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Improved Flying Probe-Inspired In-Circuit Tester for Practical Laboratory Activities

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***Abstract*— This paper presents an innovative, improved, and sensorless Flying Probe-Inspired In-Circuit Tester (FPICT) for verifying the interconnects of Printed Circuit Boards (PCBs). The proposed tester, due to its portability, can be easily deployed in laboratory environments for practical purposes. Thus, our research aims to demonstrate the effectiveness of the FPICT in increasing the learning rate of young scholars in Test Engineering Education (TEE). A total number of 16 high school students from "Caius Iacob" Technological High School of Electronics and Automation of Arad, Romania, were selected as the target group for the test platform studies. Before the practical laboratory activities, we performed a series of tests to evaluate the reliability of the improved FPICT. The experimental results show that the proposed FPICT is suitable for smaller and medium-sized PCBs and proves efficient regarding the probe’s positioning accuracy (99.06% for measurement testing), navigation time (an average of 8.20 seconds for single point testing), power consumption (an overall of 14.67W for all considered test cases), and cost (around 30 dollars). The obtained results indicate that the FPICT prototype passed the initial tests and can now be utilized in a learning environment for the final product validation stage.**

Keywords*— *Flying Probe, In-Circuit Testing, Printed Circuit Board, Fault Detection, Education

I. INTRODUCTION

Engineering education has captured the interest of the national and international engineering societies for almost two decades, as seen by the proliferation of research institutes, conferences, and publications devoted to the subject, as well as an increase in federal financing for initiatives committed to engineering education research [1].

Despite old [1-4] and new [5,6] efforts to develop a global engineering education [7], there is a clear tendency to divide the field into different disciplines [8], such as electrical and computer engineering [9], to futureproof the careers of young scholars. One of the overlooked, but still demanded engineering domains in the industry today is TEE [10]. TEE blends theoretical concepts of PCB node verification with practical laboratory assignments where scholars shift from passive learning to active engagement and thus stimulate deeper thinking. However, the lack of proper test platforms and equipment in technical schools around the world represents a major challenge to engineering education [11]. The situation in Romania is no exception to this rule since the closure of several technical schools has left young students without access to qualified assistants as well as appropriate test equipment to undertake laboratory investigations.

Recent initiatives to provide affordable and equal access to education have appeared on the United Nations (UN) agenda, with one example being the UN Sustainable Development Goals [12]. Taking these factors into account, this work proposes a hybrid sensorless FPICT for measuring the voltage and current parameters of Integrated Circuits (ICs). Our test platform, which combines the capabilities of a Flying Probe Tester (FPT) with the precision of a Coordinate Measuring Machine (CMM), offers a reliable, simple-to-use, and cost-effective solution to the aforementioned challenges.

The paper is organized as follows. In Section II, we present related automated devices that aid the practical laboratory activities of teachers and young scholars. Section III details the design concept and mechanical components of the proposed improved FPICT prototype. In Section IV we describe the experimental setup and results regarding the reliability and learning rate efficiency of the FPICT device. Finally, Section VI presents the conclusions of this paper.

II. RELATED WORK

Research regarding educational robots and machines in learning institutions has been conducted for many years, targeting not only young scholars but also kindergarten children. The authors in [13] investigate the relationships between user experience and children’s perceptions about educational robots. The study suggested that robot content concentrating on socio-emotional traits should be created for educational purposes and that a robot should be located in the classroom for individual use. Similarly, Kim et al. [14] propose a robot motion programming methodology based on a three-level robot motion hierarchical structure and a gesture variation mechanism. Experiments and evaluation tests were conducted using a graphical robot motion simulator and a real robot named Engkey, showing that the proposed motion programming methodology can assist the real robot in performing a variety of activities for interactive English study in primary school or interactive games for the elderly.

Modern technological breakthroughs have given birth to physical teaching platforms involving the employment of robot arms [15-20], which foster young scholars' learning and strengthen their interaction with the industrial environment.

The authors in [15] present the design and construction of an educational robot arm that can be easily deployed in a laboratory for practical assignments. The robotic arm performance analysis was completed using Matlab, Simulink, and SimMechanics. The experimental results prove that the proposed robotic arm is a valuable tool for students, engineers, technicians, and other professionals in the domain. The work in [16] achieves a similarly andromorphic robotic structure that can be utilized in laboratories by young scholars, anticipating that future students will be able to experiment with the control strategies of each actuator while comparing the robotic arm's movements to their own.

Robotics is a very important field of technology and industry, but due to factors such as the high cost of industrial equipment, workrooms, and specialized trainers, to name only a few, industrial robotics education has remained relatively limited and expensive. The authors in [17] show that some of these disadvantages can be avoided by employing a more compact educational robot arm and remote control via an interactive e-learning environment. Similarly, the authors in [18] cover the technical solutions that were implemented to provide students with the opportunity to learn the fundamentals of industrial robot programming through an interactive environment. Their proposed robot arm is not as accurate as manufactured robots but provides comparable capabilities in a more advantageous design.

Following the COVID-19 pandemic, engineering education turned to be toughed more online rather than in person. This transition, however, has created a void in laboratory instruction delivery. The authors in [19] proposed a laboratory platform with a 6-DoF remote access robot arm as a possible solution to the problem, comprising of an ESP32 camera, servo motors and drivers, eliminating the necessity for direct physical interaction with the end user. This research is an important step in the development of remote access laboratories, particularly in fields such as automation and engineering, where hands-on expertise is generally necessary.

Educational systems are constantly on the lookout for new educational technologies that will boost their students' knowledge and assist them in acquiring the necessary skills for the new industrial era. According to the research in [20], when used effectively, technology improves student performance by stimulating interactions between instructors and students and encouraging cooperative learning, teamwork, problem-solving, and communication skills. Their work shows that spatial thinking is a vital skill for a successful learning process and that students who lack spatial thinking will struggle to pass science, technology, engineering, and mathematics (STEM) courses. Consequently, the work describes the design and implementation of a novel educational kit which is able to aid the development of spatial thinking, specifically applied to two-dimensional Cartesian Coordinate Systems (2D-CACSET), which was created with the Educational Mechatronics. As shown by their experimental results, students gained information and abilities which can be used in the future while working with more sophisticated prototypes as well.

In our paper, we distinguish ourselves from the above-mentioned works by designing, constructing, and deploying an improved FPICT for educational purposes. This CNC-like machine is a miniature model of an industrial Flying Prober (FP) which we deployed for practical assignments in a high school laboratory. As shown by our experimental results, we succeeded in enhancing the scholars' spatial thinking abilities regarding the CMM, measuring instruments (e.g., digital caliper for distance measurement) as well as modifying and analyzing the voltage and current parameters of PCBs.

III. IMPROVED FLYING-PROBE INSPIRED IN-CIRCUIT TESTER FOR PCB EVALUATION

As stated in the Introduction section of the paper, the FPICT is based on the testing principle of an FPT and the test point mapping capacity of a CMM. A test device, dependent on established coordinate points, is an equipment that acts in three dimensions, and hence the prototype proposed in this study revolves around an integrated circuit board that requires verification (Arduino UNO). In particular, the tester begins with the Cartesian coordinates (X, Y, Z) that are initially set to the reference point of the system, as shown in Fig. 1.

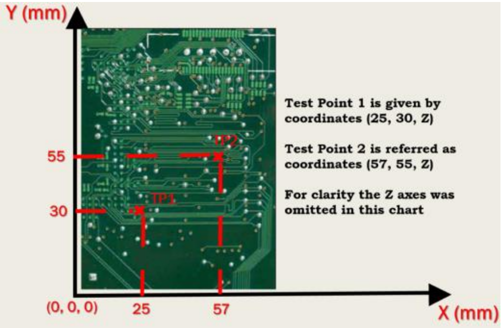

Fig. 1. Test Point Assignment to a Random PCB.

The distance from the reference point (0,0,0) to the selected test nodes heavily influences the probe's path. For example, the coordinate pair (X = 25mm, Y = 30mm) is used to identify the test pin TP1. This test node can be reached in space by moving the probe 25mm ahead and 30mm left until it is positioned above the pin. The following operation has been omitted from the graph in Fig. 1 because it involves lowering the probe by Z mm until it contacts TP1, a dimension that has a constant value in the majority of instances. Similarly, to reach node TP2, the device will follow a path indicated by the coordinate point (X = 57 mm, Y = 55 mm).

It is therefore essential that the probe's path from the origin (0,0,0) to the test nodes be properly mapped. Such a procedure for mapping the pins to be tested is illustrated in Fig. 2. Since the mobile probing device is forced to return to the reference position after each measurement operation, defining an optimal navigation path is difficult. The present work, on the other hand, focuses on enhancing the mechanical equipment to increase the overall operating speed of the designed instrument. For this reason, the construction stages of the improved FPICT prototype (mechanical and electronic

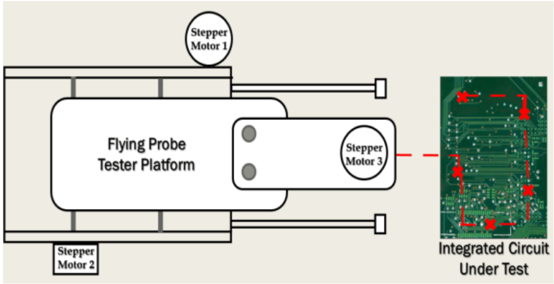

Fig. 2. Test Point Mapping for a Random PCB.

components) capable of evaluating small, medium, and large PCBs will be provided in detail as follows:

A. The Mechanical Structure of the Improved FPICT

The prototype was mounted on a hardwood board with the following dimensions: Length (L) = 609.6 mm; Width (l) = 304.8 mm; Thickness (g) = 15 mm, resulting in a total space for testing of A = L x l = 609.6 x 304.8 = 185,806.08 mm^2. All three mechanical axes were constructed as follows:

- The *X-axis* is situated above the main platform and comprises two metal guide rods (both 270mm long) with a fine-pitch threaded rod in the middle, as shown in Fig. 3 (left). Because the stepper motor rotates the threaded bar in two directions, the secondary platform will move by the corkscrew rule, acting as a nut on the screw. The X-axis reference point is marked by a Mechanical End-stop Limit Switch (MELS) located at the end of the same axis.

- The *Y-axis* is positioned in the lower section of the main platform, with the stepper motor mounted on the hardwood board. The primary platform, which is 340 mm in length, 80 mm in width, and 8 mm in thickness, is supported by two metal guide rods 180 mm in length, as can be seen in Fig. 3 (middle). A threaded bar with a fine pitch the same length as the rods was fixed in the middle of the gap between the two metal rods, allowing the mobile probe to slide faster than the previous prototype.

- The *Z-Axis* is composed of a 110mm long white-toothed grid that interacts with the stepper motor cogwheel attached to the end of the main test platform. The translation limit is set to 80mm, which is sufficient for the probe (nail) to make contact with the PCB terminals, as shown in Fig. 3 (right).

B. The Electrical Components of the FPICT

All three mechanical axes specified above are controlled by an Arduino MEGA2560 microcontroller, three L298N motor drivers, three Stepper motors, and three MELS. As shown in Fig. 3, the three MELS also have connections to the Arduino Mega board to determine the starting point of the three axes.

The Arduino Mega is a microcontroller board having 54 digital input/output pins (14 of which can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, ICSP access, and a reset button. With all of the listed capabilities and a high number of digital pins, it provides an optimum solution for the project at hand. The board can be powered by an external power supply ranging from 6 to 20 volts. If the supply voltage is less than 7V, the 5V connector will provide less voltage, and the board may become volatile. When a voltage of more than 12V is used, the voltage controller may overheat and cause damage to the board. As a result, the proper voltage range is between 7 and 12 volts. The power consumption of the Arduino Mega 2560 board is rated at 0.27 watts after 8 hours of testing at the USB port with a current of 52-54 mA in a state of average use. A total of 15 digital inputs/outputs are utilized for this project, which are distributed as follows: pins 22-25 on the X-axis, pins 26-29 on the Y-axis, pins 30-33 on the Z-axis, and pins 46-48 to receive feedback from MELS.

The L298N Motor Driver Module is a high-power motor driver module that can power both DC and stepper motors. An L298 motor driver IC and a 78M05 5V regulator are used in this module. The L298N Module is capable of controlling up to four DC motors or two DC motors with directional and speed control. Only when the jumper is inserted may the 78M05 voltage regulator be enabled. When the power source is less than or equal to 12V, the voltage regulator powers the internal circuitry, and the 5V pin can be utilized as an output pin to power the microcontroller. When the power source is more than 12V, the jumper should not be used, and a separate 5V should be supplied through the 5V connector to power the internal circuitry. The *ENA* and *ENB* pins regulate the speed of Motor A and Motor B, respectively, whereas the *IN1* & *IN2* and *IN3* & *IN4* pins control the direction of Motor A and Motor B. The main application of L298N Dual H-Bridge motor drivers can be found in robotics, making it the ideal choice for the improved FPICT platform.

A limit switch is an electromechanical element that consists of an actuator that is mechanically coupled to a group of contacts (terminals). When the actuator interacts with a foreign object (for example, a metal object) during PCB testing, the MELS is triggered and begins delivering a signal to the contacts (terminals) to determine whether the connection power should be on or off. Limit switches are thus practical and low-cost devices that enable or disable a certain process when MELS is stimulated by an external cause, employing a lever-type switch. When actuated, the toggle switch is connected to draw the signal to logic LOW. When the switch is triggered, an LED on the microboard will light up. MELS is utilized in our scenario to determine the starting Cartesian coordinates for all three axes of the mobile probe equipment. MELS is typically used in conjunction with the RepRap Arduino Mega Pololu Shield (RAMPS), but it can also be used in combination with other microcontrollers such as the AtMega2560. The highest working voltage is 200 V, and the current can reach up to 2A. MELS defines the reference points from which the mobile probe-equipped device will begin inspecting the DUT.

C. The Working principle of the Improved FPICT

The test procedure for the FPICT is divided into three stages, as shown in Fig. 4. It is important to note that before executing the main program, the FPT machine goes through a series of preliminary steps known as modules. In this manner,

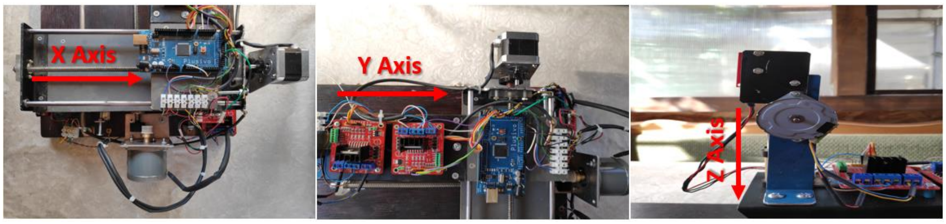

Fig. 3. Improved Flying Probe-Inspired In-Circuit Tester Mechanical Structure comprising the X-Axis (Left), Y-Axis (Middle), and Z-Axis (Right).

the learning diagram will help young scholars become familiar with the working principle of the educational FPICT.

a) First Stage – at this level we can distinguish four preliminary modules. The Axis Calibration module sets the initial coordinates (0,0,0) of the Cartesian system which the device will take as the reference for the 3D workspace. The Distance to Steps Conversion module is performed uniquely for each variable declared for voltage evaluation. The voltage measurement is implemented with the help of the mobile probe that is connected to the *A0* input of the Arduino Mega 2560 microcontroller, and the voltage reading will always have as a reference the ground on the used development board. The test program makes use of three local variables denoted *Dist_X_mm*, *Dist_Y_mm*, and *Dist_Z_mm*, representing the distance of each axis to the origin of the Cartesian system. In the case of current measurement, at least two test points are required to be used in the program. Accordingly, a set of additional variables denoted *Dist_X1_mm*, *Dist_X2_mm*, *Dist_Y1_mm*, *Dist_Y2_mm*, and *Dist_Z_mm* are declared, where the pair (*X1, Y1*) represents the coordinates of the first test point, and (*X2, Y2*) refers to the coordinates of the second-second test point. The Z coordinate remains the same throughout the checks because the contact height of the probe with the test nodes is always constant. Since we are using stepper motors to move the three axes, the test program will translate the distance values into micro-steps, according to equation (1):

$$DistXStep = DistXmm \times StepsPerMM \tag{1}$$

where *DistXStep* is the number of steps obtained by multiplying the Cartesian distance *DistXmm* by the value of the distance in millimeters taken by one step of the motor via *StepsPerMM*. Additionally, because the Arduino Mega microcontroller has an Analog-to-Digital Converter (ADC) integrated into the board, the conversion of other parameters, such as voltage, will be done automatically according to the working principle of the ADC. The analog-to-digital converter on the Arduino board is a 10-bit ADC. The ADC on the 10 is capable of identifying 1024 (2^{10}) discrete analog levels. Some microcontrollers have 8-bit ADCs (2^8 = 256 discrete levels), and others have 16-bit ADCs (2^{16} = 65.536 discrete levels). Thus, the converter generates a radiometric value because the ADC considers the 5V voltage to be the maximum level, 1023, and any other voltage lower than 5V will be a ratio between 5V and 1023 discrete levels. The result of the ADC in our case will be retained in a variable that appears in the mathematical relation (2):

$$CountExpectedVoltage = \frac{1023 \times ExpectedVoltage}{5} \tag{2}$$

where *CountExpectedVoltage* will count the measurements with the expected results from the tests performed.

The Variables Initialization module covers two types of variables used: global and local. Global variables targeting the Stepper motor speed, steps per revolution, and precision, can be called anywhere throughout the code and allow flexible modification by the user. The local variables *Dist_X1_mm*, *Dist_Y1_mm*, *Dist_X2_mm*, *Dist_Y2_mm*, *Dist_Z_mm* are the distances from the reference point to the two test locations connected with the current measurement, correspondingly *Dist_X1_step*, *Dist_Y1_step*, *Dist_X2_step*, *Dist_Y2_step*. *VolExpectedL* and *VolExpectedH* are float variables used to set a sensitive threshold for voltage measurements, while *CountExpectedL* and *CountExpectedH* track the number of parameters that are out of range for each test. Furthermore, *curExpectedL* and *curExpectedH* reflect the minimum and maximum thresholds for the current measurement alone. The Coordinates and Parameter Values module allows the young scholars to insert user-defined values for the X, Y, and Z axes, respectively the minimum and maximum threshold values for the voltage parameters.

b) Second stage - comprises the steps required for the FPICT to visit each test node following the pin configuration shown in the upper portion of Fig. 4. To simplify the learning process, only five test points on the Arduino Uno board were chosen to verify the power supply of the Atmega328 Microcontroller Unit (MCU). Pins 7 and 8 of the Atmega328 MCU are dedicated to providing voltage to the analog GPIO terminals, while pins 20 and 21 are assigned to supplying voltage to the Arduino Uno's digital pins. Pin 1 (Reset +5V), Pin 2 (RXD +5V), Pin 7 (Analog Power Supply +5V), Pin 20 (AVCC +5V), and Pin 21 (GND) will be tested for experimental purposes. As a result, the test application will wait for the user to enter the "START" string into the Arduino IDE interface's Serial Monitor. The device will begin the routine after recognizing the string by moving the robotic arm from the reference position to the first test point (TP1) defined by the Reset pin. The Serial Monitor will display "Success" or "Fail" depending on the voltage value of the verified pin, alerting the test engineer where the damage is located. When the measurement is completed, the robotic arm returns to its original position and the testing continues with the next test point (TP2), which is placed 1 mm away from the first node. Similarly, if the voltage value is within the

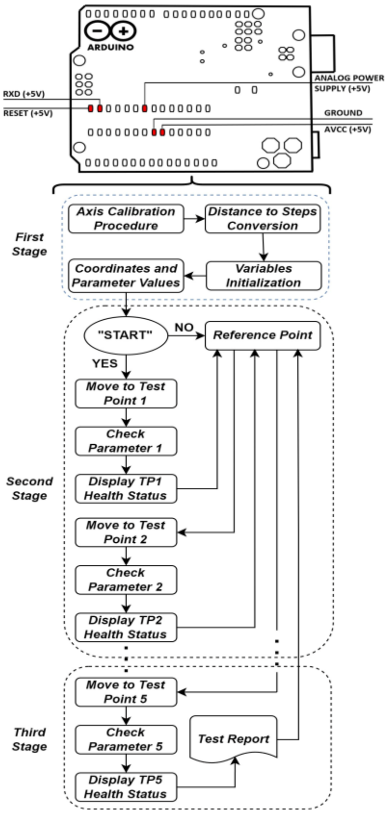

Fig. 4. FPICT Learning Diagram for Evaluating the Arduino UNO Development Board.

operational range, the FPICT will retrieve a message from the Serial Monitor to display its status, and then return to its reference point.

c) Third stage - refers to the stage at which all test nodes have been comprehensively verified by the FPICT and a test report is shown on the screen, indicating the board's final status. Based on the results, scholars can determine whether the Arduino Uno functions correctly or needs to be removed from the fixture for future manual study.

IV. EXPERIMENTAL SETUP AND RESULTS

In academia, FPTs have become an important research target for automating the optical inspection procedure [21], minimizing cost path [22], optimizing the test plan [23], and reducing test cycles [24]. Similarly, in our previous works, we developed an affordable FPICT [25] that was later deployed in a hybrid setup [26] to test the interconnects of several DUTs. The ICT fault coverage was then employed to develop an improved metrics system, which was proposed in [27]. Therefore, because FPs play a very important role in industry in academia, the need for these testing devices to be studied at a lower level, involving the basic understanding of mechanical movements, distance measurement between various PCB pins, and test scheduling is of crucial importance in the emerging TEE.

A. FPICT Speed, Accuracy, and Power Consumption

In this subsection, an investigation will be performed to optimize the prototype by enhancing the mechanical components and modifying the code parameters to reach a faster running speed and a shorter test duration. The initial prototype [25] was replaced with the second iteration of the FPICT, and the measurements were repeated for the identical test scenarios.

According to the statistics from Table I, there is a 20% reduction in test time for a single chosen verification node, with an average probe navigation time of 8.28 seconds.

Table I. Improved FPICT Variant Performance Evaluation

Test Type	**Improved FPICT Prototype Performance Test**				
	No. of Tests	***Precision Testing (%)***	***Average time per test cycle [s]***	***System Power Draw [W]***	
				Idle	***Active***
Single Point Testing	500	100	8.28	0.365	14.74
Multiple Point Testing	500	98.12	50.16		14.60
Measurement Testing	1000	99.06	1.50		14.67

Pogo pin positioning accuracy was constant at 100% across all test scenarios. In terms of the test scenario for inspecting various spots on the PCB, the same number of tests were chosen, and an accuracy of 98.12% was reached for 500 rounds, while the probe navigation time was reduced to less than one minute. The power consumption of the device was rated at an average value of 14.67W during the test scenarios. Globally, the accuracy of properly performed measurements increased to nearly 100%, demonstrating that improvements to the mechanical part as well as code optimization increased the device's efficiency, bringing it to the next stage where it will have to be used in the context of practical laboratory work.

B. FPICT Deployment and Practical Laboratory Activity

The motivation behind the FPICT deployment is the lack of educational testing equipment in the endowments of high schools with a technical profile. Based on a software implementation that eliminates the need to use expensive optical sensors, the following objectives are targeted:

- applying the concept of ICT through practical laboratory work
- measuring the distances from the reference point to the test nodes that make up the set of coordinates for the mobile axes X, Y, and Z
- familiarizing the students with the specialized catalog (reading and interpreting the ranges of voltages and currents specific to the test board)
- understanding the industrial process through a prototype (miniaturized model) that facilitates learning in an interactive way, accessible to students.

Based on the aforementioned concerns, an affordable mobile probe device was designed, developed, and tested in this work. The tool's purpose is to assist students in understanding the method of checking the contact pins on the surface of a development board (Arduino UNO) by handling the device in three-dimensional space so that at the end of the check routine a report with functional and defective pins is generated.

The target group for the test platform research consisted of 16 high school students (five girls and eleven boys) from "Caius Iacob" Technological High School of Electronics and Automation, located in Arad, Romania. The target group was divided into three subgroups according to the training level of the scholars, namely beginner (represented by the 10th-grade students), intermediate (designated by the 11th-grade students), and advanced (formed by the 12th-grade students). The practical laboratory was expected to have a total duration of 120 minutes, from which:

- the first 10 minutes were dedicated to a brief introduction to the ICT domain
- the next 40 minutes were allocated for an initial test to evaluate the general knowledge of the students regarding electronics, digital circuits, and cartesian coordinates
- the following 30 minutes were scheduled for a workshop session in which students could come in small groups around the FPICT to observe its functionality during real-time testing and modify the coordinates of the test points
- the last 40 minutes were reserved for the final test paper which targeted subjects from the ICT domain, fault detection, ADC conversion, and cartesian coordinates.

The initial test was organized in a high school classroom with additional laboratory equipment, as shown in Fig. 5 (a), encompassing nine questions regarding basic analog and digital electronics knowledge. According to the score results which are summarized in Table II, only 2 candidates, representing 12.5% of the total participants obtained a satisfactory score ranging from 40 - 60 points. More than 80% of the scholars achieved a good, very good, and excellent

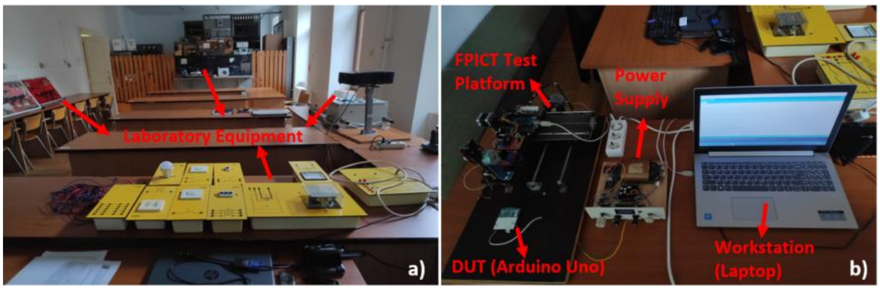

Fig. 5. “Caius Iacob” Technological High School of Electronics and Automation Laboratory (a) where the FPICT Equipment (b) was deployed.

Table II. Score Distribution for the Initial and Final Test

Test Type	**Score Distribution for Student Performance Evaluation**							
	40 - 60 Points		***61 - 80 Points***		***81 - 95 Points***		***96 - 100 Points***	
	(#)	***(%)***	***(#)***	***(%)***	***(#)***	***(%)***	***(#)***	***(%)***
Initial Test	2	12.5	6	37.5	7	43.75	1	6.25
Final Test	3	18.75	6	37.5	6	37.5	1	6.25

score. More precisely, 6 students, representing 37.5% of the candidates, obtained a good score (61 - 80 points), 7 students, representing 43.75% of the scholars obtained a very good score (81 – 95 points), and one student, representing 6.25% of the total candidates, scored an excellent grade (96 – 100 points).

Following the preliminary test, the students were divided into small groups for the actual laboratory work organized around the FPICT equipment, as can be seen in Fig. 5 (b). We highlighted the FPICT's benefits and drawbacks during the 30-minute session, focusing on the learning diagram depicted in Fig. 4. Then, by adopting the stages of the diagram, we performed a series of test cycles to analyze each of the selected Arduino Uno pins. Based on the test scenarios, students showed increased interest and improved their spatial perception. Following the practical presentation, students could change the device's data inputs to see how the cartesian coordinates affect the location of the robotic arm.

Finally, the second test consisted of a nine-question quiz covering both theoretical and practical aspects of ICT. The questions addressed topics from error definition and defect detection to the mechanical and electrical structure, as well as its testing capabilities. Based on the outcome of this quiz, we were able to assess the student’s theoretical and practical skills. Thus, according to the final test results, depicted in the second row of Table II, only 3 candidates scored lower than 60 points, representing 18.75% of the total amount of scholars. However, similarly to the previous test, more than 80% of the students scored sufficiently to reach the good, very good, and excellent categories. More exactly 6 persons, representing 37.5% of the students, obtained a good score (61 – 80 points), another group of 6 scholars (37.5% of the total students) achieved a very good score (81 – 95 points), and one scholar (6.25% of the candidates) obtained 100 points.

V. CONCLUSIONS

High school students have limited or no access to testing devices such as FPTs due to limited or non-existent affordable testing equipment, with existent industrial FPTs available for sale being very expensive, in the order of thousands of dollars. Therefore, this paper proposes an improved, sensorless, and innovative FPICT model for practical laboratory activities regarding TEE. We demonstrate that the probe positioning of the improved FPICT prototype is more accurate compared to our initial proposed FPICT [25], achieving 100% for a single test point, 98.12% for multiple test nodes, and 99.06% for all measurements made. In terms of power consumption, the improved FPICT prototype has a global power consumption of 14.67W. The improved FPICT proves to also be able to lower the test time for a single test point location by approximately 20%, bringing the overall navigation time of the test probe for all test points found on the considered PCB under just one minute.

In our experiments, we evaluated our improved FPICT equipment and successfully proved that it can be used as an effective educational instrument, able to improve the spatial thinking of high school students regarding TEE. More exactly, via a 120-minute workshop that we organized at the “Caius Iacob” Technological High School of Electronics and Automation in Arad, Romania, we evaluated a total amount of 16 scholars which were selected as the target group for the practical laboratory activities. Regarding the initial test, 12.5% of the candidates obtained satisfactory grades, while 87.5% presented good, very good, and excellent theoretical knowledge about basic electronics notions. Concerning the final test, according to our internal correction scale, 18.75% of the participants obtained satisfactory grades, and 81.25% obtained good, very good, and excellent scores.

It is important to mention that during the practical laboratory assignment, the young scholars were encouraged to interact with the FPICT equipment in real-time testing scenarios. By following the working principle of the improved FPICT, based on the simplified learning diagram seen earlier in Fig. 4, the students improved their spatial perception and acquired new knowledge in TEE. Despite its effectiveness in terms of reliability and educational potential, compared to FPTs that use sensors, our improved FPICT has a few disadvantages such as increased testing time due to the robotic arm retracting after each measurement to the reference point, and that the precision of the device is also heavily influenced by the quality of materials which are used in the construction phase. Another drawback to the sensor-based variants, is that our improved FPICT can only test voltage and current values, whereas other models found in the industry can also measure capacitance, resistance, frequency, and other parameters. However, our improved FPICT proposed in this paper has a cost of around 30 dollars compared to thousands of dollars, can be deployed and easily used by students of any age due to its small size and portability, and demonstrated high acceptance in our experiments with high school students in a real high school laboratory.

As future work, we plan to make our improved FPICT device available through an online TEE-oriented GUI where students can easily use it remotely, having access to all testing facilities, both hardware and software, without the need of being present in a laboratory room when learning test engineering.

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