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IMPLEMENTATION OF THE DIGITAL TWIN CONCEPT IN THE CASE STUDY OF A ROBOTIC MANUFACTURING CELL FOR MACHINING OPERATIONS

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Abstract: *In the context of the ongoing evolution toward the Industry 4.0 model, the concept of the Digital Twin is emerging as a central element of digital transformation within the industrial environment, providing an integrated framework for the interconnection of physical and virtual processes. The scientific paper presents the implementation of the Digital Twin concept within a company based in Oradea, Romania. The case study focused on a robotic manufacturing cell designed for machining operations. The project involved the integration of physical and virtual components (the digital model) to enable real-time monitoring, data acquisition, and process optimization. The robotic cell includes handling, CNC machining, and subcomponent assembly processes, all digitally represented and executed through a 3D virtual model connected to physical equipment via industrial IoT solutions. Process monitoring within the cell is facilitated through a dedicated interface that provides real-time information. The results confirm that adopting a Digital Twin framework in machining cells significantly contributes to the advancement of smart manufacturing and the integration of Industry 4.0 principles.*

Key words: *Digital Twin, Industry 4.0, Digital interface, manufacturing cell, CNC machining, process monitoring, human-machine interaction.*

1. INTRODUCTION

In modern industry, the interaction between human operators and automated production cells is essential to achieve flexible and efficient processes. Accordingly, a user-friendly menu interface was developed for the manufacturing cell. This interface allows both technicians and process engineers to easily monitor and control robotic and CNC systems.

The menu aims to reduce operational tasks by enabling real-time visualization of process parameters through graphs or automated monitoring screens, quick adjustment of process conditions, and immediate feedback on manufacturing status. By using such a menu, system management complexity is reduced, operator errors decrease, and productivity within the production cell is enhanced [1],[2].

In paper [3], the concept of digital manufacturing systems is presented from the perspective of using digital simulation tools and

Information and Communications Technology (ICT) specific to industrial engineering. In paper [4], the specific concepts of Industry 4.0 are developed, among which Cyber-Physical Systems (CPS) and Digital Twins (DTs) are highlighted. An increasing number of authors [5],[6],[7], emphasize that the development stage corresponding to Industry 4.0 is being surpassed by a new and important stage (revolution) — Industry 5.0, [8].

This research paper presents the design and implementation of the interactive menu, focusing on its features and usability aspects, which significantly influence the manufacturing process. Furthermore, considering the integration of the menu within the Industry 5.0 framework, special attention is given to the benefits of digitalization and human-machine collaboration [9],[10],[11].

The research paper is structured into several chapters covering: the current study within the company, the design and description of the

digital interface, a detailed presentation of its functionalities through graphical interfaces, and conclusions regarding the impact of this solution on the manufacturing process.

The main objective of this paper is to present the design and implementation of a digital interface for the integrated manufacturing cell, enabling easy interaction between users and automated systems. This interface aims to simplify the operation and monitoring of the industrial robot and CNC equipment, reduce operator errors and optimize intervention times, increase the efficiency and flexibility of the manufacturing process, as well as contribute to the digitalization of the production process in accordance with Industry 4.0 principles. Currently, Industry 4.0 involves the digitization and interconnection of information within the production system, while Industry 5.0 envisages the interaction of human intelligence with artificial intelligence. This line of research has also been explored in detail in my Ph.D. thesis [12].

Some ideas are being outlined regarding what the concept of Industry 6.0 should entail. Among other things, this concept would imply the absence of any interaction between humans and machines (equipment), the absence of any human-to-human interaction, and the absence of any interaction between humans and technical documentation. Everything is carried out through an application: a photo is taken of a rough sketch, one click, and the part is produced [13].

Despite the impressive progress made in Industry 4.0 technologies, current research shows that human-centered design is often overlooked in manufacturing interfaces. Most human-machine interfaces (HMIs) tend to prioritize automation and monitoring features but frequently neglect how usable and intuitive these systems are for the people operating them [14]. This is especially concerning because human error accounts for 60-80% of failures in complex manufacturing systems, making it clear that creating more user-friendly, human-focused interfaces—designed for technicians and engineers—is essential to improving safety and efficiency in digital manufacturing. [15],[16].

Whilst Industry 4.0 and the emerging Industry 5.0 paradigms have significantly

advanced human-machine collaboration through cyber-physical systems and digital twin technologies substantial challenges persist in developing intuitive interfaces that effectively minimize operator errors and optimise manufacturing workflows [4],[14],[15]. AI-based digital twin applications are systematically categorized into three principal dimensions: operator, process, and product, with the operator dimension focusing specifically on enhancing safety and ergonomics through intelligent assistance mechanisms [17]. Current digital twin implementations often lack comprehensive human-centric features, thereby limiting their potential for seamless human-system integration [15],[17]. Contemporary research indicates that human error accounts for approximately 60-80% of failures in complex manufacturing systems, emphasizing the critical importance of developing more intuitive, operator-focused interfaces [14].

Furthermore, the transition towards Industry 5.0's human-centered approach necessitates interfaces that not only enhance operational efficiency but also support the cognitive and collaborative capabilities of human operators [9],[10],[11]. This fosters a productive synergy between humans and machines, enabling more intuitive, flexible, and innovative work environments [16],[18].

This research addresses these identified gaps by developing and implementing an interactive digital interface that prioritizes both technological sophistication and human usability [10],[19]. The integration of Augmented Reality within Human-Manufacturing Cell Interaction represents a significant advancement in collaborative technologies, highlighting their role in enhancing collaboration, trust, and safety parameters [20],[21]. Current Digital Twin implementations have demonstrated transformative potential in intelligent manufacturing, facilitating real-time data-driven simulations and virtual representations of physical assets and systems [22],[23].

2. GENERAL OVERVIEW OF A CASE STUDY ON A ROBOTIC MANUFACTURING CELL FOR MACHINING OPERATIONS

2.1 Description of the technological flow

The Disk Limiter product, shown in figure 1(c), is a subassembly found in several internal combustion engine models. By studying the technical documentation of the part, depicted in an isometric view in figure 1(c), it can be seen that this product consists of three components: a disc made from a die-cast aluminum alloy and two metal components (two steel inserts). Figure 1(a) presents the aluminum alloy part in an isometric view, while Figure 1(b) shows the two metal inserts, the bushing (1) and the pin (2) [12].

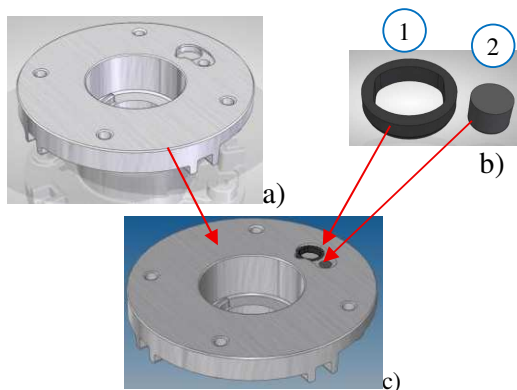


Fig. 1. a) 3D model of the die-cast aluminium part; b) 3D models of the two metal inserts, bushing and pin; c) 3D model of the Disc Limiter product in isometric view [12]

The integrated manufacturing cell within an automotive parts manufacturing company in Oradea, layout present in figure 2, consists of 2 CNC machining centers (1), an auxiliary subcomponent feeding system (2), a KUKA industrial robot (3), a multifunctional gripper (6) for inserting subcomponents attached to the industrial robot, hydraulic fixed devices mounted on each CNC machine (5), and an external hydraulic pump (4). The robot serves a multifunctional installation for the insertion of subcomponents (pins and bushings) and performs the assembly operations of subcomponents in the parts on each CNC machine, which are oriented and fixed using hydraulic devices.

The industrial robot picks up the subcomponents from the cell's subcomponent supply station and assembles them into semi-finished products inside the CNC machines after completion of machining operation OP10

(operation 10). Thus, the robot, shown in Figure 2, plays an essential role in the transfer and positioning of subcomponents for the next stages of the process.

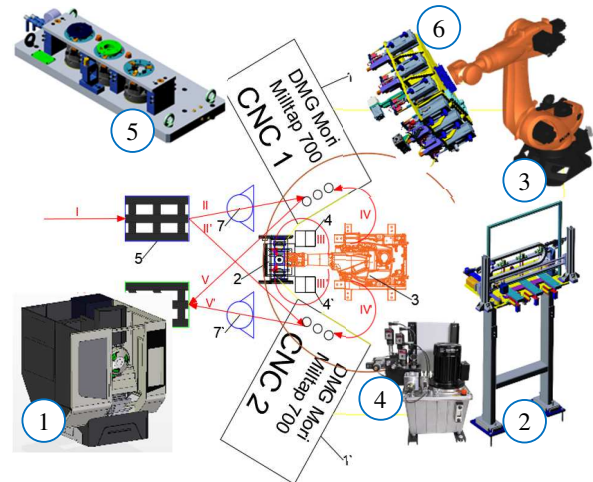


Fig. 2. Robot manufacturing cell layout [12]

2.2 Role of the industrial robot

The complete manufacturing process flow within the cell encompasses several sequential operations: subcomponent feeding, initial machining (OP10) in the CNC center, robotic transfer and assembly of subcomponents into the semi-finished parts, followed by final machining (OP20). Upon completion of all operations, the finished product is removed from the manufacturing cell. This logical sequence is illustrated in the process flow diagram shown in Figure 2 and 3, which highlights each operational step and the corresponding equipment involved.

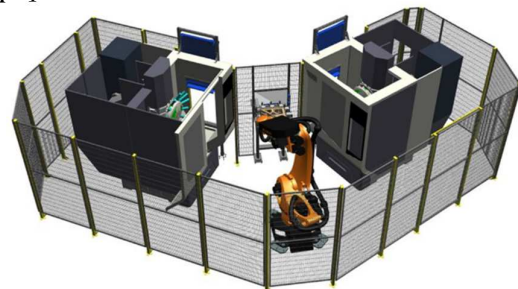


Fig. 3. 3D model of the robotic manufacturing cell

The process flow in the integrated manufacturing cell is synchronized to ensure continuity and operational efficiency. The cell includes two CNC centers, each performing two machining operations: OP10 and OP20.

Between these two operations, the KUKA industrial robot is responsible for assembling the subcomponents during the process. The manufacturing sequences for the studied manufacturing cell are presented in Table 1.

Table 1

Manufacturing sequences in the robotic manufacturing cell [12]

Sequence	Description
Step 1	Manual loading of the parts onto the hydraulic clamping and positioning device
Step 2	Machining OP10 – automatic
Step 3	Retrieval of subcomponents from the supply station
Step 4	Automatic opening of the CNC door
Step 5	Automatic assembly of the pin and bushing by the industrial robot
Step 6	Automatic closing of the CNC door
Step 7	Machining OP20 – automatic
Step 8	Manual unloading of the machined and assembled parts from the CNC

Before the completion of operation OP10 at the first CNC machine, the robot retrieves the required subcomponents (bushings and pins) from the loading station and remains in standby mode until OP10 is finished. This standby ensures process synchronization, prevents operation overlap, and allows assembly to occur at the correct time.

After OP10 is completed, the robot inserts the subcomponents into the CNC machine and performs the assembly of the semi-finished part in preparation for OP20. The same sequence is repeated at the second CNC machine, where the robot follows the same steps: retrieval, standby, assembly, and handover for OP20.

After OP20 is completed, the human operator unloads the finished parts, loads the raw material, and performs quality and dimensional inspection.

3. INTEGRATING THE DIGITAL TWIN CONCEPT INTO THE MANUFACTURING CELL

The integration of all components within the manufacturing cell was executed by creating a faithful virtual representation according to the real-world layout in a controlled, immersive virtual environment. This digital twin environment was established using the Process Simulate software [24].

The software environment enabled the initial programming of the manufacturing cell and the connected industrial robot, replicating the production workflow intended for the physical system (Figure 4). This virtual setup allowed the comprehensive implementation of the production sequence, taking into account actual production cycle times and inter-operation waiting periods. By simulating these elements in a virtual framework, the system permits thorough process validation and risk reduction prior to physical deployment, thereby optimizing throughput and operational efficiency.

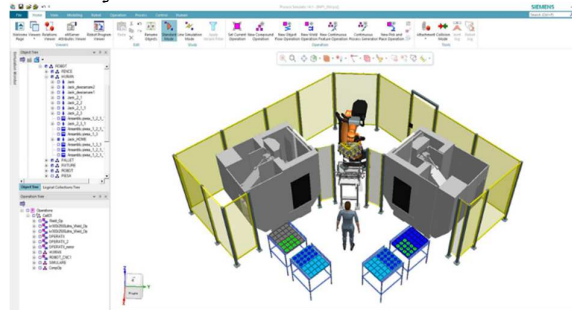


Fig. 4. Robotic manufacturing cell model integrated into the *Process Simulate* software [12]

The production workflow for the part was implemented within the manufacturing cell, respecting production times and waiting times. This allows operations to be simulated and validated in a virtual space, reducing risks and optimizing the process. An example from this case study is the kinematic validation of industrial robot movements, Figure 5.

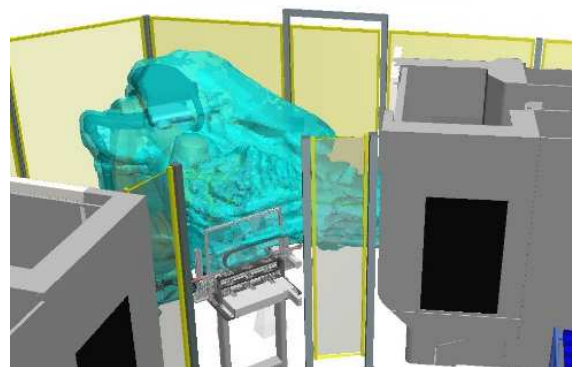


Fig. 5. The workspace of the industrial robot in a complete cycle of feeding and inserting components into the flexible manufacturing cell (bushings and pins) [12]

By simulating the process, the trajectories (paths) that are improved during the simulation phase can be observed. The robot movements

were closely analysed and optimized during the simulation phase, enabling improvements to path planning and avoiding collisions within the work envelope. This procedural validation ensures high accuracy and reliability when the robot executes real-world tasks.

The integration and synchronization of various manufacturing cell components, was a critical step supported by the virtual environment, providing a holistic simulation of cell behavior (Figure 6). This integration enhances the understanding of concurrent operations and their interactions, crucial for the design of efficient manufacturing cells.



Fig. 6. Visualization interface for the interconnectivity of the cell elements [12]

To further develop the robot program, a controller compatible with the KUKA KR 120 R2500 pro robot was employed. The choice of this high-performance 6-axis industrial robot, known for its precision, reach, and payload capacity, supports complex assembly and material handling tasks within the cell. The robot's trajectory validation through simulation ensures the programmed motions meet the desired execution criteria before being uploaded to the physical robot (Figure 7).

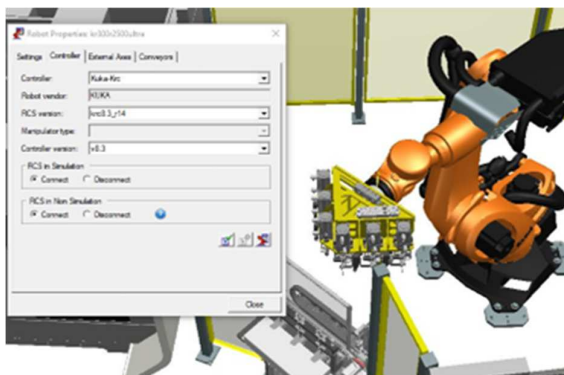


Fig. 7. The Robot Controller used for creating the trajectories of the KUKA industrial robot [12]

Consequently, the manufacturing cell program generated within Process Simulate enables full functional integration and

coordination of all cell elements, minimizing downtime and errors during physical commissioning (Figure 8). In addition, there is a manufacturing cell program code sequence to the left of the image.

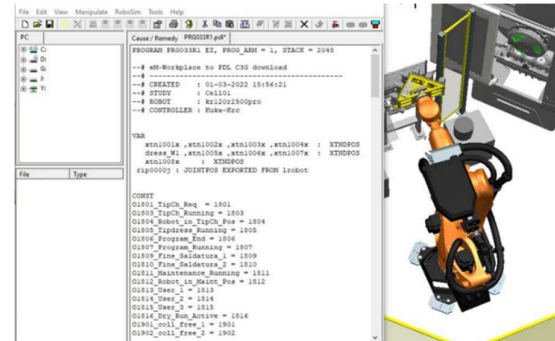


Fig. 8. Program generated using Process Simulate software for the functional integration of the KUKA industrial robot within the manufacturing cell [12]

One multifunctional device in the manufacturing cell is the robot-attached bushing and pin insertion system, which includes a force measurement and control subsystem. This subsystem monitors insertion force using one equipment for measuring and verifying these insertion forces (Figure 9). The force measurement equipment plays a critical role in maintaining assembly quality by continuously monitoring insertion forces throughout the automated assembly process.



Fig. 9. Devices Needed for Measuring and Verifying Insertion Forces [12]

As illustrated in the block diagram shown in Figure 10, the force measurement and verification system comprises several interconnected components working in a coordinated manner: a signal processing module with multiple signal conditioning stages and bridge excitation for strain gauge sensors, a dedicated industrial CPU that processes incoming force signals and manages communication protocols, and integrated

EtherCAT and Ethernet/IP communication interfaces for seamless integration with the manufacturing cell's control architecture.

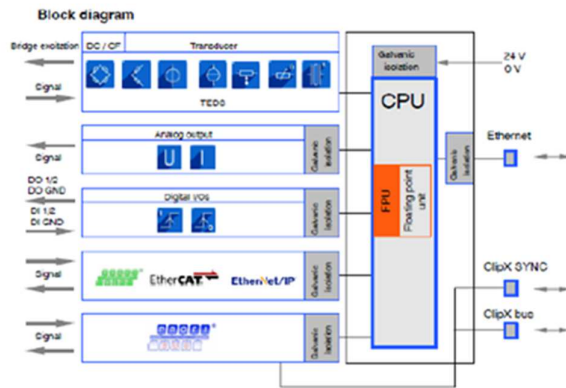


Fig. 10. Block diagram of the operation of the equipment for measuring and verifying insertion forces [12]

The system operates on standard industrial power supply (24V DC/0V) and incorporates CipX SYNC and CipX bus connections for synchronized communication with other cell components, facilitating coordinated operation between the force measurement system, robot controller, and CNC machines. This comprehensive integration provides continuous force monitoring during bushing and pin insertion operations, with programmable force thresholds for quality control and immediate feedback to the principal controller for process optimization.

4. DEVELOPMENT AND IMPLEMENTATION OF THE DIGITAL INTERFACE

To enable comprehensive real-time control and monitoring of process parameters, equipment status, and actuator positions, a sophisticated user-friendly digital interface was developed following human-centered design principles. The interface development process began with an extensive requirements analysis involving CNC technicians, process engineers, and maintenance personnel to identify critical operational needs and usability constraints. The primary objectives were to create an intuitive visualization platform that allows operators to monitor system performance, adjust process

parameters dynamically, verify equipment status in real-time, and optimize intervention times through predictive analytics and alarm management systems.

The interface design adhered to Industry 4.0 and emerging Industry 5.0 paradigms, emphasizing seamless human-machine collaboration while maintaining the technological sophistication required for advanced manufacturing operations.

The interface design process incorporated extensive ergonomic analysis and user experience optimization to minimize operator fatigue. Color coding schemes were implemented based on industrial standards (green for normal operation, yellow for warnings, red for alarms) with additional visual indicators such as progressive bars, trend graphs, and status icons to provide immediate system status comprehension. Typography was carefully selected for optimal readability under various lighting conditions typical in manufacturing environments, while button sizes and touch targets were dimensioned according to industrial touchscreen interaction guidelines.

Navigation architecture follows a hierarchical structure with quick access shortcuts to critical functions, allowing operators to drill down from system overview to detailed component diagnostics within minimal interaction steps. Context-sensitive help systems and tooltips provide on-demand assistance without interrupting workflow continuity. The interface supports multiple user authorization levels, ensuring that critical system parameters can only be modified by qualified personnel while providing read-only access to monitoring functions for broader operational teams.

Control functionality encompasses both manual override capabilities for troubleshooting scenarios and automated sequence management for normal production operations. Operators can initiate emergency stops, modify process parameters within predefined safety limits, and coordinate complex multi-equipment operations through intuitive graphical interfaces. The system incorporates interlocking mechanisms that prevent unsafe operational combinations and provides clear feedback regarding the consequences of parameter adjustments before implementation.

To enable real-time control and monitoring of process parameters, equipment status, and actuator positions, a user-friendly digital interface was developed.

Thus, for the adjustment and operation of the two CNC machining centers, an auxiliary subcomponent feeding system, a KUKA industrial robot, a multifunctional gripper for inserting subcomponents (attached to the industrial robot), hydraulic clamping devices mounted on each CNC machine, and an external hydraulic pump — all presented in Chapter 2 — a dedicated interface was designed and developed. This interface enables the user to monitor and improve the manufacturing process. Below are several interfaces created to illustrate their purposes—monitoring, control, and adjustments—common in manufacturing processes like this one. Therefore, Figures 11, 12, 13, 14 and 15 present digital visualization interfaces displaying all the actual values of the parameters that characterize each element of the cell.

A specific feature of this manufacturing cell is the subcomponent assembly operations performed between two CNC machining operations, using an industrial robot. In Figure 11, the operating statuses of the two machining centers (in this case) within the manufacturing cell (Zone 1) are shown.

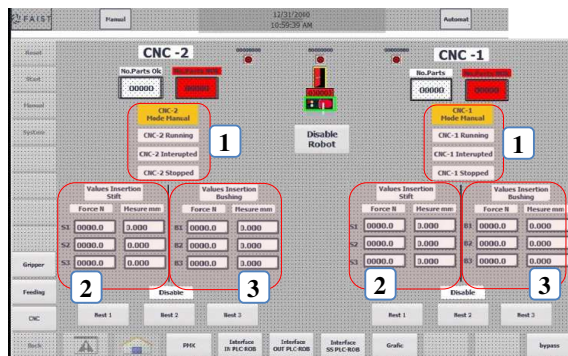


Fig. 11. Digital interface. CNC parameters, bushing and pin insertion parameters

The same digital interface also displays the real values from the assembly process — such as insertion force and stroke — for the pins (Zone 2) and bushings (Zone 3), as well as other information regarding the current stage of the manufacturing process.

In Figure 12, the position parameters of the pneumatic cylinders from the subcomponent feeding system (1) and from the multifunctional device for inserting bushings and pins (2) are shown. Additionally, the functional parameters of the inspection/control chamber (3) within the feeding system are also displayed.

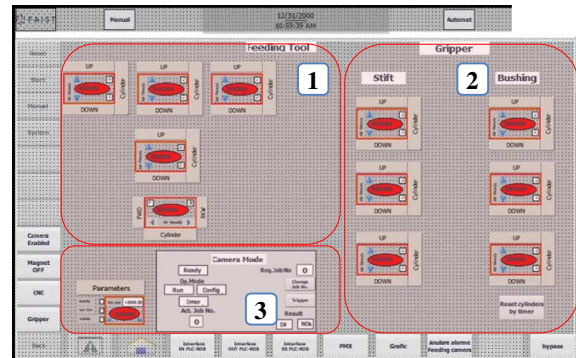


Fig. 12. Digital interface. Position parameters for the pneumatic cylinders in the feeding station (1), in the multifunctional device (2), and functional parameters of the inspection/control camera (3) in the feeding system

The designed and implemented interface shown in Figure 13 corresponds to the successful confirmation and completion of the assembly/insertion sequence of the bushings (1) and pins (2) in the manufacturing process. Additionally, this interface allows the air blowing system (3) to be activated or deactivated to remove impurities before the process.

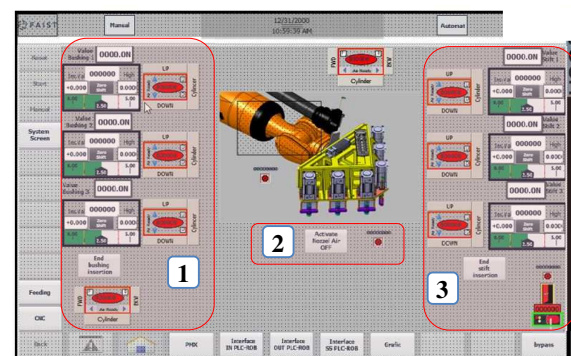


Fig. 13. Digital interface for visualizing the bushing and pin insertion process

The opening and closing systems of the CNC machining center doors, which allow access for both the industrial robot and the human operator, are actuated by pneumatic cylinders. The control and visualization interface for these systems is

shown in Figure 14. In area (1), the settings for the door accessed by the industrial robot are displayed, while in area (2), the settings for the door accessed by the human operator are shown. Area (3) allows the user to select the operating mode of the systems (manual/automatic).

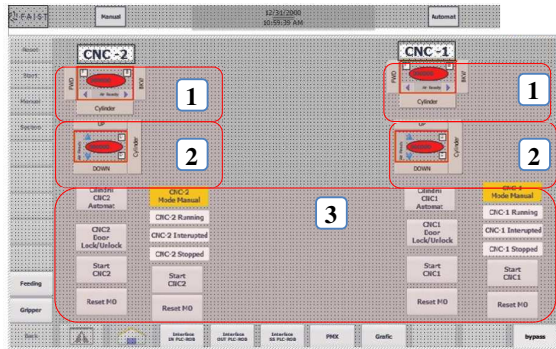


Fig. 14. Digital interface for visualizing access door systems to the machining centers

The interface shown in Figure 15 allows for the adjustment of the mounting positions of bushings and pins relative to the hole positions in the parts clamped on the hydraulic fixture located on the machining center table. Area (1) displays the mounting position corrections for the pins, while area (2) shows the corrections for the bushings.

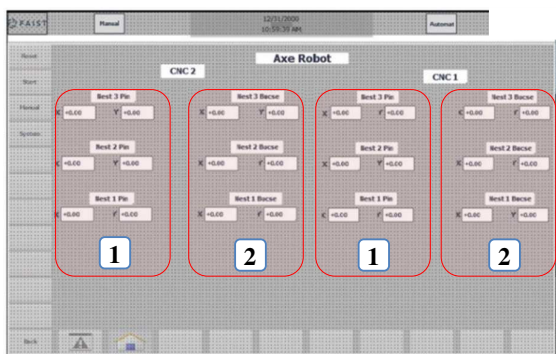


Fig. 15. Robot Axis page interface for making assembly position corrections of the inserts

The developed digital interfaces demonstrate successful integration of advanced human-machine interaction principles within the Industry 4.0 framework, delivering measurable improvements in operational efficiency through comprehensive real-time monitoring and intelligent control capabilities. The modular interface architecture not only facilitates seamless integration of all manufacturing cell

components—including CNC machining centers, robotic systems, and auxiliary equipment—but also enables precise parameter adjustments and intuitive visualization of complex production workflows. This approach to digital interface development significantly enhances decision-making capabilities while reducing lost time and minimizing the potential for human error.

5. INTEGRATION AND COMMUNICATION BETWEEN SYSTEMS

Integration and communication between the manufacturing cell systems was achieved by transferring the program to the KUKA controller and mapping the robot signals to the cell PLC using the WorkVisual 5 environment, ensuring correct and efficient integration of the automated systems, ensuring proper and efficient integration of the automated systems.

Topology (configuration) represents a method of connecting all elements of the manufacturing cell. The type of topology determines the cost, security, performance, and reliability of the workstations, for which access time to the file server is an important factor. The cell topology (Figure 16) highlights a centralized architecture, combining hardware and control logic for process optimization.

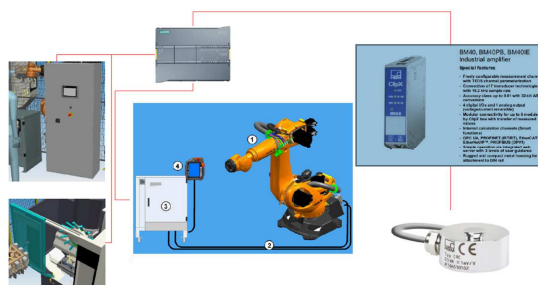


Fig. 16. Topology of the industrial robot within the manufacturing cell

The topology of the manufacturing cell shown in Figure 16 reflects a centralized integrated architecture typical of modern industrial automation systems. It is composed of a programmable logic controller (PLC), an industrial robotic arm, a load cell connected to a precision amplifier (model BM40), and a control panel for the human-machine interface. The

industrial amplifier plays an essential role in the measurement chain, providing conversion and amplification of analog signals from the force sensor, as well as configuration facilities and data transmission via RS232 interface. The signal flow is routed from the sensor to the amplifier and then to the PLC, which processes the information and coordinates the actions of the robotic arm. This structure allows fast on-site setup, precise process control and high integration capability in industrial environments with stringent reliability and accuracy requirements. The topology therefore highlights a functional synergy between hardware components and control logic, contributing to the optimization of automated manufacturing processes.

For controlling the industrial robot within the manufacturing cell, a KUKA controller running KSS (KUKA System Software) version 8.5 was used. The robot sequencing was programmed using *Process Simulate* software from the Siemens Tecnomatix suite, which allowed virtual simulation and validation of the workflow before physical implementation. Subsequently, the program transfer to the physical KUKA controller and the communication mapping between the robot and the Siemens PLC were carried out using the WorkVisual 5.0 development environment, Figure 17. Figure 4 presents the subroutines necessary for the operation of the manufacturing cell.

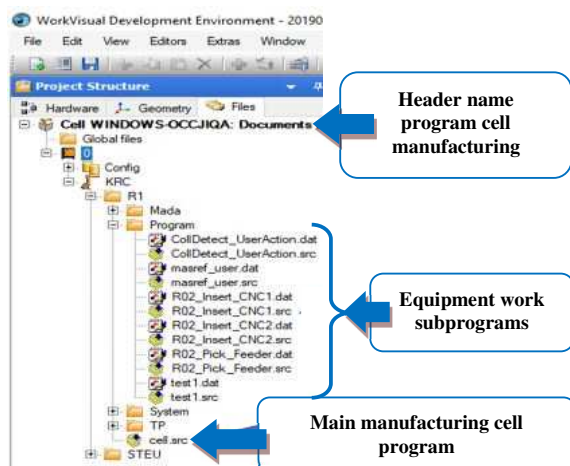


Fig. 17. The operating structure of the manufacturing cell in the *Workvisual 5* program

The effective implementation of the Digital Twin concept within the robotic manufacturing

cell is enabled through a comprehensive Industrial IoT infrastructure that provides the foundational connectivity layer for seamless integration of all system components. This IoT ecosystem establishes standardized communication protocols across heterogeneous equipment platforms, ensures real-time data synchronization between physical and virtual environments, and creates a unified information architecture that supports advanced manufacturing analytics. The distributed IoT framework enables autonomous data collection, intelligent edge processing, and predictive maintenance capabilities while maintaining robust cybersecurity protocols essential for industrial environments.

Thanks to the use of specific software modules, user interaction is intuitive and adaptable. To detect abnormal behavior not only at the level of measured variables but also at the robotic operation level, an independent feedback system is essential. This system is integrated into the designed and implemented control program of the manufacturing cell.

In the context of this implementation, the validation process has been carried out as a result of the improvement of the manufacturing process starting from the classical version, these are presented, analyzed and compared in my PhD thesis [12]. The manufacturing company and the final customer wanted a digitized structure to allow real-time tracking and supervision of the system, thus we do not have comparative data with an initial stage similar to the manufacturing cell.

The measurable impact of integrating systems into the manufacturing cell is supported by observations and data collected during operations. Reduced response time in the control process and real-time synchronization between the robot and PLC have led to workflow optimization and increased process efficiency. Although extensive quantitative analyses are not available at this stage, ongoing monitoring of key parameters establishes a solid foundation for comprehensive evaluation. Detailed results and in-depth assessments of these benefits will be presented in my forthcoming scientific paper.

Regarding synchronization of physical and virtual environments, the current implementation

has not experienced major difficulties. In terms of limitations, dependency on network reliability is a key factor. In order to prevent data loss in case of communication failure, the cell is equipped with an internal system for recording and storing process data, ensuring continuous monitoring. In terms of security, data is managed through robust protocols with strictly controlled external access to maintain confidentiality and reduce cyber risks.

Implementation costs and complexity have been evaluated in a cost-benefit context and are included in the price of parts and services delivered to the customer. The implemented automatizations allow quick reactions to possible malfunctions, helping to maintain optimal performance. At the same time, the integration of new equipment can create some scalability challenges, which requires long-term adaptive technical solutions.

6. RESULTS

The automated operation of the robotic manufacturing cell required a preliminary phase of modeling and simulation. A complete 3D model of the cell, including all components, was created using Creo Parametric software and then transferred to Process Simulate. This software enabled integration of the cell's components via a virtual controller and facilitated offline programming by simulating the sequences performed by the robot and other devices. As a result, the control and command program for the robotic manufacturing cell was developed and successfully validated through testing on the physical system.

Monitoring of essential process parameters is performed in real time via a digital control panel, which displays CNC parameters, the status of bushing and pin insertion processes, pneumatic cylinder positions, and robot axis status. This intuitive interface enables rapid intervention and reduces operational errors.

A dedicated system for measuring insertion forces of bushings and pins was implemented, ensuring high-quality control and consistency in automated assembly. Additionally, the close integration of CNC, robotic, and pneumatic systems into a unified control platform enabled precise synchronization of operations, thus

streamlining the technological flow and significantly reducing non-productive times.

The measurable impact of system integration is clearly reflected by observed reductions in response times and downtime during process execution.

The command-and-control software of the robotic manufacturing cell has been successfully validated through a series of tests carried out directly in the physical environment of the cell, demonstrating its functionality and robustness under real operating conditions.

The monitoring of process parameters in the cell is efficiently performed through the digital control panel, which provides real-time access to key variables such as CNC parameters, bushing and pin insertion process parameters, pneumatic cylinder positions in the feed station and the multi-functional device, as well as a detailed view of the bushing and pin insertion system and robot axis positions. This capability allows operators, technicians, or engineers to accurately monitor the process, intervene promptly in case of deviations, and continuously optimize the performance of the automated cell.

7. CONCLUSIONS

The study demonstrated that the comprehensive 3D modeling of the robotic cell and its integration into the Process Simulate environment significantly facilitates offline robotic programming, reducing risks associated with direct implementation and optimizing robotic paths.

The development of an intuitive digital interface enhances real-time monitoring capabilities for critical technological parameters, increasing the ability for quick corrective actions and minimizing operational errors. The insertion force measurement system contributes to maintaining quality control and repeatability in automation.

Tightly integrated CNC, robotic, and pneumatic systems allow for precise operation synchronization, improving workflow fluidity and reducing idle times. This confirms the crucial role of Digital Twin technology as an enabler of smart factories, supporting the transition towards Industry 5.0 by fostering an

efficient collaborative environment between human operators and automation systems.

Although the current implementation has not encountered major challenges in synchronizing physical and virtual environments, future expansions and equipment updates will require continued validation and proactive management of communication protocols and system scalability.

The implementation validates the critical role of user-centric design in digital manufacturing systems, demonstrating that sophisticated technological capabilities must be balanced with intuitive usability to achieve optimal operational performance and sustainable competitive advantage in modern automated manufacturing environments.

Finally, the work opens perspectives for further industrial innovation aligned with emerging paradigms of Industry 5.0 and beyond, addressing future demands for highly customized, intelligent manufacturing systems that integrate human and automated capabilities seamlessly.

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Implementarea conceptului Digital Twins în cazul unei celule robotizate de prelucrări mecanice

În contextul evoluției continue către modelul Industrie 4.0, conceptul de Digital Twin se conturează ca un element central al transformării digitale în mediul industrial, oferind un cadru integrat pentru interconectarea proceselor fizice și virtuale. Lucrarea științifică prezintă modul în care a fost implementat conceptul de Digital Twin într-o companie din Oradea, România. Studiul de caz s-a referit la o celulă de fabricație robotizată destinată operațiilor de prelucrare mecanică. Proiectul a implicat integrarea componentelor fizice și virtuale (modelul digital) pentru a permite monitorizarea în timp real, achiziția de date și optimizarea procesului. Celula robotizată include procese de manipulare, prelucrare CNC, asamblare de subcomponente, toate fiind descrise/realizate digital printr-un model virtual 3D conectat la echipamentele fizice prin soluții industriale IoT. Monitorizarea proceselor din cadrul celulei este facilitată prin intermediul unei interfețe dedicate care oferă informații în timp real. Rezultatele confirmă că adoptarea unui cadru Digital Twin în celulele de prelucrare contribuie semnificativ la avansul producției inteligente și la integrarea principiilor Industriei 4.0.

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