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DEVELOPMENT OF AN INDUSTRIAL AUTOMATIC ROBOT CELL WITH AN ELECTROMAGNETIC INTERCHANGEABLE TOOL SYSTEM

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Abstract: *The rapid development of industrial digitalization and the improvements that Industry 4.0 has brought into the world of manufacturing has led to a significant need for flexibility in terms of industrial robotic applications. The aim of this paper is to present the improvement process of an existing industrial robot cell by adding a control cabinet that includes a PLC, relays, safety circuits and an HMI. The PLC design is oriented towards flexibility, compact form and connectivity, in order to provide a device that can be used both as a machine communication interface and as a tool for testing and simulation of robotic station logic through connection with a computer running dedicated software. Furthermore, the robotic application is improved by integrating an automatic tool changer that increases flexibility, provides a new concept for tool changing that can be electrically actuated and provides an improved framework for testing the control cabinet.*

Key words: *Robotics, Electrical, Interchangeable, Automation, Simulation, Electromagnetic.*

1. INTRODUCTION

Today's manufacturing structure is much more complex than ever before. The processes have increased in complexity and flexibility and the customers have more requirements. Furthermore, the conditions of today's manufacturing impose a productivity level that puts more and more pressure on the available resources. This led to an urgent need to adapt the manufacturing processes in real time with as little time wasted as possible. Different methods of flexibility and time optimization have been developed, such as operations combination, multi-robot applications, dual tool end-effectors and much more. The problem arises when the need for flexibility is high but other elements such as available space, robot technical capabilities, and financial funds are very limited. Considering that, engineers must develop technical solutions to respect all the criteria. The evolution of the CAx bundle (Computer Aided Design/Engineering/Manufacturing) offered the possibility of pre-planning and optimization from the virtual prototype level. Doing so, different task in industrial automation such as electrical design, mechanical and electrical design, cell layout, Product Lifecyle Management (PLM) and many more are being tested and optimized in a significant faster way, with little to no supplementary fundings.

One of the most important elements necessary in a robotic cell is represented by the control and automation system. A cabinet or multiple cabinets that include all the control components such as industrial computers, programmable logical computers (PLCs), motor drives, safety components etc. generally represent it. The designing of the electrical schematics and the cabinet layout must be performed according to international standards of electrical engineering committees and associations such as International Electrotechnical Commission (IEC) or International Standard Organization (ISO).

In this context, virtual commissioning is an important approach in designing modern manufacturing processes. By allowing the control software to be tested in a virtual environment using virtual equipment, it integrates with CAD-CAM-CAE solutions as well as the Industry 4.0 framework. Virtual commissioning typically uses a digital model of a PLC to ensure machine communication, but connection to a real PLC is also possible. Using a real PLC for virtual commissioning has certain advantages, such as the possibility of testing various scenarios for the tasks that will be performed by the system. In addition, the real PLC allows more reliable testing of the control software by avoiding bugs and errors that can be encountered when using virtual models. Also, the results of software testing will be closer to those obtained under real manufacturing conditions, since the machine that runs the software is a real one, not a virtual model or a digital twin.

Because the PLC is the core of any machine communication system through I/O signals, it is encountered in virtually any robotic application. Furthermore, the prevalence of virtual commissioning in the development of modern robotic applications means that a portable PLC that is readily available for connection and testing can be used to streamline the process. One of the main goals of the study presented in this paper is the development of a compact and flexible command and control cabinet that includes a PLC, a power supply, a motor driver and a relay. This cabinet

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forms the basis of a new concept of flexible command and control units that can be used for both development and virtual commissioning of industrial robotic applications and for integration and testing of real equipment.

The other main goal of the study is to develop a new concept of flexible tool changing system. Given the level of flexibility required for robotic applications, development of the tooling system – which also includes tool-changing solutions – is a very dynamic field of research. The tool changing system presented in this paper is aimed towards tasks that integrate low payload robots. The concept offers a more flexible solution that is adaptable to various types of end-effectors, does not require compressed air and has a low size and weight. The tool changer can be easily integrated with the developed control cabinet and was included in the testing procedures for I/O functionality. Both systems were integrated with an ABB IRB 140 robot to demonstrate the functionality.

2. STATE OF THE ART

As shown above, the actual status of technological development – in the context of Industry 4.0 and smart robotics – requires flexibility for the real equipment as well as for task programming. Furthermore, the system must be connected easily to other devices and integrated into local and global networks. Virtual models and digital twins are important aspects of application planning, testing and commissioning. For these reasons, the control systems of robots integrated into industrial environments are continuously studied and developed. The focus is not only on industrial robots, but also on other types, such as mobile robots.

Ferreira et al. [1] developed a motion control system for a differential drive mobile robot. The goal was to improve the motion control of the robot as well as the trajectory accuracy. The system comprised of an articulated arm robot mounted on a mobile platform, the study being focused on the development of the platform. The developed control system comprised of a cabinet that included a 5 V, a 24 V and a 48 V power supply, a relay, an IPC and EtherCAT I/O modules and drives. It should be noted that the cabinet does not include a PLC. The control of the system was done by using a PC with the TwinCat 3 automation software installed. The concept has the advantage of a more simplified, lightweight cabinet, because the command functions are transferred to the PC. On the other hand, the solution is less flexible and compact, as it requires a permanent external connection to a PC.

Solowjow et. al. [2] devised a bin picking task using a Siemens S7-1516 PLC. The system included a KUKA KR 3 Agilus 6-DOF robotic arm, a Robotiq 2F-85 parallel jaw gripper and an Intel RealSense D435 RGB-D camera. The robot controller was connected to the PLC through PROFINET. The Control cabinet included, besides the PLC itself and the power supplies, a HMI for human interaction and an E-STOP button. This solution uses a real PLC instead of relying on a PC for computational power, resulting in a command unit that can be fully embedded into the application, with lower power requirements.

There is also significant concern in the research field regarding open control systems. Kajzr et. al. [3] developed an open PLC-based robot control system for 3D concrete printing. The concept is based on an industrial B&R PLC. An automatic code generator is used to convert control models from the Simulink module in Matlab to C/C++ instructions that can be run by the PLC. This concept allows libraries and standardized blocks and modules to be translated into code that can be used to control robotic tasks.

3. MATERIALS AND METHODS

In order to develop, test and validate the proposed systems, a robotic cell based on an ABB IRB 140 industrial robot was used. The cell also included supports for part centering and manipulation, as well as a belt conveyor that performed the input and output operations. The cell was enclosed by safety panels, with an access door equipped with status sensor that detected when the door opened. The robotic cell is shown in Fig. 1.

For the tool changing system, two different grippers were used, one with two fingers and the other with three fingers. The robot was controlled through an IRC5 controller. In addition, in order to control the flow of compressed air to various pneumatic devices integrated into the application, a 5-way electro valve was used.

The study used the following methodology:

- the structure of the cell, together with equipment connections, was studied;
- the characteristics of the control box and the tool changer were defined;
- the circuits for the control box and the tool changer were designed using EPLAN Schematics;

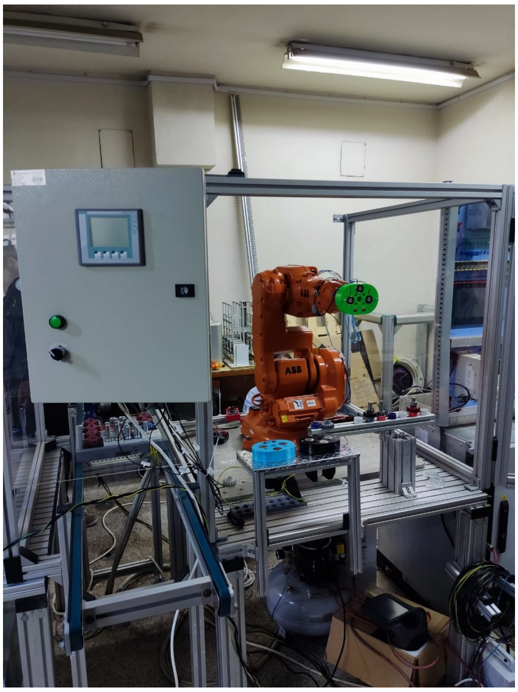


Fig. 1. Robotic cell including the ABB IRB 140 articulated arm robot.

- the functionality of the system logic was validated using TIA Portal;
- the manufacturing process of the tool changer components was validated using Fusion 360;
- the control process of the tool changer components was validated using CAMIO Studio;
- the layout of the application, the integration of the developed systems and the robot test programs were validated using ABB RobotStudio;
- the functionality of the integrated system was validated using the robot cell based on ABB IRB 140.

4. ELECTRICAL DESIGN AND CONTROL CABINET

During the process of designing and constructing the control cabinet a series of standards (such as IEC 62491.2008) were followed for correct selection of cables and safety elements, the product manuals provided by the manufacturer were used to determine the optimal cooling space and mounting systems. The cabinet includes the following main elements:

- A 24 VDC power supply for the main logical computer and all sensors;
- A 12 VDC power supply for the three electromagnets integrated into the automatic tool changing system;
- The main computer unit which is represented by a programmable Logical Controller (PLC) from Siemens;
- The control elements which include a motor drive for the conveyor belt and an industrial relay which controls the tool changing system;
- The safety circuit which consists of a miniature circuit breaker (MCB) chosen taking into account the safety specifications of all connected elements;
- The cables, selected according to the current requirements – for the 220 VDC circuit a cable with 2.5 mm^2 cross section was used, while for the 24 VDC and the 12 VDC circuits a cable with a cross section of 1.25 mm^2 was used.

After the corresponding selection of cabinet components, the schematics and the layout were designed using a dedicated software, EPLAN P8, which includes the modules EPLAN Schematics for 2D electrical schematics and EPLAN Pro Panel, which was developed for 3D design of cabinet layouts, as shown in Figs. 2 and 3.

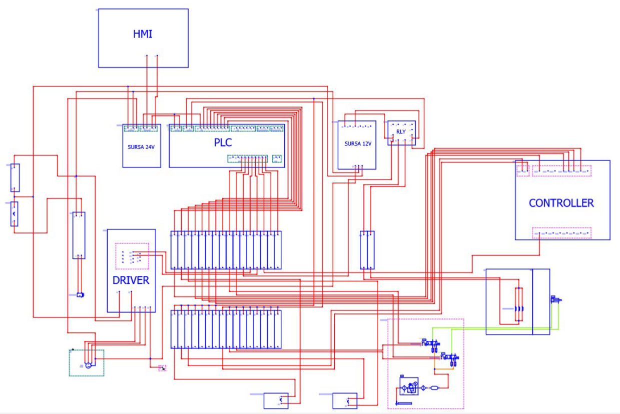


Fig. 2. General electrical schematic.

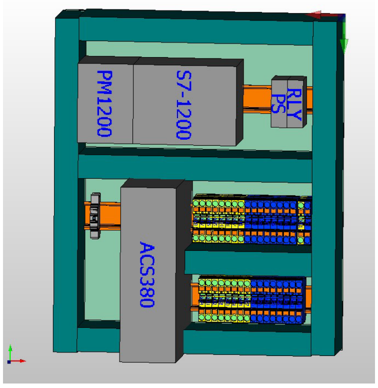


Fig. 3. Cabinet layout – Digital Twin.

Fig. 4. Cabinet layout – Real version.

The software allows us to determine the corresponding dimensions of the cabinet, the position of the components and the approximate length of each cable used [4], as shown in Fig. 4. The real control cabinet built on the designed specifications is shown in Fig. 4, together with the ABB ACS 380 invertor used to drive the conveyor motor.

5. AUTOMATIC TOOL CHANGING SYSTEM

As mentioned above, the demand for flexibility has become an important requirement in the modern automated manufacturing processes with industrial robotic cells. A solution to this requirement is represented by the usage of an automatic tool changing system [5, 6]. This type of system consists of a master and a slave flange, with the master mounted on the robot and a slave flange connected to each end-effector integrated in the application. Such systems are also being developed and sold by international level companies such as ATI Industrial Automation or Schunk. The principle they chose for locking and unlocking the slave flange from the master one is by using a pneumatic liner cylinder that pushes several steel balls, such as the ones used for bearings, in a specific channel obtained only by aligning the cylinder head with the slave flange.

The principle used for connecting and disconnecting the system is based on the usage of electromagnetic field and its physical characteristics of attracting metallic objects. Three electromagnets were placed in a triangle shape so that the attracting force is generated in three different non-coaxial points to increase the surface of contact and the dissipation of forces. An important aspect was to assure the proper holding force for the magnets. This force was obtained by the usage of a proper current determined by the manufacturer at which the magnets work, in this case 12VDC, but more than that, the intensity of current that is passing through the magnets. A proper current value is necessary for the optimal functionality of the magnets [7]. A lower current value would lead to a lower holding force, which means that the manipulated object can be dropped due to inertial forces that manifest during movement. A higher current value would lead to the overheating of the magnets, which can result in mechanical and electrical damage of the tool changing system. The main disadvantage of the integrated electromagnetic tool changer is the lack of a failsafe system that prevents the detachment of the tool from the robot in the event of a power failure.

Conventional pneumatic systems are capable of keeping the tool attached to the robot even when the pressure in the compressed air circuit is lost due to integrated one-way valves. For the electromagnetic system, either a supplementary safety mechanical system or the integration of an uninterruptible power supply (UPS) is required to maintain the current in the electrical circuit until the robot is in a neutral position and the interchangeable system is safely disconnected and positioned in the tool magazine.

In addition, the system was developed with the purpose of mounting pneumatic grippers, which comes with the challenge of assuring the proper sealing to obtain the necessary pressure for the end-grippers. This was capable due to a series of specific fast-change pneumatic fittings that come with a proper sealing. Fig. 5 shows the exploded view of the tool changer together with a pneumatic gripper with two fingers, while in Fig. 6 a gripper with three fingers is used.

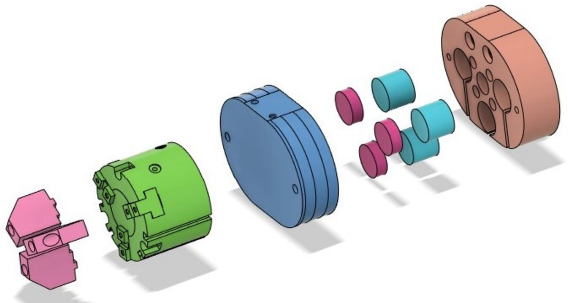


Fig. 6. CAD model of the system equipped with a parallel three fingers gripper.

The prototype of the tool changing systems were built using additive manufacturing for the magnet supports and the connecting flanges.

The tool changers built for experimental testing during the study were designed as prototypes. In order to analyze the manufacturing efficiency of a potential final product, it should be taken into account that the magnet supports and the connecting flanges would consist of more durable materials that would require machining operations. The research included a preliminary study of the manufacturing conditions and requirements for these parts to draw conclusions regarding the feasibility and duration of the machining operations. Thus, a CAM simulation was performed using a CNC milling center with vertical spindle, as shown in Figure 5. The simulation included the machine type, material type (for the purpose of the analysis, an aluminum grade 6082-T6 was used), machining operations, tools used and the specific parameters of milling [8]. A simulation for geometry control on a Computer Measuring Machine (CMM) is necessary to validate the manufacturing process prior to that [9]. Fig. 7 shows the CAM simulation performed using Fusion 360, while Figs. 8 and 9 show the simulation of the control process.

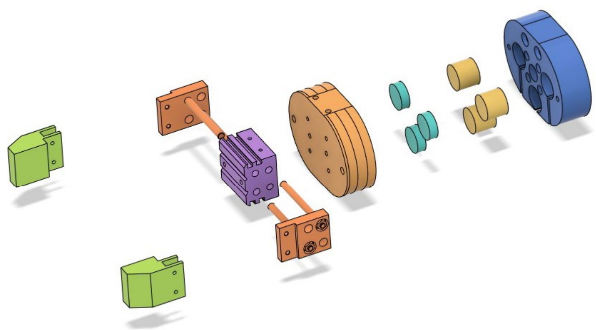


Fig. 5. CAD model of the system equipped with a parallel two fingers gripper.

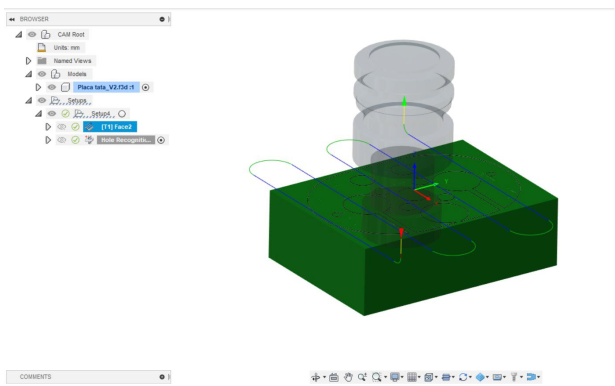


Fig. 7. CAM Simulation.

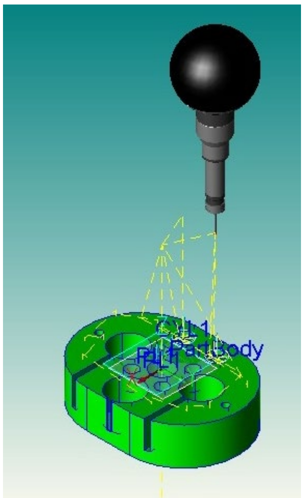


Fig. 8. CMM Simulation.

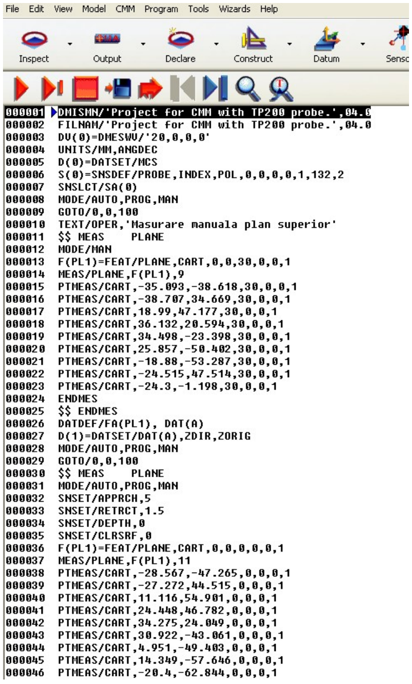


Fig. 9. CMM Program.

6. CONTROL PROGRAM, SIGNALS AND HUMAN-MACHINE INTERFACE

The Siemens PLC integrated into the cabinet represents the main computer unit that controls the communication between the systems included in the application. It uses the RS232 (point to point) communication protocol, ladder programming, as shown in Fig. 10, together with the logic of combined inputs, such as sensors and microswitches, and outputs, such as solenoid valves, electromagnetic magnets, motor drive etc. It also communicates with the robot controller due to its IO Module Board (DSQC328), which changes signals on different communication channels. Other communication protocols such as ProfiNet or ProfiBus can be used, especially for safety modules [10]. The communication between the machines integrated into the application is based on I/O signals, defined as shown in Fig. 11. Figure 12 shows the signal configuration on the PLC.

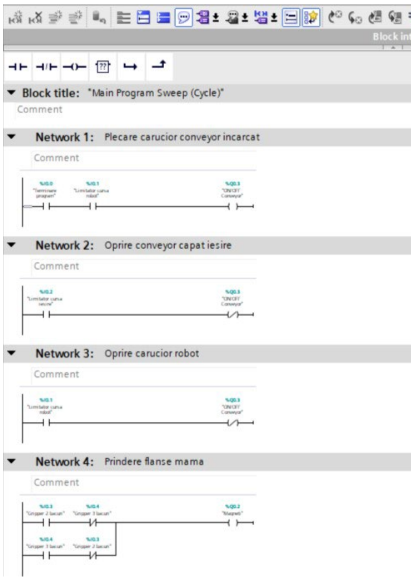
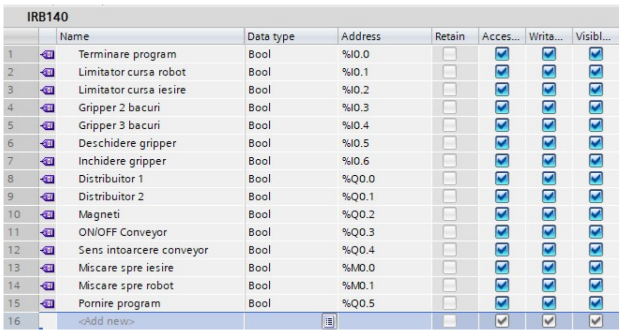


Fig. 10. Ladder Program.



IRB140

		Name	Data type	Address	Retain	Acces...	Writa...	Visibl...
1		Terminare program	Bool	%I0.0	☐	☑	☑	☑
2		Limitator cursa robot	Bool	%I0.1	☐	☑	☑	☑
3		Limitator cursa iesire	Bool	%I0.2	☐	☑	☑	☑
4		Gripper 2 bacuri	Bool	%I0.3	☐	☑	☑	☑
5		Gripper 3 bacuri	Bool	%I0.4	☐	☑	☑	☑
6		Deschidere gripper	Bool	%I0.5	☐	☑	☑	☑
7		Inchidere gripper	Bool	%I0.6	☐	☑	☑	☑
8		Distribuitor 1	Bool	%Q0.0	☐	☑	☑	☑
9		Distribuitor 2	Bool	%Q0.1	☐	☑	☑	☑
10		Magneti	Bool	%Q0.2	☐	☑	☑	☑
11		ON/OFF Conveyor	Bool	%Q0.3	☐	☑	☑	☑
12		Sens intoarcere conveyor	Bool	%Q0.4	☐	☑	☑	☑
13		Miscare spre iesire	Bool	%M0.0	☐	☑	☑	☑
14		Miscare spre robot	Bool	%M0.1	☐	☑	☑	☑
15		Pornire program	Bool	%Q0.5	☐	☑	☑	☑
16		<Add new>			☐	☑	☑	☑

Fig. 11. Signal definition and addresses.

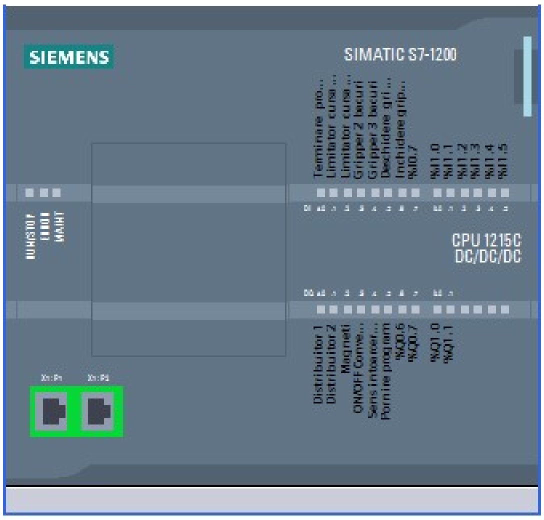


Fig. 12. Signals locations on the PLC.

A Human Machine-Interface (HMI) is an important element for rapid intervention and modification of robotic cell functionality. An HMI, shown in Figure 11, is represented by a digital screen which transmits a variety of system parameters and variables in real-time and has the capability of letting the human operator interfere during the process and modifying different characteristics such as flow parameters, operations selection, signals activation/deactivation etc., based on a

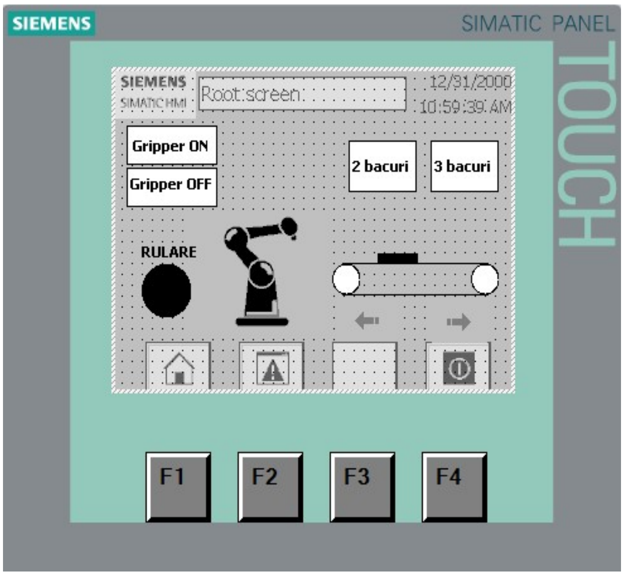


Fig. 13. The Human-Machine Interface (HMI)

Supervise Control and Data Acquisition (SCADA) system [11]. In this case, the HMI transmits information about conveyor position, the robot status, the end-tool and the pneumatic system, but also the automatic interchangeable tool system configuration.

7. ROBOT PROGRAMMING AND SIMULATION

In today's robotics cell, a crucial part of developing a project is represented by the simulation primordial to any real-life decision in the layout and the functionality of the automation cell. ABB RobotStudio is an application proprietary to ABB industrial robots with the capabilities of online/offline programming and simulation. In this application virtual robot models are used, which correspond perfectly to the real robots for which geometrical validation can be made based on the model presented in [11, 12]. The virtual model of the IRB 140 is shown equipped with the 2-finger gripper in Fig. 14, while the real system is shown in Fig. 15. For the 3-fingers gripper, the virtual model is shown in Fig. 16, while the real system is shown in Fig. 17.

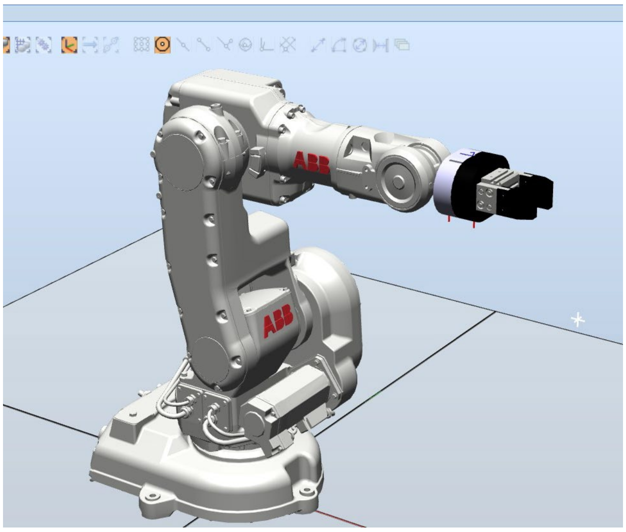


Fig. 14. Robot equipped with the two-finger parallel tool – Digital Twin.

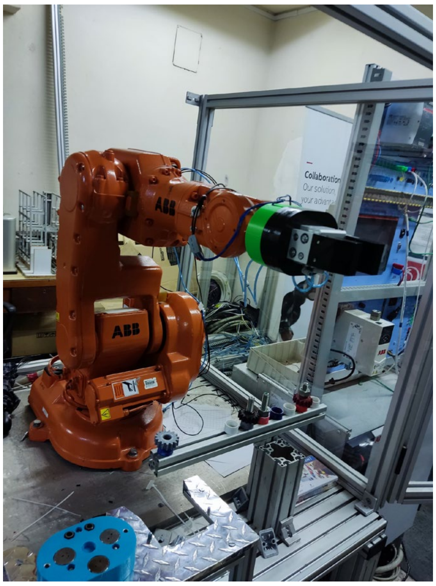


Fig. 15. Real robot equipped with the two-finger parallel tool

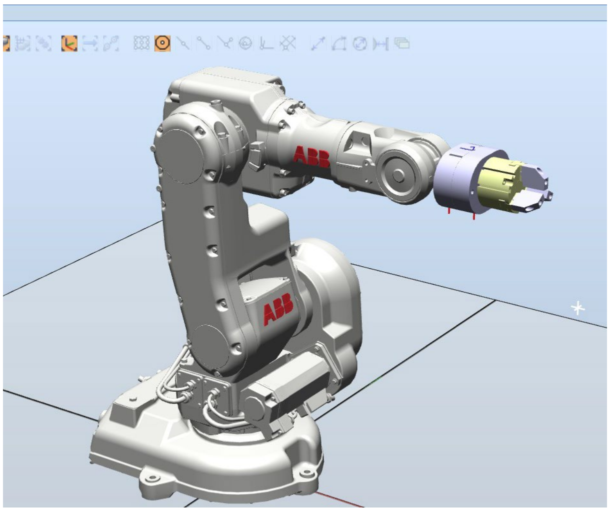


Fig. 16. Robot equipped with the three-finger parallel tool – Digital Twin.

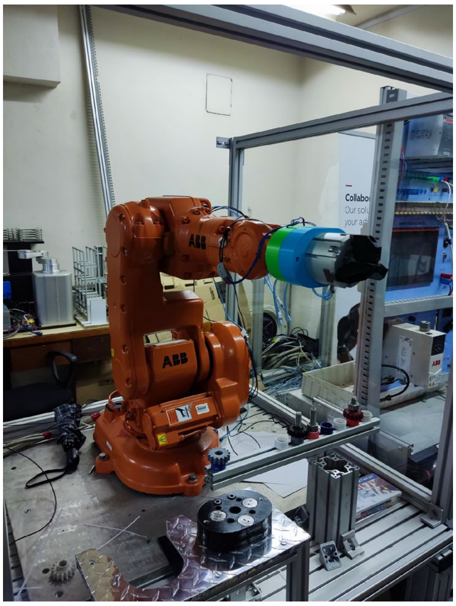


Fig. 17. Real robot equipped with the three-finger parallel tool

8. PNEUMATIC SYSTEM

An important aspect of the automatic interchangeable tool system is represented by its capabilities to be equipped with different pneumatic end-tools, offering the integrator and the user a wider variety of configurations, not only with electric grippers. Nowadays, pneumatic grippers are very common in the industrial field and tend to have a slightly lower market price compared to electric versions. In addition, being capable to be configured with pneumatic grippers it opens the possibilities to be integrated within specific manufacturing processes with special requirements, such as operating in environments with a high risk of explosions due to presence of easily inflammable gases, as an example, the oil industry or the energy industry.

To do so, a specific pneumatic circuit was developed. The main issue was to assure a safety decoupling of the interchangeable system and to close both the pneumatic ways that were designed to operate the end gripper. A solution with an automatic pneumatic island, consisting of several solenoid valves was chosen, Fig. 17. Using two separate solenoid valves it could connect the normally closed way of each one to one of the pneumatic ways designed for the gripper, whether the normally open way was blocked, restricting the airflow through it [13].

The default configuration consists of both the solenoid valves being in the normally close state and the gripper with no air through its system. Being so, the coupling and decoupling of the system can be made in safety circumstances without the possibility of compressed air interfering and affecting the position or the contact between the master and slave boards. For opening one of the two pneumatic circuits of the end-tool one of the two solenoid valves must be commanded, each one having assigned a specific role, either to open the gripper, or to close it. On the same principle, a deburring tool can be mounted on the automatic interchangeable tool system and used properly, the way of rotation being selected with the usage of the two solenoid valves.

The pneumatic circuit was designed and simulated with the help of a specific design software from the company Festo, FluidSim, as shown in Fig. 18. The pneumatic circuit integrated into the robotic application is shown in Fig. 19.

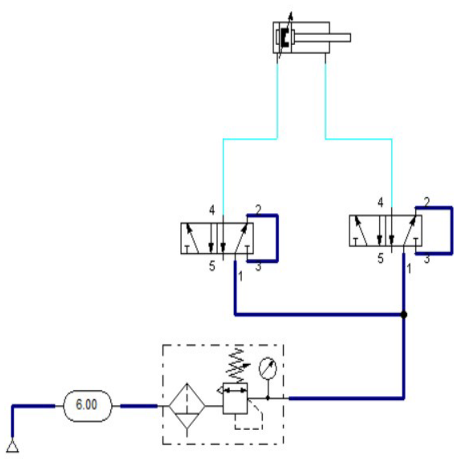


Fig. 18. The design of the pneumatic circuit.

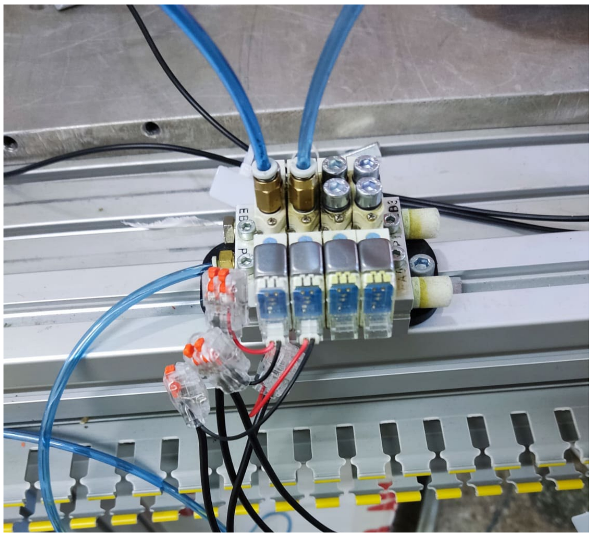


Fig. 19. The automatic pneumatic island.

9. CONCLUSIONS AND FURTHER DEVELOPMENT

The study presents the development of a compact and flexible control cabinet for industrial robotic applications that includes a PLC, relays, safety elements and power sources, together with an automatic tool changing system used for testing and robotic tooling optimization. With the rapid evolution of manufacturing industry and the necessity of newer technologies, more demanding challenges will have to be overcome, such as automatic tool changers that offer a significant increase in flexibility, while maintaining a lower supplementary cost, less footprint and a high modularity and configurability. In addition, the direction of research in the field of control cabinets aims towards more compact design and flexibility.

The control cabinet can be used to manage machine-to-machine communications through I/O signals. The experimental testing of the developed cabinet highlighted the following advantages:

- Compact frame. The cabinet has relatively small dimensions, is portable, and can be easily transported to another location even by human operators.
- Flexibility. The connections provided for the control cabinet as well as the minimalist design ensure that it can be integrated into a large variety of robotic applications.
- High re-programmability provided by the included PLC.
- Possibility to connect with a computer and industrial robotic simulation software.

Taking into account the above specified advantages, the control cabinet can be used to manage communications for robotic industrial applications. Furthermore, the device is suitable for testing purposes, due to its flexibility and portability. Because of its features, it can also be used as a temporary replacement for more complex control systems. The cabinet can be used in the conceptual stages of robotic applications development, being suitable for integration into robotic industrial process simulations. This makes the developed cabinet a highly versatile concept that can also be used as an instrument besides its conventional role as a control system.

The automatic tool changer designed during the research has the following advantages:

- It is compact and lightweight. The device can be scaled to suit most low to middle range robot sizes.
- It can be adapted to various application requirements. The number of integrated electromagnets and their size can be varied accordingly.
- Does not require pneumatics.
- It has wider position tolerances for the connection between the flanges, because sealing the pneumatic connectors is not necessary.

The automatic tool changer can be used with pneumatic and electric grippers, as well as various other end-effector types. Its size depends on the payload required and the number and type of electromagnets used. The main disadvantage of the tool changer concept is the lack of a failsafe system that is required to keep the end-effector connected even when the electromagnets are no longer powered.

Both developed systems have the potential to be further developed and to represent a solution for robotic cell optimization and increased flexibility. Planned improvements include the following:

- design optimization to increase efficiency;
- more detailed simulations to determine optimal parts placement, robot path planning and trajectory optimization with the goal of reducing cycle times as much as possible based on the model presented in [14];
- replacement of electromagnets with pneumatic assisted permanent magnets;
- development of a failsafe mechanism for the tool changer;
- implementation of communication protocols such as ProfiNet, ProfiBus or IO-Link in order to increase the capabilities of the control cabinet;
- integration of vision cameras in order to extend the applicability of the developed control system to unstructured work environments.

The developed concept of a control cabinet that can be used for both flexible robotic cell integration and testing, research or simulation represents an original contribution of the study. The level of flexibility, as well as the compact form of the cabinet provides a robust framework for future development. In addition, the automatic tool changing system based on electromagnets, which provides a more versatile, electrical powered alternative to the standard pneumatic-driven tool changers, represents another original contribution.

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