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MACHINING OF PRINTED CIRCUIT BOARDS USING AN INDUSTRIAL ROBOT IN A SIMULATION ENVIRONMENT

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Abstract:
This paper is devoted to the design, simulation, and optimization of a robotic cell designed to machining printed circuit boards (PCBs) using a stationary milling machine mounted on an industrial robot. The main goal was to create a digital model of the production workplace in the RobotStudio environment, which allows testing robot movements, program logic, and functional arrangement of the entire system prior to physical implementation. The use of offline programming reduces costs and risks, enables rapid tuning of robot paths, and minimizes collision states. An important part of the design was the creation of a custom gripper made by 3D printing. This gripper combines vacuum suction cups with pneumatic clamping, which allows gentle manipulation of PCBs without damaging electronic components. The created cell model includes a conveyor system, a milling machine, a protective Plexiglas cover, and a camera to recognize PCB types. The simulation confirmed the functionality of the entire cycle, the optimized length of which is 56.58 s. The results show the potential of digital design for automated manufacturing cells and open the space for future research in the field of effectors, advanced control, and artificial intelligence in industrial automation.

Key words: industrial robot, robotic cell, gripper, RobotStudio, simulation, milling

INTRODUCTION

The introduction of industrial robots into production processes is one of the key drivers of continuous progress in the manufacturing industry. In recent years, we have seen rapid advances in technologies such as artificial intelligence and new approaches that allow humans to collaborate with robots. This era introduced the so-called collaborative robots that can work hand-in-hand with humans, significantly impacting the programming and control of these robots.

The surge in the implementation of robots shows the industry's growing recognition of the benefits of automation and robotics. The automotive industry remains one of the largest customers of industrial robots, and these devices have become an integral part of its production processes. Complex operations such as spot welding in car body manufacturing require a high degree of automation, with industrial robots playing a key role in this context. With the growing number of robots introduced, the question arises of how to efficiently program and configure these devices while reducing downtime and optimizing deployment. With the growing number of robots introduced, the question arises of how to efficiently program and configure these devices while minimizing downtime and optimizing their deployment. One of the best solutions to this problem is the use of the offline programming method, which provides considerable flexibility and efficiency in the setup and control of industrial robots.

Different design and simulation environments for offline program creation serve not only to present the final design to the customer, but also provide many other advantages that are invaluable for the integrators and engineers involved in the automation project. These tools allow integrators to experiment with different placement options for robots and other equipment in the work environment. This means that they can precisely plan where and how the robots will perform their tasks to achieve maximum efficiency in the production process. They also make it possible to predict possible collisions and conflicts in different configurations, which is vital to ensuring the safety of production operations. In addition, these environments enable the creation of detailed project documentation, which is essential for accurate planning and implementation of automation systems. This allows engineers to maintain a detailed overview of all aspects of the project, including the configuration, programming, and setup of the robots, which lead to better control and optimization of the entire production process.

This paper focuses on the case study of creating a robotic cell designed to machine printed circuit boards using a stationary end mill. In this context, the industrial robot in the cell plays a decisive role as an integration element that handles the boards and performs the necessary operations in the final mill. Our study will address the complex design, programming, and simulation process of this robotic cell, with the aim of exploring and demonstrating the benefits of using the off-line programming method in this specific manufacturing context.

In the field of industrial automation, there is an ongoing need for effective tools for the design and verification of robotic workstations before physical implementation. One of the main problems is the optimization of the trajectories, the design of a reliable gripper, and the verification of the robotic cell without expensive prototyping. The purpose of this paper is to evaluate the contribution of ABB RobotStudio simulation software for the design, simulation, and optimization of a robotic workspace dedicated to printed circuit board (PCB) machining, focusing on collision minimization, manipulation efficiency, and end-effector design.

The scientific contribution of this work lies in the integration and validation of a digital twin approach to designing a robotic workplace for PCB milling. Unlike typical robotic cell implementations, this study proposes a hybrid gripper mechanism that combines vacuum suction and pneumatic clamping, with an additional conceptual redesign toward shape-conforming encapsulation. Furthermore, simulation-based optimization led to a reduction in cycle time, which is a significant improvement. The work also includes an analysis of robot loading. These aspects collectively demonstrate how simulation tools can be used not only for offline programming but also for early-stage design validation and performance optimization. This methodology has potential applications in agile manufacturing environments, where rapid reconfiguration and validation of robotic cells are critical.

RELATED WORK

In the following sections, we will demonstrate that many interesting approaches and solutions have been developed in the field of robotic cells and automated manufacturing processes, serving as both inspiration and reference for our work. These studies address various aspects of robotic cells, including part sequencing, robotic movements, optimization of manufacturing processes, and their applications in various industries. The following papers introduce diverse methods and technologies in the context of robotic cells that address various production tasks and scenarios. The following papers present different approaches and technologies in the context of robotic cells that deal with different manufacturing tasks and applications. These investigations have significantly expanded our understanding of robotic cells and their potential in modern industry.

The article [1] examines the sequencing of parts and the control of robot movements in a robotic cell. In this article, production systems with a flow line, which deal with the production of various parts, are thoroughly analyzed. In this article, production systems with a flow line, which deal with the production of various parts, are analyzed in detail. This research makes a notable contribution to the optimization of production processes in robotic cells, aligning with our focus on the efficient use of robotic solutions in industry.

In our design of the production cycle, we drew inspiration from article [2], in which the authors comprehensively addressed the challenge of cyclic planning in a robotic factory, where a specific type of product is repeatedly produced. In this situation, the robot was responsible for transporting parts between different machines. The main goal of their research was to find the shortest cycle schedule for the robot, as this is a crucial factor in the optimization of production processes. This insight served as a valuable guide in designing an efficient production cycle for our robotic cell.

In the article [3], the author provides a detailed description of a robotic cell designed for additive manufacturing based on fused deposition extrusion. This cell has two robotic manipulators with 6 degrees of freedom, which can manipulate non-planar and planar layers of material. This article focuses specifically on algorithms for decomposing parts into layers with different resolutions and generating collision-free trajectories for these manipulators. Although our focus is on the implementation of a single industrial robot, this article served as an inspiration to create trajectories for the robot.

In the article [4], a robotic system is presented, specialized in automatic injection into batch-suspended cells. This research focuses on the material injection process and emphasizes the importance of efficient robot manipulation in such applications. Subsequently, we applied this insight to the sensitive handling of our board.

Article [5] presents recent advances in robotic cell microinjection technologies. The study explores several key technologies and their strengths and limitations in this specialized industry. This research represents a significant contribution to the development of microinjection technologies in the field of robotics and the processing of fine components, similar to our application.

The study [6] specializes in optimization-based heuristics in the context of the robotic cell problem. This problem arises in automated cells and involves complex material flow with a single transport robot and material flow restriction. The authors aim to develop effective solutions to this issue. This article illustrates that our robotic cell will also be part of a larger production line.

For future inspiration, article [7] outlines a vision in the field of robotics that includes cognitive functions for human-robot collaboration in work environments. This vision envisions systems that can analyze work situations, suggest solutions, and interact with robots in real time.

In document [8], an in-depth analysis of the productivity of different scenarios in robotic cells is performed through a cycle comparison. In the document [8], a thorough investigation of the productivity of different scenarios in robotic cells is carried out by comparing their cycles. This research aims to evaluate the performance and efficiency of robotic cells, comprising multiple machines and a handling robot. This research aims to evaluate the performance and efficiency of robotic cells, which form complex devices that contain several machines and a handling robot. The main goal of this analysis is to provide key information on how various scenarios impact the overall productivity and operation of robotic cells. These findings are highly valuable for optimizing manufacturing processes and designing robotic cells taking into account various factors and scenarios to achieve an optimal level of performance.

The paper [9] proposes an extension to the sheet lamination process using a robotic sheet handling cell. This research focuses on material handling and highlights the use of robotic cells in this area. This insight informs how to effectively handle material in robotic cells, which is highly relevant to our project.

In the text [10], the challenge of scheduling cycle production in an unbuffered double-gripper robotic cell is addressed. The goal is to find the optimal sequence of robot movements to maximize long-term average throughput. The goal is to find the optimal sequence of robot movements to maximize the long-term average throughput of the cell. This research is an important contribution to the optimization of production processes in robotic cells.

Our current study will focus on the specific case of creating a robotic cell to process printed circuit boards using a stationary final mill. Building on the knowledge from previous research, we aim to contribute by emphasizing efficient design, programming, and simulation within this specific manufacturing.

ROBOTIC CELL DESIGN

When preparing for the construction of a robotic cell, in simulation or physical form, the first and most crucial step is selecting its fundamental components. When preparing for the construction of a robotic cell, be it in its simulation or real form, the first and key step is the correct selection of its basic building elements. This step involves the careful validation and evaluation of multiple critical factors. This step involves a thorough verification process and the consideration of several key factors. One of the most important aspects is the selection of the appropriate type of industrial robot and the exact specifications, which must be fully aligned with the specific requirements and demands of the given application. In our particular case, we selected the ABB IRB 120T industrial robot. This decisive choice was driven by multiple carefully evaluated factors. This decisive choice was motivated by several factors that we carefully considered. One of these factors was the constraints related to our available workspace and the specific constraints that we had to respect. In this way, we chose a robot that was the optimal solution for our needs and ensured smooth and efficient operation of our robotic cell.

The ABB IRB 120T robot is exceptional in terms of technical specifications. The ABB IRB 120T robot is exceptional in terms of technical features. It has six axes, which gives it high flexibility in movement, and its dimensions put it in the category of small industrial robots. What makes this robot even more special is its design weight of 25 kilograms, making it the smallest representative in this category. One of the significant benefits of this robot is its built-in electrical and pneumatic wiring in the main body. This feature is highly valuable in practice, as it greatly simplifies the connection of the end effector, such as a machining tool or another device, to the control unit. In addition, it allows for seamless access to the necessary pneumatic resources, thereby ensuring reliable cell operation. In addition, it allows for seamless access to the necessary pneumatic resources, ensuring reliable cell operation. This integrated approach helps reduce the risk of cable collisions with the surrounding environment, which improves the safety at work and the operational efficiency of our workplace. In this way, the ABB IRB 120T robot contributes significantly to the successful operation of our robotic cell.

DESIGN OF A ROBOTIC MANIPULATOR

To properly design a robotic gripper, we must first understand the geometric and physical characteristics of the object (matrix) to be handled by the robot. In order to be able to properly design a robotic gripper, we need to know in advance the geometric and physical properties of the object (matrix) that the robot will handle. In our case, it is a printed circuit board matrix (Fig. 1). The matrix consists of four Arduino UNO platforms. Various electronic components such as the processor, connectors, and buttons are mounted on the board. Since they are electronic elements, the gripper must be designed to avoid contact with the installed electronic elements, as they could be damaged during gripping or handling. Since they are electronic elements, it is necessary to grip the board in such a way that the solid parts of the gripper do not come into contact with the installed electronic elements, which could be damaged during gripping and subsequent handling. The grip design is further complicated by the fact that during handling the board will be processed in an end mill and the clamping area must be minimized to reduce interference with the board surface.

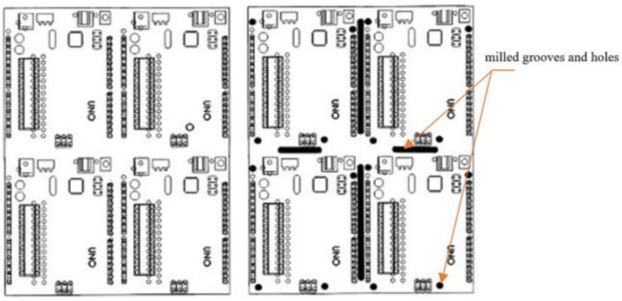

Fig. 1 The board before (left) and after machining (right)

During milling, mounting holes and grooves are created on the board [11]. On the left (Fig. 1) is shown the board before technological processing, and on the right we can see the final processed product. In the picture on the right, the grooves and holes that the robot is milling are marked in black.
The conceptual gripper design for holding the board can be seen in Fig. 2.

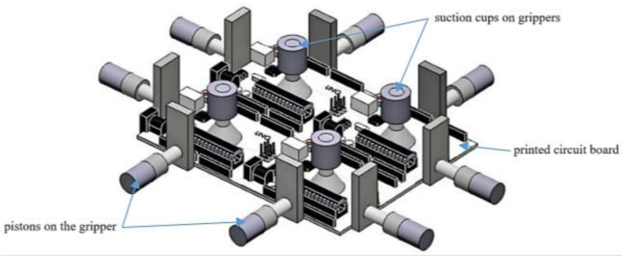

Fig. 2 Holding the board in the gripper

The figure shows the initial contact of the gripper with the board, which is provided by four vacuum suction cups. Under the influence of negative pressure, the board is initially grasped and lifted to the level of the gripper body. After lifting, four pairs of pneumatic pistons extend from the sides (Fig. 2). The method for extending the side pistons consists of the arresting string mechanism, where, when the vacuum supply is interrupted, the pistons will be extended. The extension of the side pistons will ensure that the board is clamped in the gripper.
The final design of the gripper can be seen in Fig. 3.

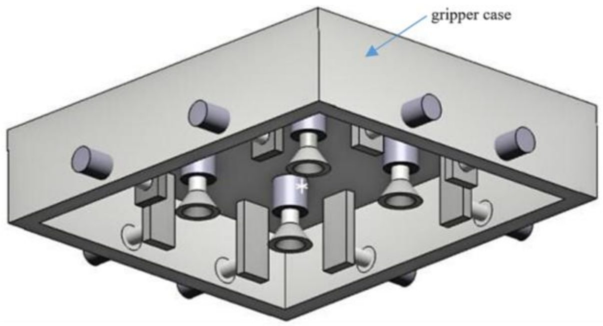

Fig. 3 Graphic representation of the gripper

The validity of the holding principle and method can only be confirmed through proper testing once a functional gripper prototype is built. Whether the principle and method of holding the board is correct can only be proven by performing appropriate tests after making a functional model of the gripper. Testing will also demonstrate the robot's maneuverability when using the gripper. The test will also demonstrate the maneuverability of a robot with the gripper. In the computer model, we can select the appropriate materials to build the functional prototype and also conduct strength tests by applying various forces to the gripper design.

LOADING OF THE PROPOSED ROBOTIC MANIPULATOR

When designing a robotic workplace, it is important to consider the end-effector load on the robot. When designing a robotic workplace, it is important to take into account the end-member loading of the robot. In the case of a gripper, it is also crucial to consider the weight and geometry of the object being handled. In the case of a gripper, it is also necessary to take into account the weight and geometry of the grasped object that the robot will handle. The transported weight is a key factor in selecting the appropriate robotic manipulator. Knowledge of the weight transported is even an essential criterion when choosing the right type of robotic manipulator. Although the center of gravity (CoG) and load diagram were analyzed for the custom-designed gripper, it must be noted that the machined object (PCB) is relatively lightweight. Therefore, in this specific application, the CoG analysis has minimal impact on the robot's load handling capabilities.
When dealing with large dynamic movements and impacts, the load diagram may be insufficient; therefore, it is necessary to calculate the moment of inertia of the load along individual axes (J0X, J0Y, J0Z). To determine these parameters, it is recommended to use a CAD program capable of calculating these parameters. To determine these parameters, it is recommended to use one of the many CAD programs that can determine these parameters. To assess additional parameters of the robotic manipulator's load, the Robot. The ABB load software is a useful tool, providing a percentage-based graph of the robot's load (Fig. 4).

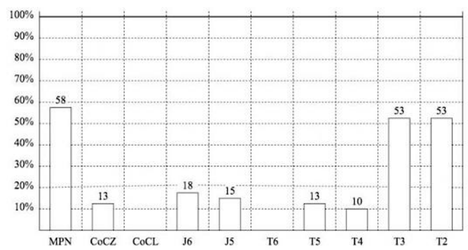

Fig. 4 The percentage of the robotic manipulator's load

Where MPN – maximum permissible mass, CoCZ – center of gravity distance from the wrist along the Z-axis, CoCL – center of gravity distance from the wrist along the L-axis, J6, J5 – moment of inertia relative to axes 6 and 5, T6-T2 – static torque for axes 6 through 2 [12]. The combined weight of the gripper and clamped board accounts for 58% of the robot's maximum load capacity. The highest value of 58 % of the maximum allowed load capacity of the robot is carried by the weight of the gripper together with the weight of the clamped board. Following the calculations in this chapter and the evaluation of the load percentage graph, we can confirm that the proposed end-effector concept is adequate and the IRB 120T industrial robot should not experience overloading, which was selected for cell design.

CREATING THE WORK CELL

To construct the cell housing the industrial robot, we used Bosch Rexroth aluminum structural profiles. To create the cell in which the industrial robot is located, we used Bosch Rexroth structural aluminum profiles. These structural profiles are commonly used in special-purpose machines, safety fencing, conveyors, and other industrial applications. These structural profiles are used as structural elements in single-purpose production machines, protective fencing, conveyors, and other industrial production solutions. The advantage of using this type of structure is the availability of a wide range of profiles and connectors, which leads to high structural integrity. The advantage of using this type of structure is the choice from a wide range of different types of profiles and connecting elements, which leads to good final strength of the structure. The use of this typed system also saves both time and resources during structural design (Fig. 5).

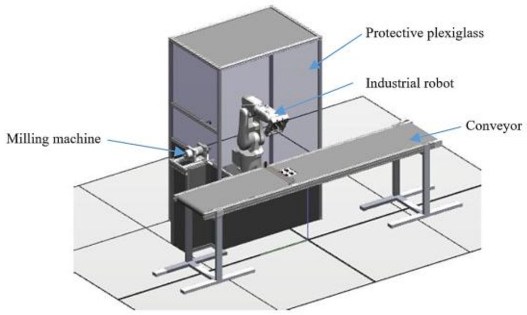

Fig. 5 Created model of robotic cell

Profiles can be integrated into the station layout as any other component. Profiles can be added to the station design in the same way as other components. By placing the profiles, we created the structure and used the CAD object creation tool in RobotStudio for enhancements. By placing the profiles, we created a structure and, to supplement it, we used the tool for creating CAD objects implemented in RobotStudio. The tool allows us to draw basic geometric shapes that can be combined into complex structures. The tool allows us to draw basic geometric objects that we can combine into more complex shapes. The objects created by us, with which the basic construction of profiles is supplemented, were modeled as Plexiglas sheets. The objects created by us, with which the basic construction of profiles is supplemented, are represented by plexiglas sheets. Plexiglas acts as a safety fence and prevents debris from contaminating the workplace.

After creating the structure of the cell, we incorporated a belt conveyor to deliver materials to the station. After creating the structure of the cell, we added a belt conveyor to the model, which serves to transport the material to the station. The robot places the finished product on the conveyor for subsequent processing. The resulting product is also placed on the conveyor by the robot and travels to further production operations. Subsequently, we added an end milling machine to the model, which is positioned on the side of the structure for easy operator access during tool changes. Subsequently, it was necessary to add an end-milling machine to the model, which is located on the sidewall of the structure, taking into account good operator access in the event of a need to change the tool. The last graphic component in the station is an industrial camera, which is used for clamp detection and board type identification.

CREATING THE CONTROL PROGRAM

The workflow of creating a program in RobotStudio consists of the following steps:

- creation of positions and paths,
- position orientation checks,
- range controls,
- program synchronization to the control unit,
- program modifications,
- collision checks,
- starting the program.

Even before the actual programming, it is advisable to define the coordinate system of the work object, which will simplify the configuration of the program in the event of a change in the position of the objects.

Fig. 6 shows target taught by the industrial robot.

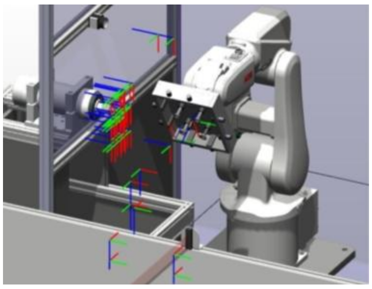

Fig. 6 Displaying taught robot targets

The 3D models of the robotic gripper and the PCB matrix, as shown in Figures 2 and 3, were created using SolidWorks. These models were exported in STEP format and subsequently imported into ABB RobotStudio for simulation and integration into the cell layout. The robot was programmed using the RAPID programming language within RobotStudio, using both manual path teaching and SmartComponent-based logic to simulate external devices such as the conveyor and sensors (Fig. 7).

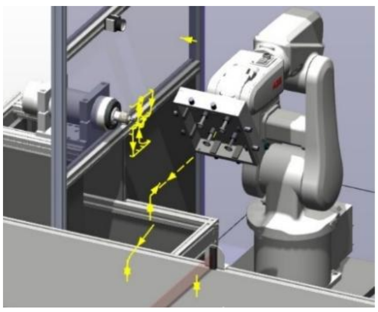

Fig. 7 Display of created robot trajectories

Although the simulation environment allows for collision detection between the robot and other static elements in the modeled workspace, it is important to note that this relies heavily on the accuracy and currency of the model. Any physical changes to the layout, such as repositioning equipment or adding temporary structures, can result in unforeseen collisions if the digital model is not updated accordingly. Moreover, simulation lacks real-time feedback and sensor-based awareness. Therefore, combining simulation-based validation with physical sensors or safety systems remains essential in real-world deployments to ensure collision-free operation.

The creation of smart components – SmartComponent [12, 14] in RobotStudio allows the creation of objects (with or without 3D models) that perform specific functions. Creation of smart components – SmartComponent [12, 14] is used in RobotStudio to create an object (with or without 3D representation) that has certain functionality. Functions can be implemented by code or by combining predefined components. Functionality can be created using code or by grouping basic components. These basic components include sensors, logic gates, timers, motion actions, graphic actions, and many others. Using these components, operations outside the industrial robot can be simulated. Using these components, we can simulate operations outside the industrial robot. If necessary, for example, for the creation of the conveyor, the conveyor cannot be directly controlled through RAPID programming. If necessary, for example, for the creation of the conveyor, we cannot directly control the conveyor operation through the RAPID program. In this language, however, it is possible to define a signal or a change in the state variable in the controller, thereby sending control instructions that simulate dynamic events in the model and the associated graphical visualization of the state change. In this language, however, it is possible to define a change of a signal or a state variable in the control unit, sending control instructions that simulate a dynamic change of the event in the model and the associated graphical representation of the change of state. These components are well-suited for implementing such functionality. It is advantageous to use these components to create the functions mentioned. An example of a smart component created for holding a scanned object (Fig. 8), consists of a LogicGate, LineSensor, and Attacher.

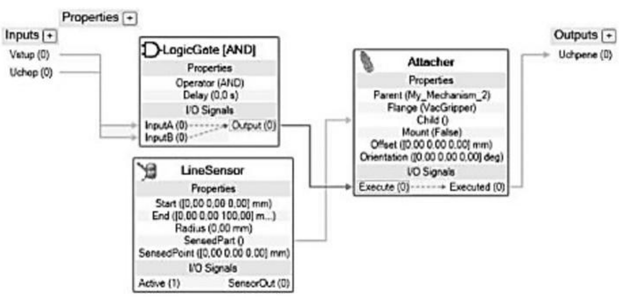

Fig. 8 An example of a created smart component

The smart component receives two external signals: Input and Grab. Two external signals Input and Grab enter the structure of the smart component. When both signals are active, the Attacher function is triggered, linking the specified object to the sensor upon detection. If both input signals are activated, the Attacher action is performed, which connects the defined object to the sensor by sensing the object. The output of the detected component switches to a true logical value. The output of the captured component will change to a true logical value. The component's I/O interface must be linked to the control unit's I/O interface within the Station Logic section.

SIMULATION RESULTS

By creating a program in the model, we developed a realistic simulated environment that replicates the production process of printed circuit board machining. By creating a program in the model, we achieved the creation of a realistic simulated environment that mimics the production process of processing a printed circuit board. This simulation enables detailed analysis and testing of various aspects of production, including determining the cell production cycle. After a thorough simulation, we determined the optimal cell production cycle, which reaches a value of 56.58 seconds. In our case, the initial production cycle duration before optimization was approximately 101 seconds. After refining the robot's trajectory and system layout in the simulation, the cycle was reduced to 56.58 seconds, resulting in a 44% improvement. This significant reduction demonstrates the practical benefit of using offline programming tools to enhance efficiency and optimize robotic processes before physical deployment. This production cycle is highly satisfactory for the given technological process, as it accounts for all key factors, including milling speed, board handling, and supporting operations. This production cycle is very satisfactory in the context of a given technological process, because it takes into account all important factors such as milling speed, board handling, and other operations. Although the optimized production cycle of 56.58 seconds was achieved in simulation, a physical implementation of the robotic cell has not yet been carried out. Therefore, a direct comparison with real-world cycle times and industrial benchmarks remains a subject of future work. However, on the basis of similar setups in literature and industry practice, this result appears to be competitive for low-volume automated PCB processing. More research is needed to assess how simulation accuracy translates into real operation, particularly in terms of unmodeled effects such as actuator delays, vibrations, or sensor noise. In particular, achieving this optimal cycle ensures that the robotic cell operates efficiently and reliably. It is important to note that achieving this optimal production cycle ensures efficient and reliable operation of the robotic cell. This outcome is a key result of our work, reinforcing confidence in the efficiency and performance of the production process and enabling precise planning and optimization of production operations under real-world conditions.

Based on additional insights, it appears to be advisable to revise the gripper mechanism before producing a functional prototype. Taking into account the additional information obtained, it seems appropriate to modify the gripper grip before creating a functional model. Instead of using the original friction-based grip, we propose adopting an encompassing grip approach (Fig. 9). With this change, we would modify the side pistons by incorporating grooves to accommodate the board's body during gripping.

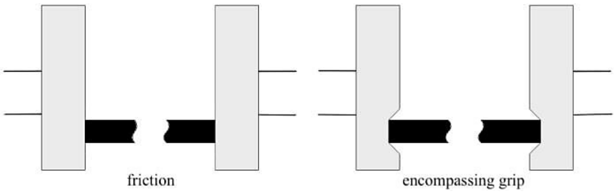

Fig. 9 Grip method of the gripper

We assume that the proposed redesign of the gripper will exhibit a comparable gripping time to the original vacuum-based solution. Minor deviations in gripping duration may occur and should be appropriately reflected in the overall cycle time during program execution. Likewise, the load imposed on the robot may differ slightly due to design changes. However, given the low mass of the printed circuit board, we do not expect the new gripper concept to significantly affect the robot's load capacity or operational performance.

DISCUSSION

In our research, we focused on designing a robotic cell that is tasked with processing printed circuit boards utilizing a milling machine integrated with an industrial robot. In our research, we focussed on the creation of a robotic cell which has the task of processing printed circuit boards using a milling machine as part of an industrial robot. Our proposed implementation introduces innovative approaches for a fully automated production cell. Our proposed implementation brings new approaches to a fully automated production cell. We aim to design a workplace aligned with the principles of sustainable development [15, 16]. This study provides insights into developing such a cell with modern software tools. This study offers insight into the creation of such a cell using modern software equipment. In addition, we developed a customized end-effector solution for operational handling. In addition, we design a custom solution for a robot effector to handle operations. During this process, we carefully chose the fundamental components of the robotic cell. During this process, we carefully selected the basic building elements of the robotic cell. One of the most important aspects was selecting a suitable industrial robot capable of performing all required operations. One of the most important aspects was to decide on a suitable industrial robot that would have the characteristics to handle all the necessary operations. We concluded that the ABB IRB 120T is the ideal candidate for this task, featuring integrated electric and pneumatic lines that simplify the connection of the end-effector.

In the introductory part of our article, we refer to several studies that address similar topics. In the introductory part of our article, we mentioned several works that deal with a similar topic. These articles span diverse areas of automation and robotics that are highly relevant to current research and industry. These articles cover a wide range of areas in automation and robotics that are of great importance in the current research and industrial sector. In the following, we expand on this context and examine how our findings align with prior research. In the following, we deepen this context and analyze how our findings in this work compare with previous research. One of the important trends in the field of automation is the workflows of robots operating within flow line systems [17]. This approach emphasizes robot utilization for diverse manufacturing tasks, to enhance efficiency and precision. This approach focuses on using robots to perform various tasks within the manufacturing process, increasing efficiency and accuracy. Our research builds on this concept by developing a robotic cell designed to perform targeted manufacturing tasks. Our work builds on this concept as we focus on a robotic cell that aims to handle specific manufacturing tasks. In addition, we found that there are studies focused on robotic factories employing advanced production automation. Furthermore, we found that there are articles dedicated to robotic factories based on complex production automation. Our study also moves in this direction, as we designed a fully automated production cell, representing a step toward the vision of future factories. Our study also moves in this direction, as we tried to design a fully automated production cell, which is a step towards what future factories could look like. Another interesting direction in the field of automation is additive manufacturing based on fused deposition extrusion [18]. This process has the potential to revolutionize the manufacturing industry, and our work, which explores innovative methods for the development of robotic cells, is relevant in this evolving context. This process has the potential to revolutionize the manufacturing industry, and our findings, which focused on new approaches in the creation of a robotic cell, can be considered relevant in this context. Finally, numerous approaches target automated injection in batch-suspended cells [4], which is another aspect of manufacturing automation. Our study is devoted to manipulation operations with printed circuit boards and thus also touches on this type of technology. Overall, our findings align with many established principles in automation and robotics and offer novel insights and recommendations for robotic cell development. Overall, our findings are consistent with many existing guidelines in the field of manufacturing automation and robotics, and contribute new approaches and recommendations for the specific field of robotic cell creation. In this way, we contribute to the development and progress of this important field.

Areas that could be enhanced further in our research include a more robust and realistic gripper design, originally fabricated using 3D printing. Areas that could be further improved in our research include a more realistic design of the gripper that we created using 3D printing. Although this printed tool served as a functional prototype and offered advantages such as rapid prototyping [19] and the ability to quickly iterate, we must consider that it lacks the mechanical properties of a production grade gripper. Although this printed tool served as a functional prototype and had certain advantages, such as rapid prototyping [19] and the possibility of rapid design iteration, we must consider that it does not reflect all the strength properties of a real gripper. It is important to note that when milling a printed circuit board, vibrations and shocks may occur, which may negatively impact machining accuracy and reliability. It is important to note that when milling a printed circuit board, various vibrations and shocks occur, which can significantly affect the accuracy and reliability of the entire machining process. Therefore, our next step would be a more in-depth investigation and redesign of the gripper that would not only grip boards effectively while also resisting vibrations and shocks. Therefore, our next step could be a deeper investigation and development of a gripper that would not only be able to grip boards effectively but would also resist vibrations and shocks. This could lead to notable improvements in PCB machining quality and enhance the robotic cell's reliability in actual production settings. This could lead to a significant improvement in the overall quality of printed circuit board machining and increase the reliability of the robotic cell in a real production environment. We can also explore challenges related to emerging technologies, processes, and materials [20].

This work identifies several promising directions for future research:

- Optimizing robot selection: A more in-depth comparison of various industrial robots and their suitability for automated production cells could be conducted. It is possible to focus on a deeper comparison of different industrial robots and their capabilities in the context of automated production cells. This could lead to a better understanding of the ideal choices for specific manufacturing tasks.
- Expanding the use of modern software equipment: Future research could investigate the broader application of advanced software tools within robotic cells. Further research studies could focus on expanding the use of sophisticated software in robotic cells. New applications and methods could be explored to improve the performance of automated systems.
- Development of effectors and actuators for robots: The development of new types of effectors (manipulation tools) and actuators [21, 22, 23] for industrial robots represents a vital avenue for investigation. The development of new types of effectors (manipulation tools) and actuators [21, 22, 23] for industrial robots could be an important research direction. These effectors could be designed for specific manufacturing tasks to improve precision and operational efficiency.
- Integration of artificial intelligence and machine learning: Another direction includes integrating cutting-edge AI and machine learning technologies into robotic cells [24, 25] enabling more adaptive and intelligent robotic responses to various scenarios.
- Optimization and research of industrial robot trajectories [26, 27].
- Safety aspects of automation: Research could also explore the safety dimensions of automation, particularly in terms of worker protection and human-robot collaboration [28].

These areas represent promising avenues for further investigation aimed at advancing robotic cells and automated manufacturing processes.

Our study offers several key insights for both academic research and industrial practice. Our study has important implications for research and industry for several reasons. The first finding we present concerns the selection of an industrial robot for a robotic cell. Our analysis identified the ABB IRB 120T as the most suitable choice for our application, due to its integrated electrical and pneumatic infrastructure. Our analysis showed that the ABB IRB 120T is the optimal solution for our purposes, thanks to its integrated electric and pneumatic line. This finding has broad implications, as selecting the right robot is critical to the success of automation initiatives. This finding has broad implications, as the correct choice of robot is a fundamental factor for the success of an automated process. The second finding concerns the use of modern software equipment in the robotic cell. This part of our research has shown that sophisticated software can significantly enhance the efficiency and adaptability of manufacturing processes. This part of our research has shown that sophisticated software can improve the efficiency and flexibility of manufacturing processes. This is particularly relevant in today's dynamic industrial landscape, where there is a need to quickly adapt to new production requirements. Finally, our findings make valuable contributions to the domain of manufacturing automation, which is crucial for industrial competitiveness. It is related to the existing literature, as our approaches align with the global trend toward increased automation in manufacturing. It is related to the existing literature, as our recommendations and new approaches are in line with the growing interest in automation and robotics in the world of manufacturing. Our study can serve as a basis for further research and innovation in this area, providing meaningful insight into the strategic role of automation in modern industry.

CONCLUSION

The paper focuses on creating a robotic workplace in the RobotStudio application. The paper focuses on creating a robotic workplace in RobotStudio application software. The task consisted of creating a robotic cell to process a printed circuit board using an end mill. An industrial robot in the cell manipulates the board in an end mill, thereby creating the necessary mounting holes and grooves in it. The article specifies the robotic cell along with the structure of the automated production unit. In the article, we specify the robotic cell as well as the structure of the automatic production unit. The next part deals with the preparation of the workplace, the selection a suitable industrial robot, and the creation of a gripper model can be used to manipulate the printed circuit board.

The paper achieved its goal of verifying the possibilities of digital design of a robotic cell using ABB RobotStudio simulation software. The simulation succeeded in optimizing the production cycle to 56.58 seconds and designing a custom gripping mechanism combining vacuum suction and pneumatic clamping. Although this was a pilot implementation, the results indicate that digital tools can significantly accelerate the design phase, reduce error risks, and lower costs before real-world deployment. In future work, it would be appropriate to experimentally verify the functionality of the proposed gripper and quantitatively compare the performance of the designed cell with other configurations.

The last part of the work is devoted to the implementation of the cell in the RobotStudio design environment. A cell model is created with all the necessary devices and components. The programming of the model resulted in a realistic simulation of the printed circuit board milling process. When the model was programmed, a realistic simulation of the manufacturing operation of printed circuit board milling was created. The created program can be uploaded directly to the control unit of the real robot. The simulation also allows to test whether the robot collides with other devices. If a collision is detected, the program can be easily modified by modifying the robot's path at the collision point. In case of such a detection, the program can be easily modified by changing the path of the robot in which the collision occurs. This avoids unnecessary costs due to potential damage to real equipment. In this way, additional funds will not be spent in the event of damage to the real equipment. Off-line programming has many advantages, but it is important to state that such a deterministic method will always need to be fine-tuned in a real workplace, where various other influences also enter the positioning of the robot, such as joint wear and resulting positioning inaccuracies. Off-line programming has many advantages, but it is important to state that such a deterministic method will always require modification of the program in a real workplace, where various other influences also enter the positioning of the robot, whether it is the wear of the robot's joints, and the resulting positioning inaccuracies. These factors cannot currently be fully addressed using this programming method, but we will see what the development of this technology will bring in the future.

The application of offline programming in our robotic cell design proved to be beneficial in several aspects. Firstly, it enabled collision checks during early stages of the project, helping to avoid potential design errors without the need for physical prototyping. Secondly, the simulation tools allowed us to fine-tune robot trajectories, which would be more time-consuming and cost-intensive on real hardware. Although exact cost reductions were not quantified, the development process benefited from faster iterations and reduced downtimes, confirming the potential of offline programming to minimize risk and support cost-effective deployment. These findings substantiate the claim stated in the abstract regarding the key advantages of offline programming.

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Statement on the use of AI

We hereby declare that AI assistants have been used in this work for grammar checks of the texts and grammatical fixes of the texts (entire work). We used the following models: ChatGPT 4.0 and Writefull.

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