Work cell for assembling small components in PCB

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***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.**

***Keywords*— Cobot; PCB assembly; work cell;**

I. 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 [1, 2]. 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 [3].

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 [4]. This limitation considerably decreases the production efficiency of PCBs assembled with this type of components when compared to those that only have SMD components.

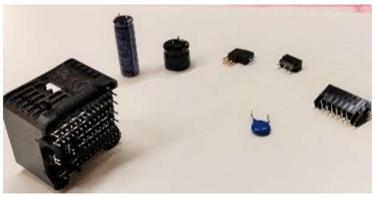

Figure 1 - Example of non-SMD components.

Aiming to mitigate the limitation mentioned above and take advantage of the rise of collaborative robots (cobots) [5, 6], 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 [7]; (2) a vision system for component validation [8, 9]; and (3) an external device for controlling and monitoring the work cell [10].

II. REQUIREMENTS OF THE WORK CELL

Taking into consideration the goal of reducing or eliminating the need for manually inserting different components into PCB, but maintaining quality and efficiency during the insertion process, a set of requirements were defined, of which the most relevant are: (1) the cell must have an automatic transport system for the PCB boards; (2) it must have the ability to identify the different PCBs; (3) adapt the program and gripper according to the PCB and components to be assembled; (4) it must perform accurate and secure gripping and insertion for the different components; (5) the system needs to validate each component prior to insertion, using for example, a vision system; (6) needs to assure that the PCB is correctly and fully assembled within 30 seconds; and for last (7) it also requires collecting information relevant to the operation of the work cell, making it available in a database for future analysis and study.

III. 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, with a range of 700mm and less than 0.1mm of accuracy and repeatability; (2) the FH1050 vision system by Omron, which has various image acquisition and processing functionalities, with a minimum 2M pixels as resolution to cover the entire insertion area; 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, with multiple communication facilities, specially OPC-UA, and must have database interaction capabilities. 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.

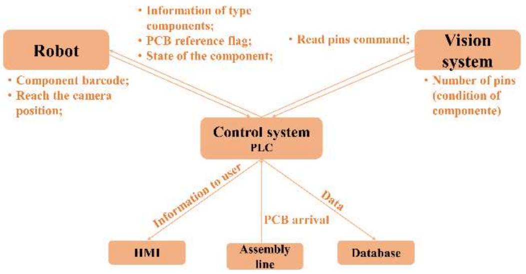

Figure 2 - Data exchanged between the three subsystems.

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.

IV. 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 full process of this work cell, each subsystem will be explained in a more detailed way.

A. 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. Both tasks will be solved using the TMFlow software, whereas, for the vision tasks, the TMvision software is employed.

1) 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 [11]: identifying functions, like barcode reading, color classifier and string match; and find functions, like pattern match, blob finder, fiducial marks, and others.

Every PCB comes with an associated barcode to know precisely which type (and amount) of component that PCB takes. 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 3).

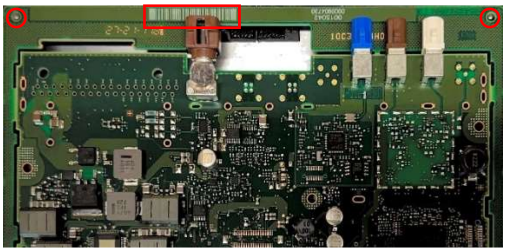

Figure 3 - Example of a barcode and fiducial marks in a PCB.

Once the cobot reaches the position to do the referencing, it will find the fiducial marks (Figure 3) 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.

B. 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 [12]. 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 4).

Red – 2 groups
Yellow – 2 lines
Green – 2 lines
Blue – 20 pins
Purple – 14 pins
Orange – 4 pins
TOTAL: 44

Figure 4 - 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 4), 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.

C. *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 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, during these steps, the PLC will store relevant data, such as the number of PCBs filled, the number of damaged components, and the time to fill one PCB, among others.

V. 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: how much time does it take for the cobot to fill a PCB and the reliability of the external vision system.

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 5).

A. *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.

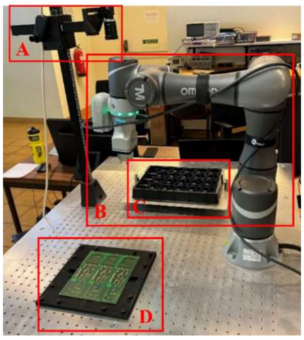

Figure 5 - Environment of the work cell.

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 1 shows the time recorded for each speed setting.

Table 1 - 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).

Comparing to a human worker, which initially takes around 20 seconds to fill a PCB, without inspection, this time was reduced to an average of 15 seconds after a few attempts, making it a bit faster than the cobot. But in this case, the operator is susceptible to tiredness and distractions, making their precision and efficiency decrease over time, unlikely the cobot that is capable of maintaining his pace at his highest level.

B. *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 6).

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 has also the capability of showing in which area the damage is, presenting a result of 10 out of 10 successful validations.

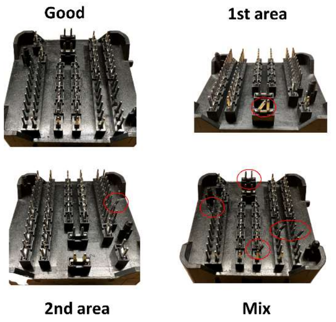

Figure 6 - Examples of the components used.

VI. 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.

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.

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

VII. 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.

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