP		Get position XYZ
GC		Run GCODE
SXY	% Speed	Set velocity XY (0-100%)
SZ	% Speed	Set velocity Z (0-100%)
L1		Laser On
L0		Laser Off
RESETS		Force a reboot
IMAGEXY		Take a image in XY
TEMPXY		Take temperature in XY
TP		Read the Test Point
PICK		Pick a component
PLACE		Place a component
V1		Turn on vacuum pump
V0		Turn off vacuum pump
A	0-360º	Set rotation degree
IDLE		Force idle state
RUN		Force run state
STOP		Force Stop state

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IV. Sensors

The goal of this machine is to help in the process of testing and repairing electronics circuits. For this purpose, it is necessary to include sensors able to acquire valuable information about the board and its behaviour. It has been chosen to include one high-resolution camera and its illumination system, infrared thermal sensors, and one electrical test probe for this goal.

In this implementation of the machine, all the sensors are located in the head unit. The sensor system uses an independent control of the machine's main one, which allows us to use a different protocol from the Marlin GCODE and make modifications for our needs in a simple way.

As shown in Fig. 4, the system is connected through a single USB cable to the PC. This system is implemented on a single board that internally connects the head camera and the microcontroller to the computer through an internal USB 2.0 HUB.

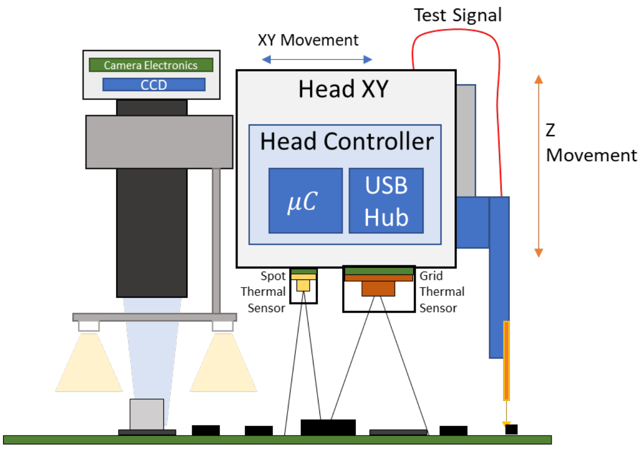

Fig. 4. Illustration of the head unit with the sensors.

A microcontroller ESP32-WROOM-32E handles all the sensors and the light solution. This SOC (System On Chip) stands out for being based on an Xtensa dual-core LX6 microprocessor and for including integrated modules of Bluetooth Classic, BLE (Bluetooth Low Energy) and WIFI. This SOC was chosen due to the knowledge of the group about the platform and because it offered simple libraries for the sensors.

The development of the firmware for the acquisition sensor was carried out by two different bachelor-thesis. The first one developed the acquisition of the thermal solution and studied the connection between the microcontroller and the computer. In this work, it was also studied connecting the microcontroller with the PC by BLE. The second student integrated the solution into the current head unit and added the control for the illumination system and control for the addition of stepper motors. For both projects, it was defined clear specifications for the data needed to acquire and the communication protocol. In their works, they faced three stages: the study of the state-of-art and their objectives, the development of the firmware and PCBs and a final step of validation and integration of their solution.

A. Optical Image and Illumination

The goal in the computer vision module is to allow the system for automatic optical imaging techniques, like scanning or component solder visualisation, but also for research goals in the area of Artificial Intelligence. In this context, quality lighting is essential, and the best way to achieve it is through an advanced lighting system.

The system uses a ring of Neopixel LEDs based on the WS2812 model (Fig. 5). This family of LEDs contains 3 RGB LEDs and a control circuit integrated into the package. The transfer protocol only uses one line and allows all the LEDs to be chained through its input and output ports, requiring a single pin to control the entire ring.

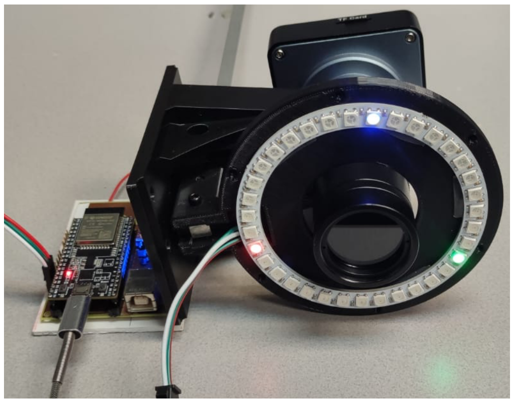

Fig. 5. Image of the lighting system during development.

The microcontroller handles the ring configuration and the communications with the computer by the UART (Universal Asynchronous Receiver-Transmitter). The current protocol allows us to control each LED individually but also to define how many LEDs are turned on, the illumination intensity and the rotation of the illumination area in degrees.

The illumination system is controlled by the LPLight driver, which is responsible for converting the LPComands received by the LPMachine into those specific to the head control system. The software has been designed to allow a portion of the LEDs to be turned on and their position to be angularly rotated, as shown in Fig. 6. The illumination rotation is intended to facilitate a manual optical inspection by the user. Because the circuits are composed of components of different heights, shadow areas can be generated between them, being able to rotate the lighting allows the user to control the generated shadows, eliminate bright spots, or facilitate the reading of the component references.

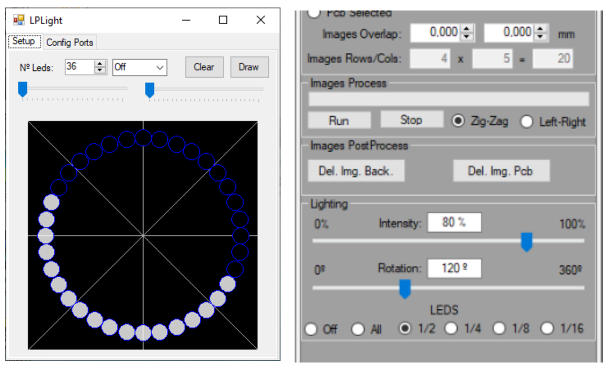

Fig. 6. LPLight visual interface.

One of the main tasks of the lab system is capturing an accurate image of the PCBs. Having a high-resolution image

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and accurate image is necessary for performing reverse engineering tasks, inspecting manufacturing defects, generating high-quality reports, and developing new algorithms for advanced AOI (Automated Optical Inspection) [3].

Capturing an accurate image of a large area is not a simple task. One single picture requires a long viewing distance, and it includes deviations in the image due to the effect introduced by the optics adapted to a wide angle of view. The alternative is to capture multiple partial images of the board with accurate information of the coordinates and the size of each image for later composing all of them into one single image of the system. This strategy has also been used by reference manufacturers of AOI equipment, for example, OMRON. We have the device OMRON RNS II-pt [4] as part of the group equipment, so we took it as a reference for state of the art in this area.

Before generating composed images, it is necessary to calibrate the field of view of our camera and lenses. We are using a high-quality USB (Universal Serial Bus) camera with a resolution of 2.1 Mpx and microscope lenses that give an ampliation of 20X. To calibrate the field of view, we used visual references with a millimetre scale over a piece of glass. The reference is positioned over an empty PCB to equal the expected focal distance and centred with the camera to calculate the view area. The current configuration obtained a width in the image of 11,78 mm for a resolution of 1920 pixels, which resulted in a pixel density of 163 pixels/mm.

Finally, there is the process of capturing the images itself. The machine moves the head unit to the different capture positions by following a zigzag path over the board, as shown in Fig. 7. The position to capture each image is calculated in the LabPcb software from the pixel density value. Multiple strategies were tested for capturing the images, but the best resulted in introducing and slight overlap between the images, which helps reduce any deformation that could happen in the borders of the image.

During the process of capturing the images, the computer software records each picture and combines them into a single image. This process can be memory intensive due to the large size of the composed image. For an industrial board of format Eurocard, the system captures up to 160 partial images, which results in a combined resolution of 336 megapixels.

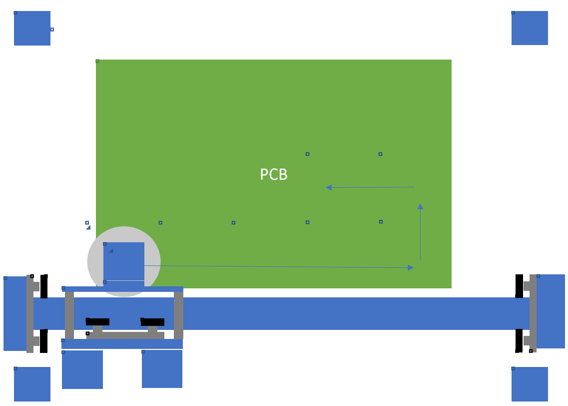

Fig. 7. Capture of a composed image in the machine.

B. Electrical Test

In the process of testing and repairing, it is necessary to analyse the board's behaviour. There are two distinct types of electrical tests: passive and active. On the passive test, the circuit is not powered during the test, so there are two or more test probes that touch the board in a different location for measuring the impedance, capacity, and continuity between them. This type of test is safer for the board and requires lower preparation, but it cannot find every possible problem in the circuit.

It has been opted for an active test for our solution, but is not discarded extending the functionality to a passive test in the future. With this test, the circuit is powered during the process, and there are one or more probes placed on the board's test points for measuring the signals present on each.

Opting for the active test has two main benefits. First, it simplifies the machine as it only needs one probe to touch the board, implying that only one head unit and one motion system are needed. In Fig. 8, there is a schematic view of the test system, where on the head, there is one test probe that captures the signal while the ground is connected directly to the board's power supply.

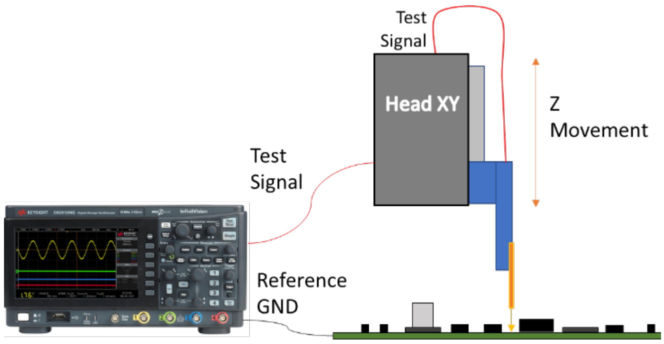

Fig. 8. Scheme of the electrical test system operation.

The second benefit of this solution is that it allows the user to evaluate the board behaviour quickly and analyse the internal signals. This can be done without our equipment, but it implies soldering tiny cables to the test points due to most of the boards having small SMD components.

C. Thermal Image

Due to the integration level of the systems nowadays, thermal testing is a key for detecting some faults. This system implements two low-cost solutions to perform temperature mapping.

Generally, working machines in electronics laboratories do not include a thermal measurement system. An interface was developed for acquiring the temperature data using a sensor Melexis MLX90614. This sensor can work adequately in ambient temperatures from -40ºC to 125ºC and with object temperatures between -70ºC and 380ºC with a resolution of 0.02[5]. According to the encapsulation of the sensor, different fields of vision are achieved. In the case of this work, the encapsulation is AAA, having an angle of vision of 35º.

Also, the temperature array sensor AMG8833 has been implemented. This device works between 0ºC and 80ºC with a resolution of 0.25ºC [6] and the vision angle is 60º.

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Moreover, the optical centre of the sensor has a vision angle of ±5.6º, so the image got is distorted, as seen in Fig. 9.

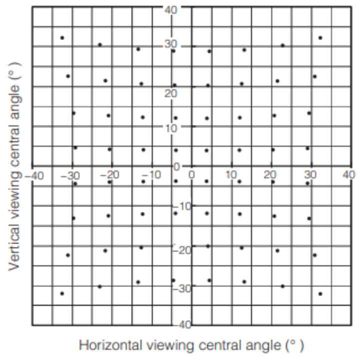

Fig. 9. Pixel's distortion in degrees of the AMG8833 sensor. [6]

The communication between these sensors and LPController uses a microcontroller and the I^{2}C protocol, as seen in Fig. 10. This is a master-slave protocol used by most integrated circuit manufacturers. It uses two bidirectional lines: Serial DAta (SDA) and Serial CLock (SCL), removing a large number of connections and making designs modular. The Melexis sensor uses SMBus protocol, a version of I^{2}C with some limitations in terms of working frequency, which cannot be greater than 100 kHz. Moreover, only reading and writing commands can be used [7]. In this case, these limitations are not crucial, so this bus is used to implement the solution.

The sensors are placed at the bottom of the head unit, which is the closest part to the circuit, giving more accurate measures. One of the functions permitted by this strategy is the scan of the field of work capturing AMG8833 array sensor data to generate a thermal image of the PCB. An example of the visualisation of our software is illustrated in Fig. 10.

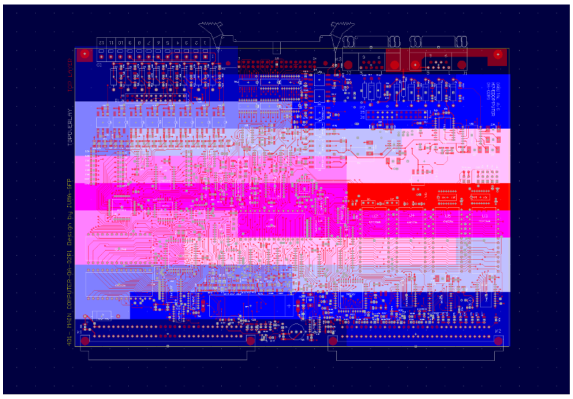

Fig. 10. Visualization example of a PCB's thermal image in LabPcb.

V. Results

The presented machine has been developed to help our industrial electronic circuit repairing tasks. As mentioned, this machine also has capabilities within the academic environment and other applications not yet exploited. This section will analyse the results obtained for each type of data prepared to capture.

In Fig. 11, there is the result of a composed image obtained from one of the PCBs manufactured by our team. The PCB has a dimension of 100 mm by 59 mm, and the image obtained is composed of 81 partial images. The final resolution is quite large, with 16,900 pixels in width by 9,617 pixels in height and a resolution of 162 megapixels.

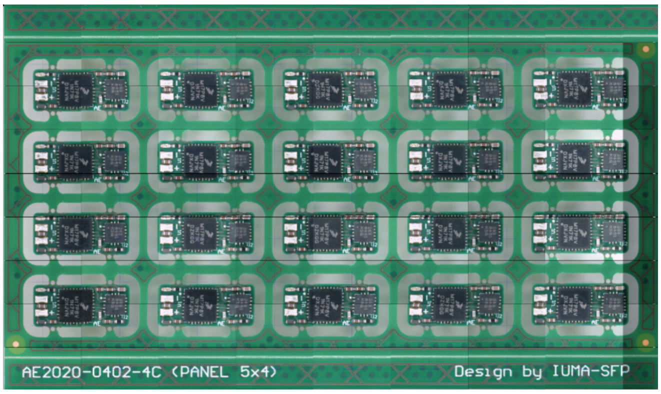

Fig. 11. Composed image obtained from the system.

In the image, it can be appreciated some interesting details. First, the alignment between the images is close to reality but has an error in the range of +/- 0.15 mm. It is also noticeable that the brightness in the images is not constant between the different areas. This problem happens due to our lack of control in the capture settings of the current camera. For solving this issue, the camera will be changed to an industrial camera that includes a specific API (Application Programming Interface) for handling all the capture parameters. As a last observation, the chosen illumination has been a success. In our tests, the system has shown a uniform illumination without introducing reflections or shadows in the camera's field of view.

Next step, we tested the thermal image capture system. We tested it by placing a PCB in the machine with a heater under its left side. The result (Fig. 12) shows the thermal gradient between the hottest area, which is on the left and has a temperature of 62ºC, to the lowest, which has a temperature of 26º C.

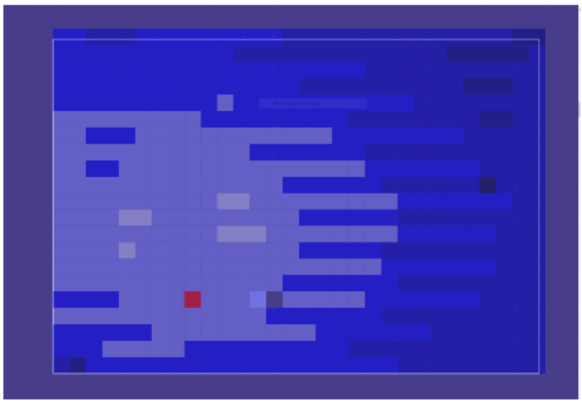

Fig. 12. Result of a thermal image obtained from the system.

In this image, there are a couple of details to improve. At first, the software will be improved for having a continuous gradient in colour between temperatures. Then, one red pixel shows a temperature outside the expected value range. This could happen due to some errors in the communication. The goal is to reduce the outliers' error by obtaining a measure as an average of three captured values.

Finally, it has been tested the accuracy of the test system. With the presented design, the measurement and visualisation of the test signal are realised on external equipment, so it has not been tested independently. The probe placement has been

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measured to have an accuracy of +/- 0.25 mm. This result indicates that the system is capable of capturing signals from most of the test points included on commercial PCB boards.

VI. Conclusions

This presented publication has our research on developing a new cost-effective solution for the automatic test of electronic circuits in university laboratories. This device has been made publicly available on our GitHub page for anyone interested in the project to be able to replicate our solution. At our team, the solution has been successful in two different ways.

This project was started because we needed a tool to help us carry out electronic circuit repairs for the maintenance of wind turbine control systems. In the tests, this tool has made it possible to accelerate our activities in this area. However, it has also brought another benefit. Now, the time needed to teach a new person the repairing activities is shorter. This happens because by using this equipment and the LabPCB application, the users are forced to have a more organised workflow, making the tasks easier to follow for untrained professionals.

Another success in the project comes from an educational point of view. This work has been carried out thanks to the collaboration of several students through two Final Degree Projects of the Telecommunications Technologies degree and two internships carried out in the Prototype Manufacturing Service of the IUMA (Instituto Universitario de Microelectrónica Aplicada). The development of this system has made it possible to carry out practical and didactic work in which students have been able to carry out a practical and interdisciplinary approach to R&D (Research and Development) focused on a product.

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