Human-Robot Collaboration (HRC) with Vision Inspection for PCB Assembly

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Keywords: Cobot, PCB Assembly, Work Cell.

Abstract: Flexibility and speed in the development of new industrial machines are essential factors for the success of capital goods industries. When assembling a printed circuit board (PCB), since all the components are surface-mounted devices (SMD), the whole process is automatic. However, in many PCBs, it is necessary to place components that are not SMDs, called pin through-hole components (PTH), having to be inserted manually, which leads to delays in the production line. This work proposes and validates a prototype work cell based on a collaborative robot and vision systems whose objective is to insert these components in a completely autonomous or semi-autonomous way. Different tests were made to validate this work cell, showing the correct implementation and the possibility of replacing the human worker on this PCB assembly task.

1 INTRODUCTION

In today's industry, any manual operation in repetitive production lines that causes delays in the production process needs to be semi-automated or fully automated so that the factory remains competitive in an increasingly aggressive and fast market. Printed circuit boards (PCBs) are a fine example of such necessity, as they are in virtually all electronic components of everyday life. Over the years, assembling electronic components on PCBs has undergone several changes, many of which aim to make this process increasingly automated, efficient, fast, and economically efficient (Altinkemer, Kazaz, Köksalan, & Moskowitz, 2000; Andrzejewski, Cooper, Griffiths, & Giannetti, 2018; Bogner, Pferschy, Unterberger, & Zeiner, 2018; Crama, Flippo, Van De Klundert, & Spieksma, 1997). This is how Surface Mount Technology (SMT) arose, with surface mount devices (Surface Mount Devices) being mounted directly on the surface of the printed circuit board, generally in an automatic way using an SMT machine. Typically, these components are smaller in size, have better electrical performance, must withstand higher soldering temperatures, and must be selected, positioned, and soldered more carefully to achieve an acceptable manufacturing yield (Iftikhar et al., 2020).

Despite the advances seen with SMDs, there are other components (Figure 1) that still need to be manually assembled on PCBs, such as diodes, capacitors, and connectors named Pin Through Hole (PTH) components (Wendy Jane Preston, 2018). This limitation considerably decreases the production efficiency of PCBs assembled with this type of

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Queirós, M., Pereira, J., C. da Costa, N., Marcelino, S., Meireles, J., Fonseca, J., Moreira, A. and Borges, J.
Human-Robot Collaboration (HRC) with Vision Inspection for PCB Assembly.
DOI: 10.5220/0011526200003329
In *Proceedings of the 3rd International Conference on Innovative Intelligent Industrial Production and Logistics (IN4PL 2022)*, pages 56-65
ISBN: 978-989-758-612-5; ISSN: 2184-9285

components when compared to those that only have SMD components.

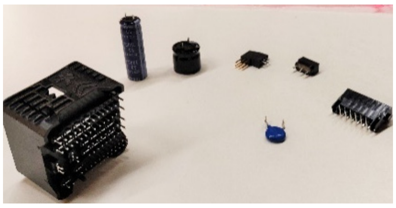

Figure 1: Example of non-SMD components.

Aiming to mitigate the limitation mentioned above and take advantage of the rise of collaborative robots (cobots) (Poór, Broum, & Basl, 2019; Vojić, 2020), this work proposes a novel industrial work cell for the automatic insertion of non-SMD components into PCBs. The proposed cell integrates three main systems from the literature: (1) a cobot to enable either collaborative or autonomous work (Robotics, 2018); (2) a vision system for component validation (David A. Forsyth, 2002; Kurka & Salazar, 2019); and (3) an external device for controlling and monitoring the work cell (Langmann & Rojas-Peña, 2016).

Througout this paper, are going to be presented the fundamental requirements of this work cell, the layout and the main workflow of this task. It is also explained the key aspects of each subsystem methodology, and to validate this work cell, three tests were made and demonstrated. Finally the results and main ideas drawn throughout this work are discussed and concluded.

2 REQUIREMENTS OF THE WORK CELL

Taking into consideration the goal of reducing or eliminating the need for manually inserting different electronic components into PCBs but maintaining quality and efficiency during the insertion process, a set of requirements were defined, of which the most relevant are the following:

- The cell must have an automatic transport system for the PCB boards;
- It must have the ability to identify the different PCBs;
- Adapt the program and the gripper according to the PCB and components to be assembled;
- It must perform accurate and secure gripping and insertion for the different components;
- The system needs to validate each component prior to insertion, using, for example, vision software to read the number of pins and make sure it is in good condition;
- Needs to assure that the PCB is correctly and fully assembled within 30 seconds;
- It also requires collecting information relevant to the operation of the work cell and making it available in a database for future analysis and study.

2.1 Cobot Subsystem

Going into more detail about the robot subsystem and taking into consideration aspects such as the components under study and the PCBs in question, the requirements of the robot are: speed and flexibility, as well as the ability to operate in conjunction with a human being; at least 700 mm range; ate least 6 degrees of freedom (DOF); accuracy and repeatability of less than 0.1 mm; multiple I/O interfaces; and support for various communication protocols.

2.2 Vision System

To validate the quality of each component, one of the most frequently used approaches in the industry is the use of a vision system. In this case, for the proper functioning of the work cell, a minimum sensor resolution of 2M pixels is required to cover the entire insertion area of the component (500x500 mm2) and still allow accurate hole inspection and pin integrity verification. In addition, this system must permit the sharing of data with other subsystems.

The system must also be able to read the barcodes in the PCBs and inspect their correct position to reference the robot with respect to it doing the correct insertion of all components. For these tasks, the camera used may have a lower resolution.

2.3 Programmable Logic Control (PLC) System

Monitoring and recording the activity of an automated process is paramount, and thus this subsystem will be responsible for managing the entire work cell (command, control, and monitoring). For this to be possible, the external device must comply with the following requirements: ethernet, RS232, and EtherCAT communication facilities; digital inputs and outputs; database iteration facilities, have OPC-UA; and be modular. As main characteristics, the same PLC must have database interaction capabilities and the capacity to make process-relevant variables available through the OPC-UA protocol.

3 LAYOUT AND WORKFLOW

To meet the requirements mentioned above, one can propose the use of: (1) the cobot TM5-700, a 6 DOF collaborative robot capable of using different grippers and that integrates its own vision system; (2) the FH1050 vision system by Omron, which has various image acquisition and processing functionalities; and (3) the NX102-9020 Omron, a PLC acting as an external device capable of monitoring and controlling all tasks and functionalities of the work cell. These proposed systems were used and are connected, using the TCP/IP protocol for data exchange. Figure 2 illustrates how the subsystems interact throughout the task. In short, the PLC receives a signal from the assembly line to start the flow, and, after that, different signals are exchanged between the cobot, the PLC, and the vision system to proceed with the task. All the essential information to be seen by the human worker is visible in an interface and then sent to a database.

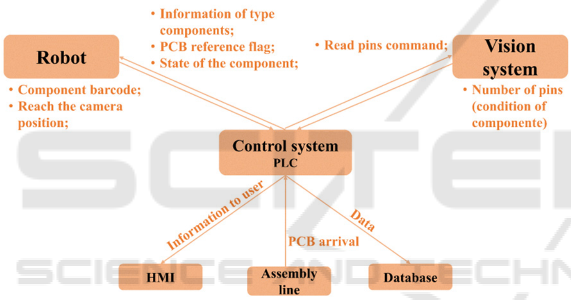

Figure 2: Data exchanged between the three subsystems.

The work cell further includes one box for the damaged components, the PCB allocation zone, and other zones for the boxes of the different types of components. Figure 3 shows a sketch of the work cell, illustrating all the components mentioned above distribution.

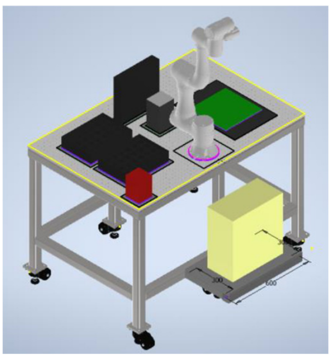

Figure 3: Sketch of the work cell.

With this distribution, the cobot can reach every position needed, independently of the velocity chosen for the task, without too much torque effort.

In a simplified way, the general task flow of this work cell is shown in Figure 4.

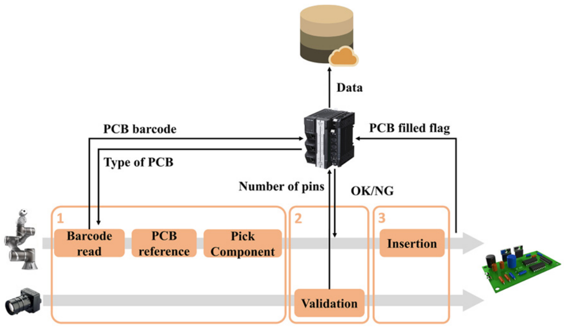

Figure 4: Flow of the work cell.

In short, the cobot will start by reading the barcode on the PCB to know what components must be inserted and do the referencing task to know where the PCB is. After that, it is time for the external vision system to read the number of pins each component has to validate its quality. Depending on the information received, the cobot will discard the component or place it in the proper PCB position upon the validation task. After placing the component, if the PCB is not yet fully assembled, the cobot will repeat the operation for another component. When finished, it will wait for the arrival of a new PCB.

4 METHODOLOGY

To execute the workflow explained above, one should consider each subsystem individually and how to integrate them to focus on precision and speed, aiming to respect the following key goal: replace the worker in the assembly of PCBs with this type of components, trying to speed up the process and reduce costs without ever losing quality.

To understand the entire process of this work cell, each subsystem will be explained in a more detailed way.

4.1 Cobot Subsystem

The cobot will have two major tasks: first, it is the subsystem responsible for the movement in the main task, including picking up a component, taking it to the vision subsystem, and, finally, placing it in the right location on the PCB. The other part is regarding the internal vision system that this cobot has. Here, the cobot will perform two analyses: read the PCB's barcode to know which component to insert and reference itself with respect to the assembly board before inserting the first component (Figure 5). Both tasks will be solved using the TMFlow software, whereas, for the vision tasks, the TMvision software is employed.

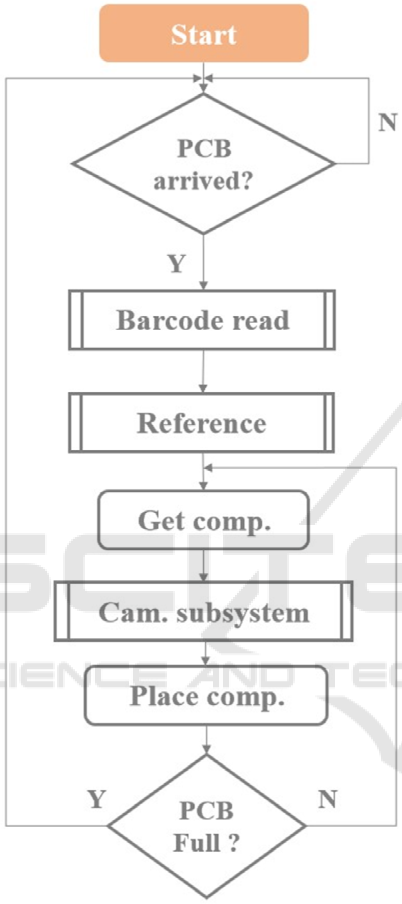

Figure 5: Workflow of the cobot subsystem.

4.1.1 Motion

Regarding this part of the task, the robot will have to move around the work cell to reach the desired positions, with the highest possible precision and speed, without compromising the safety of the environment and operator.

First, it will start in its home position, and as soon as the PCB sensor is activated, the robot moves to the zone where it will do the barcode reading and the referencing task. Upon gathering the information needed, the cobot picks the specific PCB component and moves it to the zone where the external camera will check the integrity of the pins. After validating the integrity of the component, the robot proceeds to the insertion of the same.

4.1.2 Cobot Vision System

To identify the PCB that just arrived and place the components in the correct position, even if the PCB comes tilted or just crooked, the cobot's internal vision system has two types of functionalities (Figure 6) (Omron, 2020).

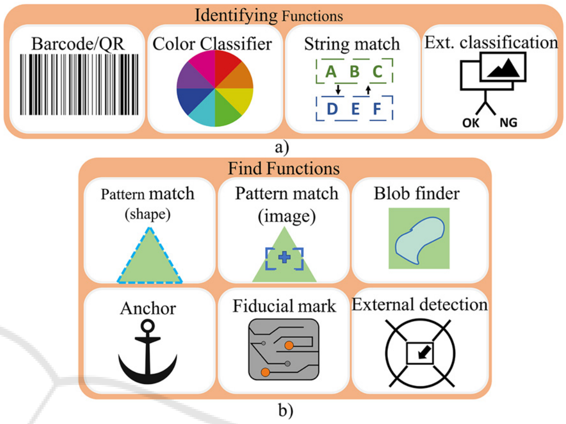

Figure 6: Functionalities available in the cobot's internal vision system: a) identify functions; b) find functions.

Every PCB comes with an associated barcode to know precisely which type (and amount) of component that PCB takes. To this end, the Barcode/QR code identify function is employed. Here, it is necessary to specify the region where the barcode can appear, and once the camera reads a barcode, it returns the specific number of that PCB. Knowing the group to which that particular number belongs, it is possible to tell which components must be inserted (Figure 7).

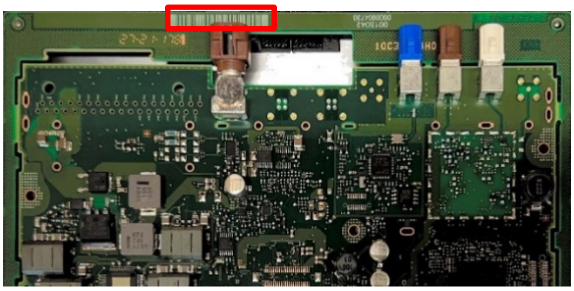

Figure 7: Example of a barcode in a PCB.

For PCB referencing, the Fiducial mark find function is employed. Fiducial marks are small targets in an assembly board placed on the top copper layer (and bottom if it is 2-layers) and allow the vision system to recognize where the PCB is (Figure 8).

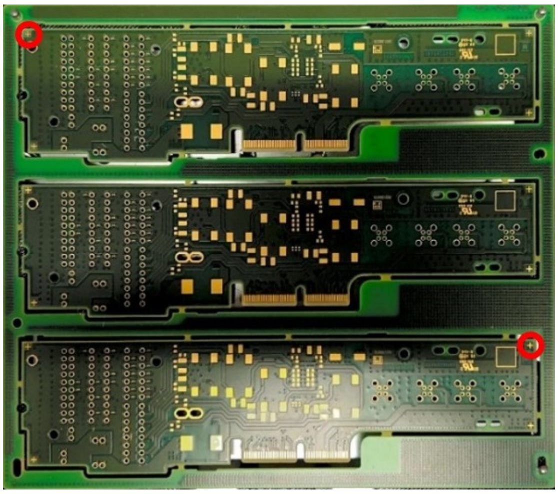

Figure 8: Examples of fiducial marks in a PCB.

The fiducial marks, the target study area, and the similarity threshold need to be selected to use this function properly. Once the cobot reaches the position to do the referencing, it will find the fiducial marks and create a new coordinate frame, where the middle point between the two fiducial marks is the origin. From this point on, regardless of the position of the PCB, the cobot will always be able to make the same movement to the insertion positions, ensuring the correct filling of the board.

4.2 FH Vision Subsystem

Here, the objective is to ensure that the component that the cobot will insert is in good condition to be possible to insert into the PCB without wasting it. Usually, this is solved by human inspection, but the goal is to replace it with a vision system to make the work cell fully automatic and faster.

The FH-1050 vision system is used, taking advantage of the FZ-PanDA software (Omron). Figure 9 summarizes the tasks peformed by the vision system.

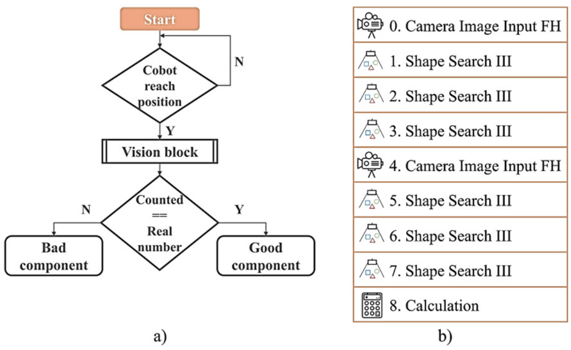

Figure 9: a) Workflow; b) vision block.

In brief, upon waiting for the cobot with the component to reach the point where the camera is pointing, the system will make one single acquisition to count the number of pins in a certain area to check if they are damaged. The idea is to divide the component into small sections, each with a specific number of pins or groups/lines of pins (Figure 10).

Red – 2 groups

Yellow – 2 lines

Green – 2 lines

Blue – 20 pins

Purple – 14 pins

Orange – 4 pins

TOTAL: 44

Figure 10: Component divided into sections and number of pins of each section.

This procedure is done using the "Shape Search III" block, where we must select the region of interest (ROI; big red box) and the subject we want to look for in that exact area (small red box, for example). Through an object detection algorithm, this function block registers a model of an image pattern based on its contour information, detects parts of inputted images that most closely match the model, and adds each similar object to the total count. An experimental study was performed to select the suitable threshold value for the degree of similarity between the template and the new image. Afterwards, the "Calculation" block is employed to find the total number of pins that were identified in each "Shape Search III" block. If the number equals those expected for the component in question (44 in the example in figure 10), the component is in good condition, and therefore the cobot will proceed with its insertion. If not, the cobot will discard this component, placing it in a specific box for damaged components.

Of note, the other two blocks present in figure 10, the "Camera Image Input FH", are used to calibrate the camera and enhance the image between analyses.

4.3 PLC Subsystem

This subsystem aims to establish a connection between the other two subsystems, being responsible for the control and monitoring of the work cell and registering the relevant data during the execution of the task, to be later stored in a database. The kind of data to keep track of includes, for example, the number of damaged components, the number of PCBs filled, the time it takes to fill each board type, and so on. Figure 4 summarizes the information exchanged between subsystems, and as shown, the whole process of this task is divided into three main parts.

First, the cobot waits for the PLC to tell it that a new PCB has arrived. Then, as mentioned before, the cobot will use its internal vision system to do the referencing task and to read the barcode, sending the reading signal to the control system. Here, the PLC will then decide what type of PCB it is and then tells the cobot what type of components to insert.

Upon picking up the component, the cobot will take it to the external vision system area. Here, the PLC will send two commands: (1) first the command measurement, where the system will run the code to count the number of pins to assess the component's condition; and (2) the get data command, where the PLC will receive from the external vision system the number of pins that the software detected. Then, the PLC compares this value with the expected value, and if the result is positive, it informs the cobot that it can proceed with the insertion. If it is not, the PLC informs the cobot to discard this component and pick a new one.

Finally, the cobot will proceed with the insertion of the good component, repeating these steps until the PCB is filled. Meanwhile, the PLC will store relevant data during these steps, such as the number of PCBs filled, the number of damaged components, and the time to fill one PCB, among others.

Table 1 explains how the information will flow between the three subsystems.

Table 1: Information exchange.

PLC takes	PLC sends
PCB sensor - PCB arrived at the assembly area	Signal/Message for cobot to start
PCB barcode from the cobot reading.	Type of PCB for cobot to know which type of components it takes
External vision system reached	Measure command for vision system
------------------	Get data command for vision system
------------------	OK/NG component for cobot
PCB assembled	------------------

5 TESTS

This section demonstrates some practical examples of this work cell, showing the correct implementation of the main systems and the compliance with the requirements. The tests were:

- Test A: How much time does it takes for the cobot to fill a PCB;
- Test B: Reliability of the external vision system;
- Test C: Monitoring and data acquisition.

These tests were employed in the following environment, where it is possible to see: (A) the external vision system for inspection; (B) the cobot with the internal vision system for barcode reading and referencing; (C) the box of components; (D) the PCB (Figure 11).

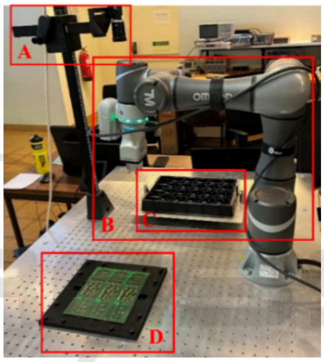

Figure 11: Environment of the work cell.

5.1 How Much Time Does It Take for the Cobot to Fill a PCB

In this test, the idea was to run the full task of this work cell and see how long it takes to fill a PCB, repeating this trial for different velocities (Figure 12).

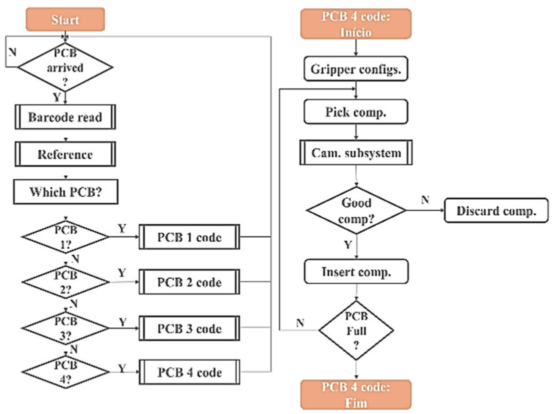

Figure 12: Workflow of the main task for PCB type 4.

The max velocity was set to 1.5 m/s, and the trials were done for 20%, 40%, 60%, 80%, and 100% of that speed. Of note, it was possible to see that the cobot never reaches the max speed because the movements that it makes during this task do not have the range needed to reach that velocity. Table 2 shows the time recorded for each speed setting.

Table 2: Time to fill a PCB with different speeds.

Velocity	Time (m/s)
20%	0:59,260
40%	0:38,672
60%	0:31,313
80%	0:29,241
100%	0:28,039

It is possible to conclude that the cobot needs less than 30 seconds to fill a PCB of type 4 (one that takes three components).

So far, one has shown that the robot can indeed meet the mentioned requirements, both in terms of speed and efficiency, but we have not observed its added value over the human operator. Thus, some additional tests were performed, where an operator tried to insert the components manually without validation of any kind. Despite initially taking around 20 seconds to fill a PCB, this time was reduced to an average of 15 seconds after a few attempts. The same type of test was executed using the cobot, observing a time of 16.280 seconds. Overall, it is possible to conclude that the cobot, besides being able to maintain this pace continuously, does not present significant delays over an operator, as it takes only 12 seconds more to fill the PCB while also inspecting it as well as the components.

5.2 Reliability of the External Vision System

This last test aims to confirm if the external vision system has the capacity and reliability to validate different types of damaged components. For that, different components were structurally compromised in different areas, and the task was run ten times to inspect how many true positives the vision system could detect. Additionally, the same test was run for one good component to validate if the system could validate its integrity either (Figure 13).

During the ten trials of each test, the external vision system showed its reliability when validating the components, verifying that it is in bad condition in all of the examples mentioned above, except for the case of a "good" component. Moreover, it also has the capability of showing in which area the damage is, presenting a result of 10 out of 10 successful validations. From the moment the cobot reaches the inspection zone, and the moment the main system (PLC) receives the answer, the camera only needs around 0,8-1s to process all this.

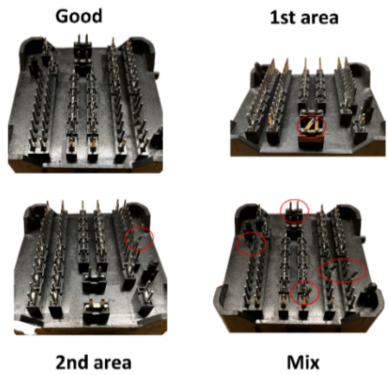

Figure 13: Examples of the components used.

5.3 Monitoring and Data Acquisition

The goal here is to test whether the PLC can retrieve the necessary information during the execution of the task mentioned above to be later able to visualize and document this data. The number of components and the number of PCBs filled with each type are examples of data that needed to be retrieved to be easier for the co-worker to know, for example, when to change the empty box of components, to know the percentage of damaged components or the number of PCBs of type 3 filled in one day.

To check the retrieved information, an interface was built using the CX-Designer software (Figure 14).

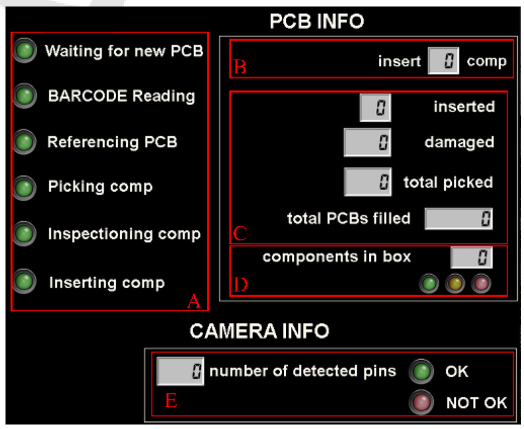

Figure 14: CX-Designer interface.

Figure 14 illustrates the five main parts of the interface:

- Section A notifies about the steps being performed during the routine;
- Section B informs the type of PCB detected during the barcode read function and the number of components it takes;
- Section C presents the number of components inserted, the number of damaged components, and the total number of picked components;
- Section D informs the number of components left in the box, showing a yellow LED when it is almost empty, and a red LED when it is empty;
- Section E lets know the number of pins read, showing the result of the external vision system.

Figure 15 shows a possible sequencing of what can be observed in the interface over several iterations.

Two images were recorded during the filling of the first PCB (Figure 15-1 and Figure 15-2). The first one shows the pick and place task and the validation task of the first component, where it is possible to see the number of pins read by the external vision system validating the component and resulting in its insertion. The second shows the expected last component of that PCB, where it was a damaged component, showing 42 read pins instead of 44, and a total of one damaged component out of a total of three. The last figure (Figure 15-3) illustrates an example of a possible iteration of the interface during a day of work.

6 DISCUSSION

During Test A, we confirmed the accomplishment of the 30 second requirement. We performed some insertion trials to compare this with a human worker, concluding that the worker can be faster by 1.280 seconds on average. However, some major requirements need to be considered, like efficiency, repeatability, and precision. Humans are susceptible to tiredness, and after hours of work, their precision and efficiency will not be the same, leading to delays in production or, in worst cases, damaged PCBs. In opposition, the cobot always performs at his highest level, sustaining these requirements throughout hours of work. These requirements are also possible with industrial robots, but they have some disadvantages, such as: they are usually more expensive, they are used for heavier payloads, and they also require an isolated work area.

Moreover, different camera positions were tested during this test to find the easiest and fastest way to achieve a more efficient work. When the camera is on top, the environment lightning variations do not affect the external vision system precision and fast decision making. There were still two other possibilities: one being the cobot’s camera performing the inspection, however this camera did not present the minimum requirements for this process; and the other was an external camera attached to the cobot, which met the quality and resolution requirements, but increased the cycle time of the entire process since the robot would need to place the component in an intermediate position to take the reading.

Test B confirms the high level of inspection by the external vision system when validating minor displacements and defects of the components’ pins. It thus delivers a sensibility and accuracy that a human eye cannot achieve.

One of the few tasks in this work cell that a human worker needs is replacing an empty component box. In Test C, one concluded that this type of information cannot be presented as a mere label but also needs to be displayed using three LEDs, representing the quantity of components left in the box, giving an explicit luminous warning to the human worker. In addition to this task, to reduce the cycle time of this process, the operator cooperates with the cobot by informing it of the limited barcode search area since each type of PCB has its barcode in different areas.

Test C confirms the high level of inspection by the external vision system when validating minor displacements and defects of the components’ pins. It thus delivers a sensibility and accuracy that a human eye cannot achieve.

As mentioned before, the human worker could replace some functionalities of this work cell, like the

Figure 15: Interface during sequenced iterations.

barcode read and the referencing functions. Here, the worker could be responsible for informing the cobot of what type of components should be inserted. However, the idea is to minimize the human interaction, and through the barcode read function is possible to pass this information in an autonomous way without wasting much time. Also, when using the referencing function, we guarantee the correct placement of each component, as even when using a mechanical interlock, there is no guarantee of the correct PCB orientation, which over time can cause displacements in the order of millimeters.

In addition to the solution proposed throughout the paper, other two approaches were considered. The first one considered the collaboration between human and robot in a way that the robot would perform the pick task and take it to the vision system, and after the component validation, it would be inserted by the human, having the transference of it between the cobot and the operator. On the other hand, in the second hypothesis, the operator would perform the validation task of the component, and after it was validated, it would be transferred between the operator and the cobot, and the cobot would perform the insertion part. Both solutions have disadvantages since they increase the cycle time of the process, with the transition of the component between the operator and the cobot, as well as relying on less accurate and precise systems.

7 CONCLUSION

In this work, was presented a solution to a prototype autonomous work cell capable of assembling PCBs with PTH components. This work cell consisted of three main systems: (1) the cobot; (2) the vision system; and (3) the PLC, exchanging information between them via TCP/IP protocol.

The first one is mainly responsible for the movement in the main task, including picking up the components, taking them to the inspection area, and inserting them into the PCB. The vision subsystem ensures the precise positioning and identification of the PCB and verifies the components' condition. The last subsystem manages both the cobot and external vision system's interactions and is responsible for monitoring the work cell by registering the relevant data generated during the execution of the task and storing it in a database.

Hereto, the three subsystems were demonstrated and explained, always showing the key aspects of the creation of this work cell. The performance of the proposed work cell was demonstrated through three examples, focusing on the most important aspects, namely exchange and acquisition of information, the validation of components, and the gain in precision and speed during PCB assembly over a human operator, all of them showing positive and successful results.

In sum, this work proves the optimization of a human process. It proves the possible replacement of the main human tasks with systems that are capable of maintaining a high level of performance throughout long periods of time.

ACKNOWLEDGEMENTS

This work is co-funded by the European Regional Development Fund (ERDF) through the Operational Competitiveness and Internationalization Programme (COMPETE 2020) of the Portugal 2020 Program [Project No. 45070, "FlexASComp"; Funding Reference: POCI-01-0247-FEDER-045070].

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