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DOCTORAL THESIS ABSTRACT

APPLICABILITY OF VIRTUAL COMMISSIONING CONCEPTS FOR INDUSTRIAL ROBOTS AS A SOLUTION TO COMPATIBILITY ISSUES BETWEEN VIRTUAL SIMULATION AND CONTROL LOGIC SOFTWARE

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- 2026 -

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Part I. STATE OF ART IN THE FIELD OF VIRTUAL COMMISSIONING

Chapter 1. CURRENT STATE OF THE RESEARCH IN THE FIELD OF VIRTUAL COMMISSIONING - Summary

1.1 Literature review - Summary

A critical analysis of the scientific literature on Virtual Commissioning of industrial robots has been conducted, focusing on key aspects that influence the efficiency and applicability of this emerging technology. Particularly, the issue of the diversity of programming languages used in the robotic industry is highlighted, as it creates significant barriers to the standardization of the control and the simulation processes. From this perspective, platforms such as SIEMENS Simatic Robot Integrator and ABB RobotStudio 10 are examined as advanced solutions for unifying the programming and the control environments, enabling the interoperability and the synchronization between simulation and control logic environments. At the same time, the limitations of the compatibility between these environments are emphasized, highlighting the need for new methods and architectures to allow a more efficient and flexible integration.

The first part of the Thesis aims to identify significant advances in the field of Virtual Commissioning (VC), as well as the actual gaps that justify the research in depth of this topic. Based on this analysis, the research presented in the Thesis seeks to develop new solutions for the Virtual Commissioning of the robotic cells, to optimize the interoperability between different software platforms and to create integrated methodologies for synchronizing virtual simulation with control logic for the industry.

The research stages of the Thesis are planned to ensure a systematic approach, starting with a preliminary analysis and a comparative study of the available platforms, continuing with the development and testing of the proposed solutions, and ending with an experimental validation of the proposed strategy and the dissemination of the results within the scientific community and industrial partners.

The current state-of-art study is based on more than 63 references, selected from over 135 read and analyzed.

1.2 Research targets

The objective of this doctoral Thesis is to investigate potential communication capabilities between ABB RobotStudio [A01] and Siemens Simatic Robot Integrator, and to unite the control systems for performing virtual commissioning (VC) tasks [A02]. The

proposed solution is intended to provide valuable and general procedures for any end-user responsible for implementing Virtual Commissioning tasks of robotic cells, while ensuring compatibility between ABB and Siemens [A03] hardware and software components integrated into any type of robotic cell. This Thesis will focus on the development of a hybrid software solution [A04], relying on the ABB RobotStudio suite, since even in its most recent version, RobotStudio 10 does not include a devoted module for Virtual Commissioning.

1.3 Doctoral Thesis objectives

From the synthesis presented in Part I of the doctoral Thesis, the main goals are:

- The foremost systems in which the robot will be analyzed and potentially integrated are assembly/mounting, pick-and-place, or palletizing applications.
- The targeted robotic cells for which the research studies will be conducted include manipulation, assembly/mounting, inspection, dimensional control, and machining with self-driven tools.
- SRI and TIA Portal are the main working environments in which interventions will be carried out to establish communication for the aim of performing VC.

Figure 1.1 illustrates the block diagram of the original methodology proposed in this doctoral Thesis, comprising the communication between the software platforms.

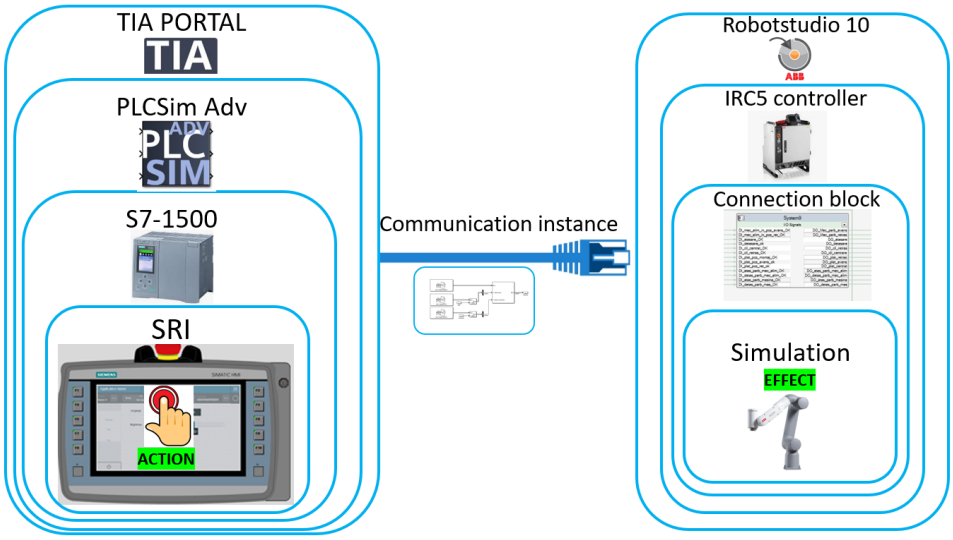


Fig. 1.1 Block diagram of the proposed methodology

Table 1.1 Major objectives

MAJOR OBJECTIVES OF THE DOCTORAL THESIS
MO1. Analysis and synthesis of the current state of the research for VC purposes
MO2. Establishing the key functionalities of the current software platforms which

will be employed in the Thesis

MO3. Identification of the gaps in actual research studies and unsolved issues in the field of Virtual Commissioning (VC)

MO4. Virtual concept of the control via a teach-pendant device for simulating robots in SRI through graphical model parameterization in the HMI screen interface
MO5. Establishing the communication and parameterization in Simatic Robot Integrator of the control code from TIA Portal with CAD models simulated in Siemens MCD

MO6. Testing and verification of the SRI integration with Virtual Commissioning environments that are not compatible with Siemens

MO7. Design and testing a connection bridge using external tools to enable additional communication between ABB RobotStudio and SRI

OM8. Conclusions and key observations

SPECIFIC OBJECTIVES OF THE DOCTORAL THESIS

Table 1.2 Specific objectives for MO1

MO1. Analysis and synthesis of the current state of the research for VC purposes
SO1.1 Research on the scope and on the importance of implementing Virtual Commissioning in production processes SO1.2 Synthesis of the current state of the research in the field of Virtual Commissioning SO1.3 Summary of recommended devoted Software for Virtual Commissioning

Table 1.3 Specific objectives for MO2

MO2. Establishing the key functionalities of the current software platforms which will be employed in the Thesis
SO2.1 Selection of the robot model for which Virtual Commissioning (VC) will be performed SO2.2 Establishing the Software Platforms in accordance with the specific objective OS1.3 SO2.3 Selection of the Software Platforms for which the communication for VC will be performed

Table 1.4 Specific objectives for MO3

MO3. Identification of the gaps in actual research studies and unsolved issues in the field of Virtual Commissioning (VC)
SO3.1 Selection of the main industrial publications addressing VC limitations SO3.2 Establishing the Methodology for applying the VC Concept

Table 1.5 Specific objectives for MO4

MO4. Virtual concept of the control via a teach-pendant device for simulating robots in SRI through graphical model parameterization in the HMI screen interface
SO4.1 Selection of the robot types available in Simatic Robot Integrator libraries SO4.2 Implementation of the HMI screens to replace the Physical Control Interface of Simatic Robot Integrator

Table 1.6 Specific objectives for MO5

MO5. Establishing the communication and parameterization in Simatic Robot Integrator of the control code from TIA Portal with CAD models simulated in Siemens MCD
SO5.1 Signals export from TIA Portal and import to MCD, indicating the limitations in the User Interface of the signal imports SO5.2 Establishing Handshake links between the signals retrieved from PLCSim Advanced and signals generated by MCD SO5.3 TIA Portal configuration and parameterization to ensure the compatibility with the OPC Server SO5.4 Design of a connection bridge using external tools to enable the communication between RobotStudio and Simatic Robot Integrator

Table 1.7 Specific Objectives for MO6

MO6. Testing and verification of the SRI integration with Virtual Commissioning environments that are not compatible with Siemens
OS 6.1 Verification and testing the integration between SRI with Factory IO

Table 1.8 Specific Objectives for MO7

MO7 - Design and testing a connection bridge using external tools to enable

additional communication between ABB RobotStudio and SRI
OS7.1 Testing a connection bridge using external tools to enable the communication between RobotStudio and Simatic Robot Integrator
OS7.2 Configuration and parameterization of ABB RobotStudio to ensure compatibility with the OPC Server
OS7.3 Parameterization and configuration of the input and output adapter blocks of RSconnect
OS7.4 Establishing the communication between TIA Portal and RobotStudio via the communication blocks in RobotStudio

1.4 Plan of the research stages

Generally, the research strategy aims to successively follow the main stages of the theoretical, methodological, simulation-implementation, and applied-experimental approach, as follows:

- Critical analysis of the scientific literature and of the recent results regarding Virtual Commissioning, with emphasizes on identifying the nowadays progress and the already proposed solutions for optimizing the VC process.
- Analysis of the definition and the evaluation of the essential parameters for the investigation on the applicability of Virtual Commissioning concepts in the context of industrial robotic cells.
- Development and implementation of a case study conceived to highlight the current limitations of Virtual Commissioning procedures and to outline the critical points when applying the actual methodology.
- Development of a virtual control model via the teach-pendant device, intended for robot simulation within the SRI environment, by parameterizing the graphical model and integrating it into an HMI interface.
- Establishing the communication and parameterization mechanisms within Simatic Robot Integrator, aiming the integration of the control code generated in TIA Portal with the CAD models simulated in Siemens Mechatronic Concept Designer (MCD).
- Testing and validation of the integration of SRI environment with other Virtual Commissioning platforms outside the Siemens ecosystem, to highlight the actual technical limitations.
- Design and experiments with an interconnection mechanism, using external software tools, to ensure additional communication between ABB RobotStudio and Simatic Robot Integrator.
- Formulation of the scientific and useful practical conclusions. Recommendations based on the experimental, theoretical, and methodological research, with emphasis on the proposed solutions for the improvement of the Virtual Commissioning process.

- Development of a mathematical model for converting SFC (Sequential Function Chart) programming structures into Ladder Diagram logic, aiming to enable standardization and optimization of the industrial robot programming processes.
- Exploration of Virtual Commissioning solutions for collaborative robots, including monitoring and traceability mechanisms based on Blockchain technology, aimed to ensure the process transparency and security.

The logic of the correlation between the research plan stages with the accomplishment of the major and specific objectives of the PhD Thesis is presented in Fig. 1.2.

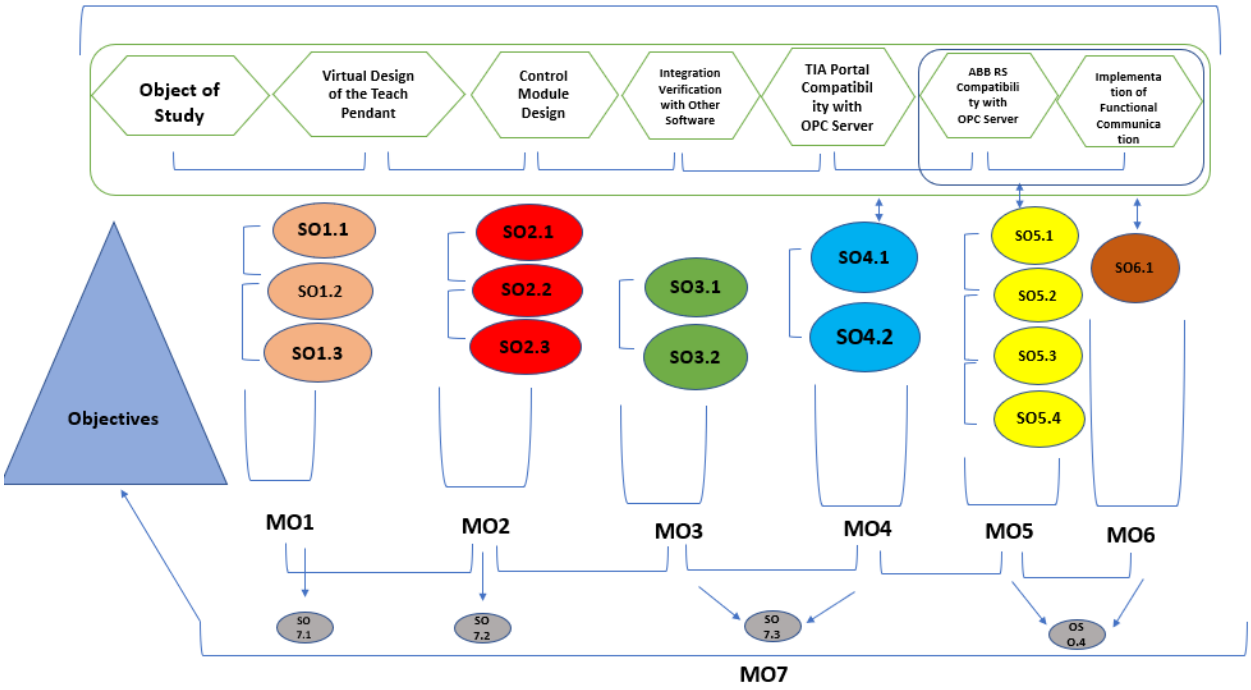


Fig. 1.2 Plan of the research stages and their connection to the major and specific objectives of the PhD Thesis

Chapter 2. TECHNICAL AND PROCEDURAL FUNDAMENTALS FOR THE IMPLEMENTATION OF VIRTUAL COMMISSIONING

2.1 Introduction. The importance of the research on Virtual Commissioning of robotic cells

This chapter provides an introductory framework for understanding Virtual Commissioning (VC) by presenting the evolution of the concept and its theoretical and technical fundamentals. It analyzes the development stages for automated industrial systems, with a focus on sequential control logic, ladder programming, and hardware/software integration in robotic cells. VC allows the control software to be tested on a virtual model before connecting to the real system, thus reducing the risks and the length of commissioning

stages, as well as an abrupt decrease of software errors, which determine nowadays up to 70% of the delays. The VC concept requires accurate digital models. The past challenges have been the model design and the integration of these models with PLCs. Four main commissioning strategies were identified: traditional, soft/HIL, reality-in-the-loop, and virtual. Although initially costly, VC has proved to reduce commissioning time by up to 75% [B20] and is now supported by advanced technologies such as Digital Twins.

The advantages of VC include parallel software testing, error prevention, an increase of operator safety, and reduced risk of machine damage. VC is carried out in three steps: digital modeling, running the software in simulation, and analyzing the results. Modern extensions include hybrid commissioning and automated methods for model generation from CAD data, and the integration of VC in the entire product development process.

2.2 Categories of hardware and software components employed for the master control of the robotic cells in Virtual Commissioning

In the industrial equipment design, understanding the interaction between system dynamics and control algorithms is essential, and rigorous testing is necessary for operational safety. Virtual commissioning (VC) using Digital Twins (DTs) allows for the reliable simulation of the interactions between subsystems (mechanical, hydraulic, electrical) and the assessment of the impact of the control code, reducing the risks to operators and equipments [B21]. Tools such as MapleSim, Tools such as MapleSim and Rockwell support the integration of digital twins, providing 3D visualization and real-time analysis.

The classification of industrial communications for VC includes traditional Fieldbus protocols, such as Profibus DP [B22] and DeviceNet, mainly employed for integrating legacy equipment. Industrial Ethernet protocols, such as Profinet, EtherCAT, EtherNet/IP, and POWERLINK [B23], are preferred for high performance and good integration with simulations. IT/OT integration is achieved through OPC UA [B24] and OPC UA over TSN [B25], ensuring the interoperability and deterministic communications. Wireless communications, including WirelessHART [B26], ISA100.11a, and industrial 5G/Wi-Fi 6 [B27], are increasingly used in distributed simulations and mobile applications. Middleware solutions such as FMI [B28] and ROS-Industrial [B29] also enable the integration of the simulation models with the real equipment, facilitating non-destructive testing and design optimization.

2.3 Main stages and methods used in industry for controlling robotic cells. Sequential control logic and Ladder programming

The PLC programming begins with the definition of the inputs, which can be digital (“0” or “1”) or analog (continuous values, e.g., 0–10 V DC), with the logic level “1” often corresponding to a supply voltage of 24 V DC or 12 V DC. Digital inputs are activated by sensors, switches, or signals from other PLCs in a master-slave architecture. The hardware

stage involves the connection of the process elements to the inputs/outputs, while the software stage involves writing and loading the program in the chosen programming language.

The IEC 61131-3 standard defines five main PLC languages: Ladder Diagram (LD), Function Block Diagram (FBD), Structured Text (ST), Instruction List (IL), and Sequential Function Chart (SFC). LD is inspired by electrical diagrams with relays, FBD provides an intuitive visual representation, ST is a textual and high-level language, IL is a low-level language, and SFC graphically describes sequential processes.

Sequential control logic uses the fundamental structures IF-ELSE, WHILE, and jump instructions, according to the classical studies of Böhm and Jacopini [B30]. Single-input, single-output structures are clearer for programmers. SFC, derived from GRAFCET and inspired by Petri nets, allows the modeling of the steps and transitions of a process, including loops, branches, or parallel sequences. SFC can be implemented in Ladder, and the IL, LD, ST, and FBD languages are considered equivalent to SFC for high-level sequences. The major advantage of SFC relies in the algorithm clarity and the ease of implementation in complex industrial applications, including parallel or branched processes.

2.4 Conclusions on the necessity of the research for Virtual Commissioning

Conclusions on Ladder Programming using Sequential Control Logic

- The PLC controller program may contain several state sequences. For example: control loop, HMI (human-machine interface), communication, etc. HMI can influence the execution of other sequences by controlling the stages of the process.
- The time-dependent dynamically controlled system and the PLC controller timers are treated similarly in the upper part of the SFC diagram and are controlled through state signals. Ladder diagrams can be easily translated into the other languages of the IEC 61131-3 standard, including Instruction List (IL). Programming in IL can be easily translated by other microprocessors. Therefore, the diagrams can be useful in the methodology and the design of embedded systems.
- The SFC programming method using the diagram language proves to be particularly suitable for sequential control in systems managed by small controllers. The clear graphical representation of the states and the transitions provides the visibility high level of the control algorithms, facilitating a good understanding of the logic by users of these controllers.

Conclusions on the factors under consideration when investigating the software and the hardware for the control of industrial robots used in Virtual Commissioning

- Establishing the PLC configuration and the associated software precedes the selection of key components to facilitate communication with a “slave” device within the

robotic cell; this approach essentially contributes to an efficient operation of the system.

- From the initial analysis of available software platforms, version 6.0.1 of RobotStudio was chosen, mostly for the improvements related to signals and communication compared to the previous release, the main arguments being the station logic export and the signal instance editing module.
- Correlated with the analysis of the software platforms, the IRC5 controller was selected as hardware component, its main advantage being the PC-based tools that optimize robot performance for short cycles and accurate movements.

From the aforementioned aspects and the information found in the scientific literature, the following conclusions can be drawn:

- Following the analysis of the advantages and disadvantages of existing Siemens products on a market shaped by the need for Virtual Commissioning of robotic cells, and estimating the number of signals (inputs/outputs) required for the intended application, a CPU S7-1200 processor will be used. The complete product code must be generated after establishing the exact list of signals, the peripheral equipment used, the selected communication method, and the implementation logic.
- To integrate PLC programming and HMI programming, as well as to efficiently communicate with the S7-1200 processor, Siemens TIA Portal programming and the data management interface will be employed in the PhD Thesis, with the version to be defined later following simulator testing, targeting the fastest possible response time.

Part II. CONTRIBUTIONS REGARDING THE APPLICABILITY OF VIRTUAL COMMISSIONING CONCEPTS

Chapter 3. METHODOLOGICAL CONTRIBUTIONS REGARDING THE APPLICABILITY OF VIRTUAL COMMISSIONING CONCEPTS TO A ROBOTIC CELL

In this chapter, the essential theoretical and methodological contributions for the implementation of the Virtual Commissioning (VC) concepts in a robotic cell are developed, according to the consecutive stages presented in Fig. 3.1. The selected case study, represented by the original virtual prototype of a robotic assembly and handling application, provides a concrete applied framework for the validation of the proposed methodologies and for the identification of the concept limits.

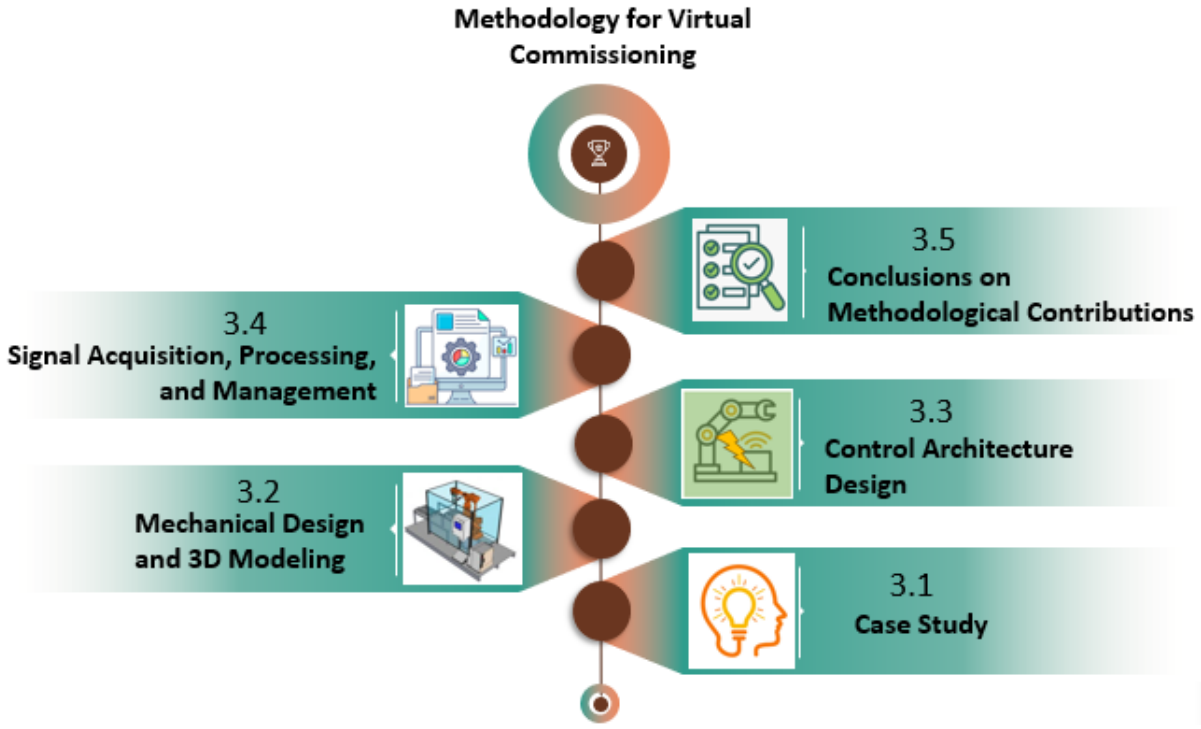


Fig. 3.1 Virtual Commissioning methodology

The following aspects are addressed in this chapter: the mechanical design and the 3D modeling of the robotic cell, as well as its components, to ensure a reliable and functional representation within the simulation environments. In parallel, specific methodologies are developed for the electrical design, including sensor integration, signal management, and the design of programming logic for the electrical and the electronic components, requisite elements for the system synchronized control.

The chapter ends with conclusions highlighting the methodological contributions achieved in the field of Virtual Commissioning (VC), emphasizing the impact of the methodological integration between the mechanical and electrical modeling, as well as the limitations of the communication between platforms, which are essential elements for implementing efficient solutions in the modern robotic industry. At the same time, the main elements necessary for applying Virtual Commissioning (VC) concepts to the offline-simulated robotic cell are highlighted.

3.1 Case study on the virtual prototype of an assembling and handling robotic application

In a robotic cell (Fig. 3.1) for assembling and handling, the system enables the manipulation and the joint of the parts using an industrial robot and peripheral equipment, including automatic feeding systems, sensors, assembling tools, control and safety systems. The actions involve the transportation of the objects along predefined trajectories and their

assembling, employing transport systems or stacks, positioning and centering stations, driving equipments (end-effectors, compressors, vacuum pumps), a robot with the controller and the electrical panel, programmable logic controller for synchronization, and sensors for monitoring the positions and states [C30]. There are two fundamental configurations: robotic assembling cell (independent unit with long cycle time and a large variety of components) and robotic assembling line (stations in series, short cycle, and limited number of components). Systems can be flexible (manual and robotic) or fixed (mechanized) [C31][C32].

The example addressed in the Thesis is a robotic cell for assembling wooden pallets that includes a robot with a double end-effector for automatic nail insertion and handling, a rotary table with two stencils for securing and loading the pallets, and a complete safety system with barriers, floor scanner, and an isolated controller. The stencils are adaptable for different pallet sizes, and the loading on the opposite side of the rotary table reduces the cycle time, increasing the safety and the production speed [C33].

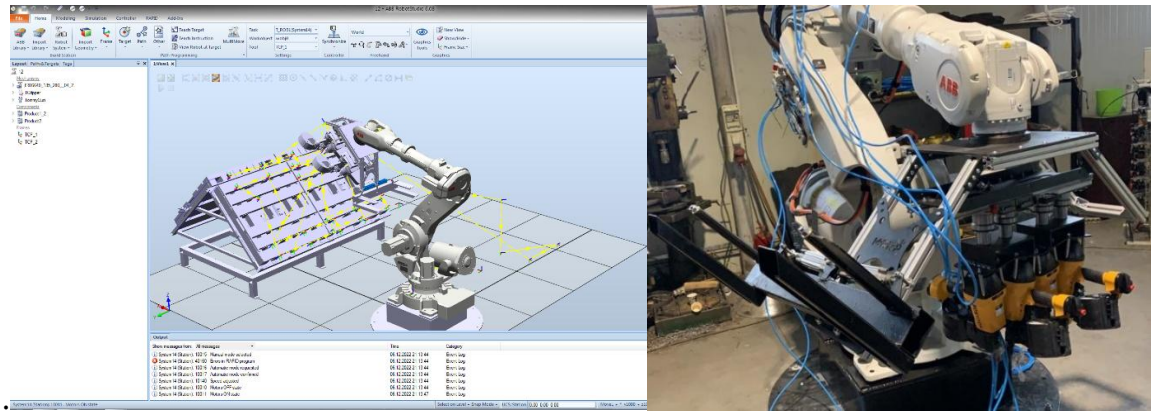


Fig. 3.1 Virtual and physical model

3.2 Methodology, mechanical design and 3D modeling of the robotic cell

The case study involved: a 3D synthesis, the parameterization, and full CAD configuration of a robotic cell using Catia V5 for mechanical design and ABB RobotStudio for programming and offline simulation. The main objective was to validate the functional performance of the robotic cell and to ensure the coherence between the virtual and the physical model. The application was configured by defining the kinematic and functional parameters required for carrying out the assembly and handling operations. Two TCP command points were established, one for the assembly process with automatic fastening nail guns and one for the pallet handling, allowing the trajectory testing, the movement optimization, and the collision risk reduction in the virtual environment. The end-effector was defined as a tool, establishing the center of gravity, the moments of inertia, and the TCP, ensuring trajectory validation and system functionality in simulation.

An important part of the delivered technical documentation is the mechanical design of the components, detailed through the conception of the 2D technical drawings, ensuring the correlation between the mechanical structure and the control strategies. The end-effector consists of a structural frame and subassemblies devoted to pallet assembly and handling, designed for the flexibility and the dimensional compensation of pallet variations.

3.3 Methodology for the development of the control architecture design of the robotic cell

After the mechanical design stage, the next step involves the selection of the sensors, signals, and programming logic for the electrical and electronic components of the robotic cell. This is one of the most important stages of the Virtual Commissioning (VC) methodology and the most critical regarding the implementation of virtual commissioning. All the equipments and subassemblies of the robotic cell must be prepared to operate safely, without the risk of damage or collisions. Within the virtual commissioning process, this stage is essential for the correct validation of interlocks, of the signal flow, and of the system response to start-up conditions.

The main objectives of the sequence are: verification of the preliminary conditions (status of the rotary table, absence of the alarms, emergency Stop signal); Initialization of subsystems (equipment power-up, variable reset, and the establishment of the robot's reference position); activation of the operative interface (validation of the start command and signaling the transition to the "Ready" state); confirmation of cell availability (sending the signal to the PLC and preparation for the next sequence).

The sequential Logic

At the logical level, the sequence can be described as follows:

- Step 0 - Stand-by: the cell is idle, waiting for the start command.
- Step 1 - Verification of the initial conditions: the sensors status are read (rotary table, alarms, the emergency Stop).
- Step 2 - Alarm reset and subsystem initialization: if the conditions are met, the system initiates the reset and the power-up sequence.
- Step 3 - Robot positioning to Home: the robot moves to the reference position, confirmed by the positioning signal.
- Step 4 - Availability confirmation: if all the conditions are confirmed, the "Ready for cycle" signal is activated.
- Transition: the system is prepared to move to the next operational sequence.

The programming sequences are: Commissioning, Pallet Assembly Sequence, Rotary Table Sequence, Pallet Unloading Sequence.

The Pallet Assembly Sequence (Fig. 3.2) is one of the most complex stages in the control of the robotic cell. Its role is to coordinate the industrial robot, the rotary table, and the

auxiliary equipment to carry out the assembly process, eliminating risks by prioritizing the alarms. This stage involves the continuous monitoring of the robot and the table states, movements validation, and the permanent verification of the errors absence as follows:

1. Management of the industrial robot movements, lift and place of the parts in sequence.
2. Coordination with the rotary table, locking/unlocking and repositioning according to the progress of the palletizing process.
3. Prioritizing the alarms, to immediately stopping the cycle in case of an error, and notifying the operator.

Steps and transitions:

P0 - Stand-by: the system waits for the "Start Pallet Assembly" command. Conditions: cell ready and no alarms → T0: upon receiving the start command and the confirmation of the alarms absence, it moves to P1.

P1 - Availability Check: the states of the robot and rotary table are read. Conditions: robot "Ready" and table fixed in the position → T1: if the robot and the table are available, it moves to P2, and so on.

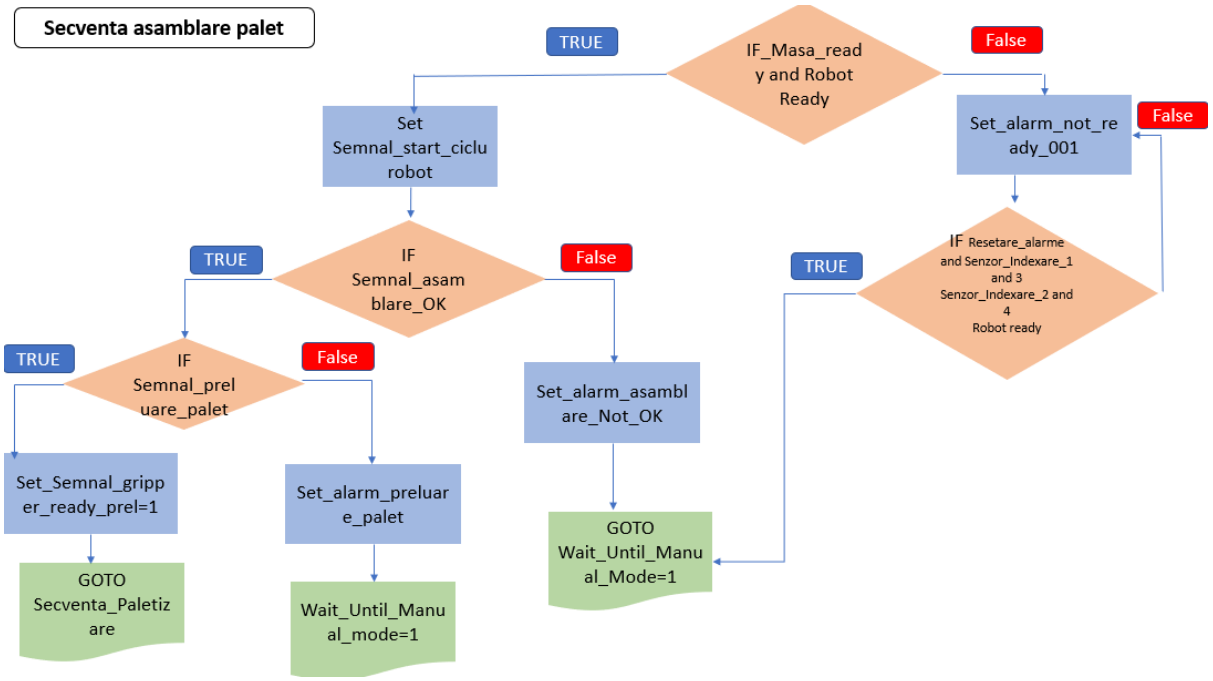


Fig. 3.2 Logical diagram for programming the pallet assembly sequence

Relevance of the Virtual Commissioning of the presented robotic cell

Virtual Commissioning plays an essential role in validating and optimizing the entire control cycle of the robotic cell:

1. **Verification of the sequential logic**: virtual commissioning allows testing all five sequences without affecting the real equipment, detecting the errors in the order, conditions, and transitions.

2. **Safety and interlocks**: to validate the correct system response, alarms, emergency stops, or collisions can be simulated before the physical commissioning.
3. **Equipment synchronization**: the robot, rotary table, end-effector, and conveyor can be tested simultaneously in realistic scenarios, ensuring that their interaction does not cause conflicts or blockages.
4. **Cycle time optimization**: virtual testing allows the adjustment of motion parameters, robot speed, and table rotation times to maximize the productivity.
5. **Flexibility in programming and modifications**: changes in palletizing patterns, sequence order, or unloading strategies can be simulated immediately, reducing time and costs for testing on real equipment.

Thus, Virtual Commissioning becomes a necessary tool for ensuring the safe, efficient, and predictable operation of the robotic cell before the operational launch.

In this research stage the design and implementation of the electrical and pneumatic diagrams, required for the control and the power supply of the robotic cell are presented (Fig. 3.3). The electrical equipment includes both the power supply and the electronic components, while protective and auxiliary devices contribute to ensuring the normal flow of the electrical energy [C34]. The electrical equipments are divided into high-current and low-current circuits, with high-current circuits representing power circuits (primary) and I/O control circuits.

The main power circuit is chosen for 400 V AC, 50 Hz three-phase voltage, according to IEC 60038, using NYY-J cables or equivalents, PVC/PUR insulated, compliant with HD 603 S1. The robot controller is powered through a dedicated circuit, protected by circuit breakers compliant with IEC 60947-2, and the grounding follows IEC 60364-5-54 norms. The electrical panel uses modular components mounted on 35 mm DIN rails, and the wirings follow EN 60947-7-1 standard. Multi-strand cables comply with UL 758 and IEC 60228, and the circuit protection is provided by modular fuses and circuit breakers according to EN 60898-1, as well as surge protection devices according to EN 61643-11.

The drive control is achieved via a 40 A three-pole circuit breaker and a power contactor, while the 24 V, 10 A power supply is protected by a 20 A two-pole circuit breaker. Safety systems include “light curtain” optical barriers (EN/IEC 61496-1), “mushroom button” emergency stops (EN ISO 13850), and safety relays compliant with EN ISO 13849-1 and IEC 62061, following redundancy and self-diagnosis principles to achieve PL d/e performance levels. The industrial PLC manages input/output signals and communicates with the robot via the DSQC digital handshake signal mode, essential for Virtual Commissioning [C34].

Pneumatic Drive Design

In most industrial systems the pneumatic drive is preferred as the main drive due to advantages such as: simple construction, robustness, reliability, productivity, low cost, and suitability for the use in explosive environments [C35].

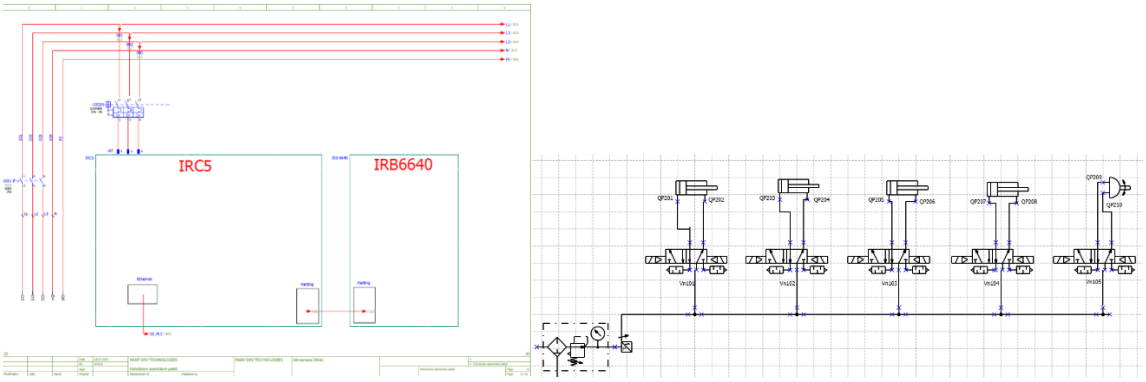


Fig. 3.3 Example of electrical and pneumatic circuit for controlling the cell

To actuate the cylinders in the robotic cell, the following devices ere employed: a main FRU group, digital pressure switch, secondary regulator, two 5/2 valves, four noise suppressors, four flow control throttles, and two guided cylinders.

3.4 Data acquisition, signal processing and management

The next stage in the methodology for applying Virtual Commissioning concepts is the acquisition, as well as signal processing and management. This stage begins with the hardware configuration and the setup of the device network required for programming in TIA Portal. For this subcategory, two elements are mandatory: the definition of the signal table (Fig. 3.4) and the selection of the processor configuration that allows VC functionalities.

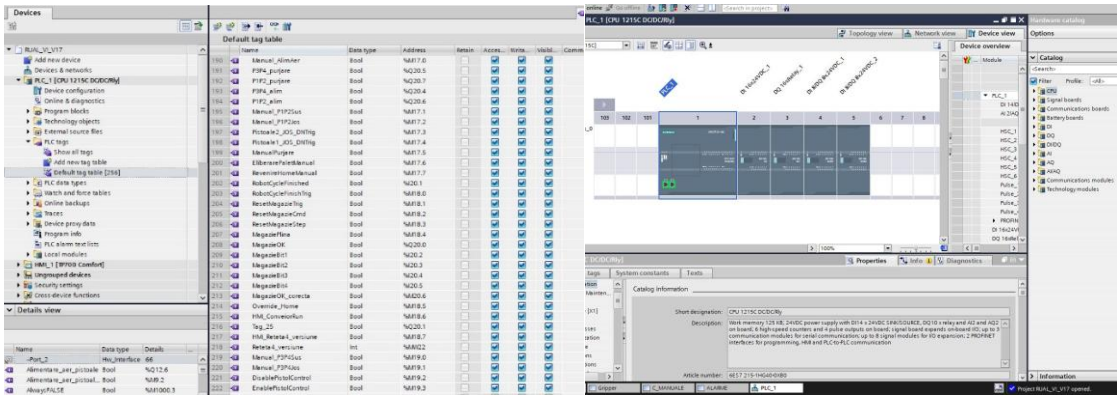


Fig. 3.4 Signal table and processor configuration

The flow of a digital signal from the position sensor that detects the cylinder locking highlights the full integration of the physical signals into the control cycle of the robotic cell. The initial signal, mechanically generated when the cylinder reaches the locking position is acquired (Fig. 3.5) by the PLC interface through the corresponding digital channels and converted into a logic bit usable in the control program.

The PLC code processes the signal according to the program logic, evaluating the predefined conditions such as the status of the robot or the rotary table. Based on this result, the program logic generates the necessary transitions to continue the automatic cycle or to trigger an alarm in the case of deviations.

The HMI code receives the signal status and updates the visual pointers of the ongoing sequence, providing real-time feedback to the operator. This information is also displayed on the physical HMI interface of the robotic cell, completing the path of the signal from the initial mechanical state to the visual and operational representation of the device. This flowchart is illustrated in Fig. 3.6 and emphasizes the importance of verifying each stage of the information flow, which is essential for Virtual Commissioning and for maintaining operational safety in robotic cells.

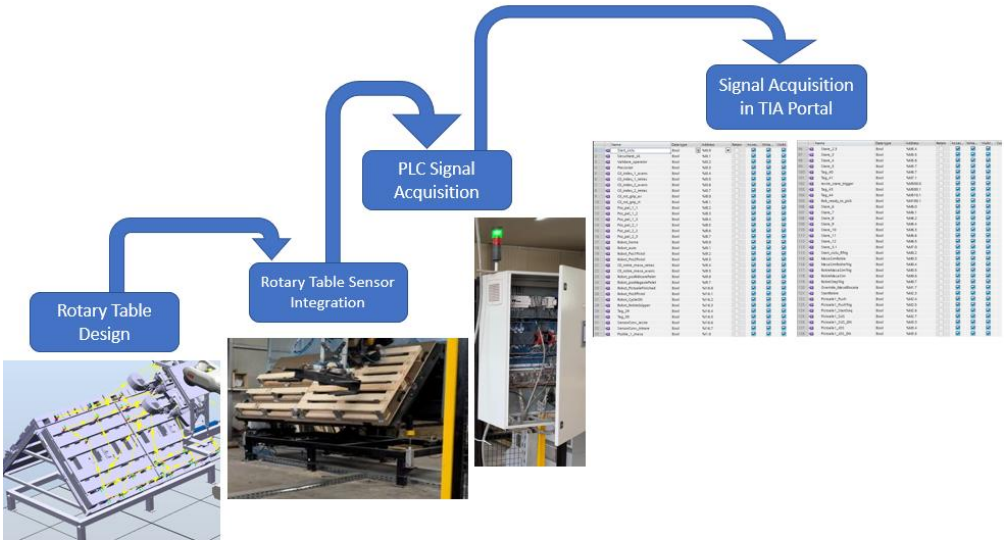


Fig. 3.5 Signal acquisition of the rotary table

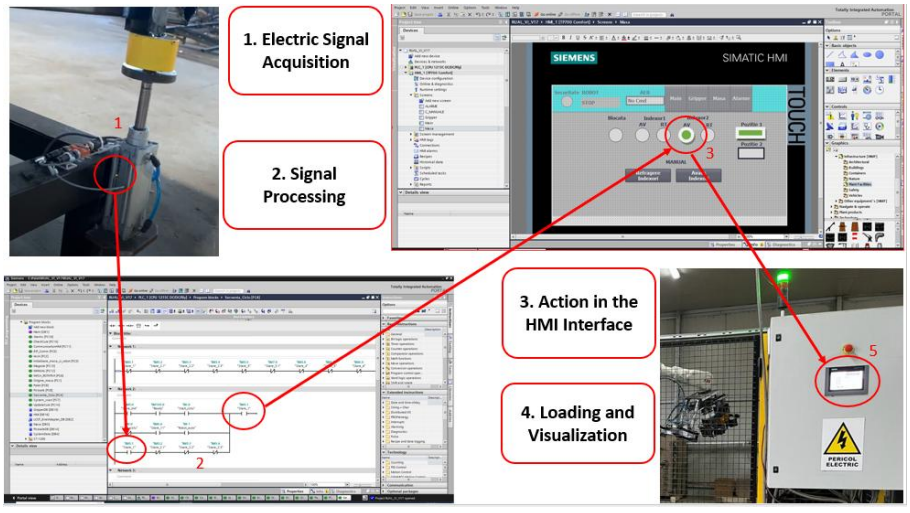


Fig. 3.6 Flowchart for data acquisition and signal processing & implementation for the rotary table

Relevance of the approach in the context of Virtual Commissioning

Virtual Commissioning allows the simulation of the entire signal path without the physical presence of the cylinder or the robotic cell, having the following advantages:

1. **Control logic validation**: Virtual Commissioning ensures that the signal is correctly acquired, processed, and transmitted across all PLC program sequences before the physical implementation.
2. **Testing interlocks and safety scenarios**: the signal can be simulated under normal or abnormal conditions, verifying the correct system response to alarms or blockages.
3. **HMI interface verification**: it is possible to evaluate how the HMI reflects the signal status, ensuring an accurate visual feedback for the operator.
4. **Reduction of the risks and testing time**: Virtual testing eliminates the risk of damage or collisions and shortens the time required for physical commissioning.
5. **System parameter optimization**: VC allows the adjustment of the signal flow, reaction times, and the transaction order so that the system operates efficiently and safely from the first physical start-up.

Thus, the complete analysis of the signal path in the virtual environment contributes to the increased safety, reliability, and predictability of the robotic cell, which are essential elements within Virtual Commissioning.

Following multiple attempts for the cell management using TIA Portal V14 and V15, the absence of the processors able to support Virtual Commissioning (VC) was noticed. Consequently, the virtual machine was parameterized and TIA Portal V16 software was installed.

Hardware configuration in the virtual environment

To perform the simulation, the CPU 1215C with a Profinet port and a serial port was selected. The chosen processor belongs to the Siemens 1200 family, which is suitable for such applications. The Ethernet communication was established using the Siemens communication protocol, namely Profinet, between the PLC processor, the HMI interface, and the robot. Regardless of the robot brand, a separate communication module is required to support the Profinet protocol.

Parameterization and creation of the operating logic

After the precise parameterization of all components of the robotic cell - including the robot, rotary table, robot end-effector, and conveyor - and after creating the local Level 1 logic for each of these components, the Level 2 control logic was developed. This includes priority cases for controlling the components of the robotic cell. The Level 2 operating logic (Fig. 3.7) was designed as a logical diagram and converted into Ladder code for the PLC according to the mathematical methodology.

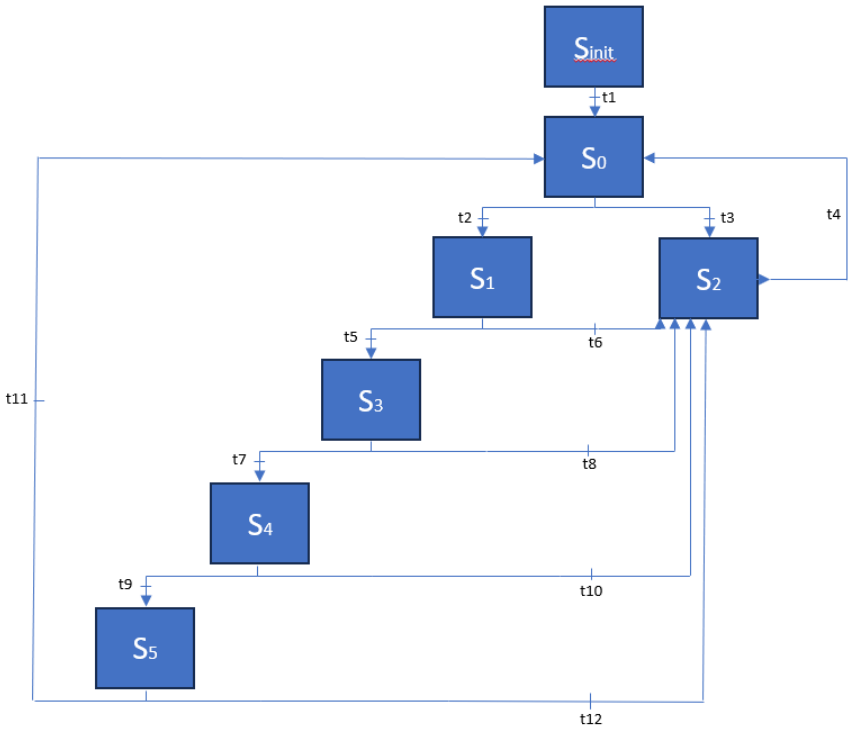


Fig. 3.7 Level 2 control logic

S_{init} represents the initial state of the system, which is defined by the following formula:

$$\sum \boldsymbol{s_{init}} = \overline{\boldsymbol{S0}} + \overline{\boldsymbol{S1}} + \overline{\boldsymbol{S2}} + \overline{\boldsymbol{S3}} + \overline{\boldsymbol{S4}} + \overline{\boldsymbol{S5}} \tag{3.1}$$

where: S_0, S_1, S_2, S_3, S_4 and S_5 are all the states of the control logic system. Additionally, for the scaling conversion „S^{-}" represents the closed contact, and „S" the open contact. The initial state is accessed at the first PLC start-up and requires that the system is not locked in any of the states.

$$\boldsymbol{s_0 = s_{init} t_1 + s_2 t_4 + s_5 t_{11} + s_0 \overline{s_1 s_2}} \tag{3.2}$$

S_0 is the state in which the status of all equipments such as the conveyor, the rotary table, and the status of the end-effector are checked.

S_1 is the state that commands the Home movement cycle, S_2 is the state that triggered the stop cycle, t_1 represents „Transition 1" which corresponds to the „ play button ", t_4 is a 300 ms timer, t_{11} is the transition triggered by the sensor for the presence of the conveyor. S_5 is the palletizing sequence of the pallets, and t_{11} is the transition of the signal for end_cycle_ok.

$$s_1 = s_0 t_2 + s_1 \overline{s_2 s_3} \tag{3.3}$$

where, t_2 is the local variable that confirms whether all system elements are ready, and s_3 is the control sequence for fastening the nail assembly.

$$s_2 = s_0 t_3 + s_1 t_6 + s_3 t_8 + s_4 t_{10} + s_5 t_{12} + s_2 \overline{s_0} \tag{3.4}$$

t_3 is the local variable for the non-functional equipment, t_6 is the local variable for the unprepared end-effector, t_8 is the local variable for non-functional assembly fastening nails, S_5 is the sequence for the pallet pick-up cycle, t_{10} is the local variable for the presence of a non-functional pick-up sensor, s_5 is the sequence for the pallet throwing and palletizing, t_{12} is the local variable for non-functional throwing and non-functional palletizing.

$$s_3 = s_1 t_5 + s_3 \bar{s_4} + s_3 \bar{s_2} \tag{3.5}$$

t_5 is the local variable for "effector ready.".

$$s_4 = s_3 t_7 + s_4 \bar{s_5} \bar{s_2} \tag{3.6}$$

t_7 is the local variable for "fastening nails OK."

$$s_5 = s_4 t_9 + s_5 \bar{s_0} \bar{s_2} \tag{3.7}$$

and t_9 is the local variable for "pick-up sensor OK.

3.5 Conclusions

During the progression of the methodological stages when performing the offline simulation and for the implementation of the robotic cell and applying the Virtual Commissioning strategy the following requirements were observed and completed. These were summarized as follows:

The main **methodological contributions** are:

- **The integration of software environments** into a unified control architecture. This demonstrates that Virtual Commissioning cannot be conceived independently of the TIA Portal platform, but requires a close correlation between the integrated modules, such as Simatic Robot Integrator, the control architecture, and the digital modeling processes. This dependency establishes a methodological approach based on the compatibility between the software tools from different suppliers.
- **Software and hardware compatibility constraints,** such as the requirement for lowest TIA Portal V16 versions or the use of specific modules like DSQC 652, create a methodological framework in which the preliminary validation of the digital configuration becomes a mandatory step. This ensures the continuity of the data flow and the full functionality of the digital twins in simulation and testing scenarios.
- **The virtual implementation** of physical controllers in HMI environment confirms that Virtual Commissioning is not limited to process replication, but involves a methodological transposition of the control logic into the equivalent virtual structures. From a theoretical perspective, this process represents a conceptual modeling of the control architecture, allowing the verification of the control algorithms in the absence of material constraints.
- **The mechanical design and the 3D modeling of the robotic cell** are in a direct methodological connection with the requirements of Virtual Commissioning. The kinematic

structure, the integration of the pneumatic actuators, and the geometric details must be defined in the design phase to ensure the compatibility with the simulation environment and the digital twins. From a theoretical perspective this highlights a shift in the design approach, where the mechanical parts become essential elements of the integrated methodology

- **Virtual Commissioning is not limited to a simple digital replica, but represents a coherent strategy for the design, validation, and optimization of the robotic systems.** It involves the integration of the automation software, the simulation environments, and the simulated controllers to verify the control logic and to assess the interactions before the physical implementation. Also from a theoretical perspective, this approach reinforces the concept of a cyber-physical network based on digital twins, reducing the gap between the conceptual design and the industrial deployment. Practical benefits (reduced launching time, increased reliability, and error anticipation) confirm the theoretical relevance of the methodology, endorsing Virtual Commissioning as a fundamental tool in the digital transformation of robotic industry.

Chapter 4. THEORETICAL CONTRIBUTIONS ON THE APPLICATION OF VIRTUAL COMMISSIONING CONCEPTS IN THE WORKING ENVIRONMENTS OF SIMATIC ROBOT INTEGRATOR - SIEMENS MCD AND SIMATIC ROBOT INTEGRATOR WITH EXTERNAL SIEMENS SIMULATION AND PROGRAMMING ENVIRONMENTS

4.1 Introduction

Chapter 4 presents the theoretical contributions on the integration and on the interoperability of the software environments in Virtual Commissioning, focusing on Siemens ecosystem. The research compares the communication between Simatic Robot Integrator (SRI) and Mechatronic Concept Designer (MCD), as well as the integration with external environments, such as ABB RobotStudio. Native connectivity between Siemens platforms is achieved through Click-to-Connect technology, allowing rapid signal synchronization and automatic interface parameterization. In contrast, the integration across different manufacturers requires manual signal mapping and the configuration of the data exchange logic. The chapter details the steps required for the signal configuration between TIA Portal and MCD, as well as the handshake communication mechanisms with the simulation environment. User interface limitations and the implementation of the teach-pendant type HMI screens for Simatic Robot Integrator are also addressed. In the end, the chapter highlights the efficiency of the integration within the Siemens ecosystem and the challenges of the interoperability with ABB platforms, providing insights into the extension of Virtual Commissioning in an industrial context.

Main Objectives

● Virtual design of the Teach-Pendant control for Simatic Robot Integrator (SRI) through the parameterization of the graphical model in the form of an HMI interface screen. This objective was necessary to be implemented to replace the hardware for testing.
● Establishing the communication and the parameterization in the SRI interface of the control code from TIA PORTAL, with the geometric models simulated in Siemens MCD.
● Verification and testing of the integration of Simatic Robot Integrator with Factory IO, a Virtual Commissioning (VC) environment different from Siemens MCD.

4.2 Virtual design and implementation of the Teach-Pendant control for Simatic Robot Integrator through the parameterization of the graphical model as a screen within the HMI interface

Simatic Robot Integrator (SRI) library enables robot control through the "Uniform Robot Data Interface to PLC" concept. The main block, RobotTask, is called cyclically and manages the communications and the internal control states, while the connection between the virtual robot and the interpreter is handled by the DataInterfaceDigitalTwin block [D40]. The PLC sends commands to the robot controller and receives feedback signals, with the communication implemented via the Profinet protocol. SRI library block functions allow the transmission of command messages. The corresponding robot interpreter must be installed on the controller to process the commands; interpreters are provided by accepted manufacturers within SRI library. The conversion of the commands and data transmission/reception (Fig. 4.1) is carried out employing a conversion module. The communication was implemented using hardware components from TIA Portal library, including PLC CPU 1516-3, HMI SRI-KTP900F Mobile, Comau X20F10E3-1 and Staubli CS9, all connected via an Ethernet network based on the Profinet protocol.

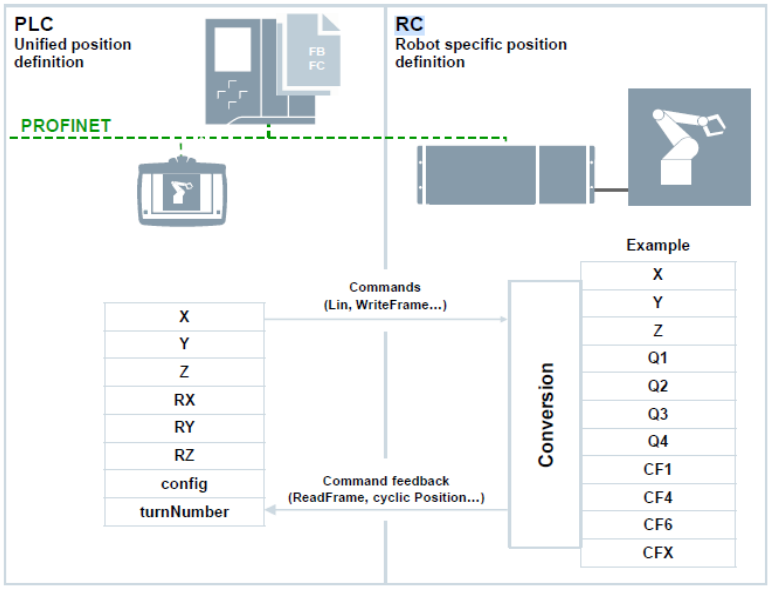


Fig. 4.1 Simplified diagram of the communication between the PLC and the robot controller

The implementation of HMI screens to replace the physical control interface of the Simatic Robot Integrator was carried out by importing the digital graphic model of a physical SRI control interface into HMI module and configuring it through logical links between the virtual buttons and the inputs and outputs of the function blocks. Siemens Simatic Robot Integrator (SRI) provides a library of industrial robot typologies for the integration into virtual production cells. The user can choose among three options: predefined robots with standard parameters provided by manufacturers such as Comau, Staubli, Universal Robots, or Kawasaki; generic architectures such as Cartesian, RollerPicker, DeltaPicker, SCARA, Articulated Arm, or Tripod, which require additional configuration; and User Defined for advanced users, allowing full definition of the robot's structure, parameters, and interfaces. This classification supports both standard scenarios and complex projects. SRI includes operational and monitoring screens (Fig. 4.2) such as Config_soft_end, JogFrame, Tool Overview, and Single_linear_movement, as well as auxiliary screens for Alarm and Diagnostics. The signals of the virtual teach-pendant are organized into three categories: Template (predefined), Tool Robotics SRI (linked to graphical commands), and Robotics_Int for coordination and positioning, ensuring complete and functional control of the virtual robot.



Fig. 4.2 The main screens, represented by the menus of interest

4.3 Establishing the communication

Address assignment. Parameterization of the control code from TIA Portal in Simatic Robot Integrator interface with the geometric models simulated in Siemens MCD

In the diagram illustrated in Fig. 4.3 the data exchange between TIA Portal working environment, via SRI, and Siemens NX through the internal simulation module can be observed. This is implemented through the communication between SIM Adv. PLC and MCD Signal Mapping.

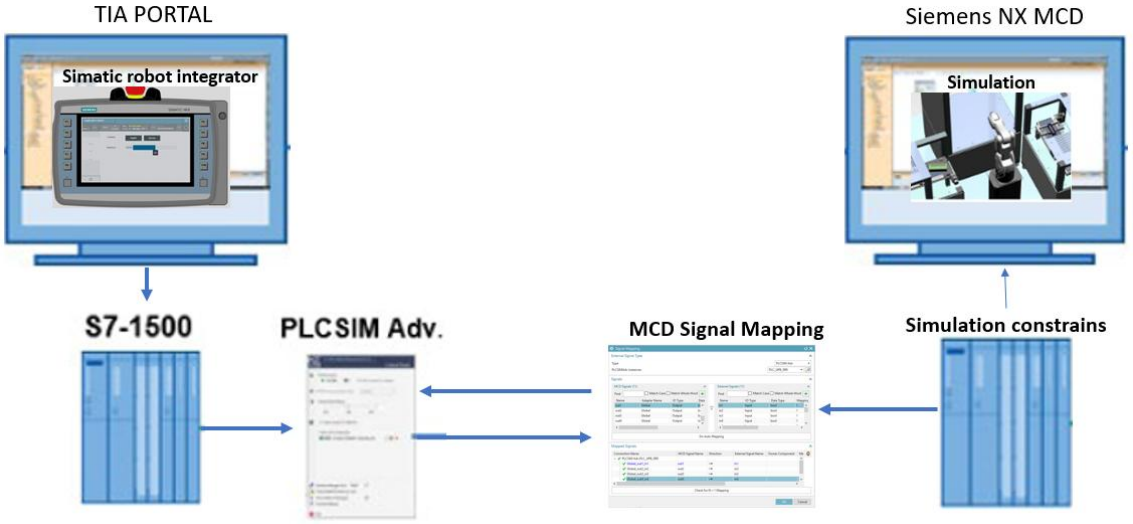
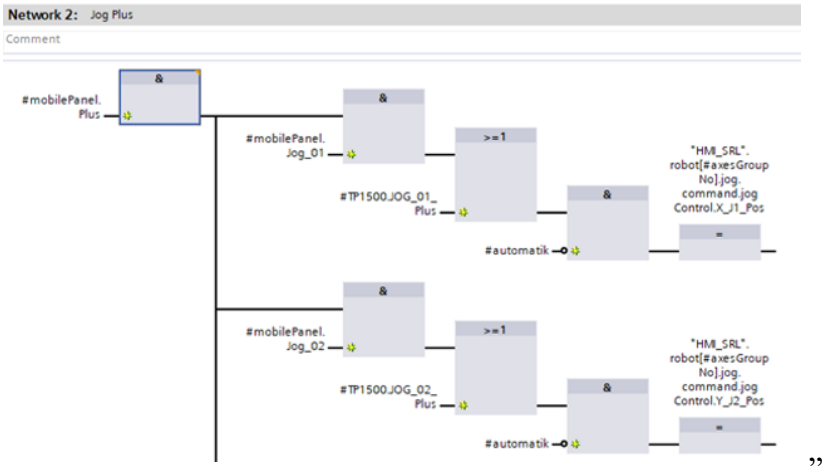


Fig. 4.3 Diagram of the information exchange

In Fig. 4.4, the programming method for the Jog_plus function is presented. At the top, the local variables of the decision block, such as “startEnableJog,” are allocated, while at the bottom, the FBD-type programming is displayed, where for each decision block, the bits generated by pressing the virtual buttons on the Jog screen are activated.



”

Fig. 4.4 Control of the Jog_plus function

In Fig. 4.5 the selection of the "Linear" mode for the robot movement can be seen (top left), while at the bottom right, the memory area activated by pressing the HMI button is illustrated, triggering the decision and the control functions for the movement mode selection.

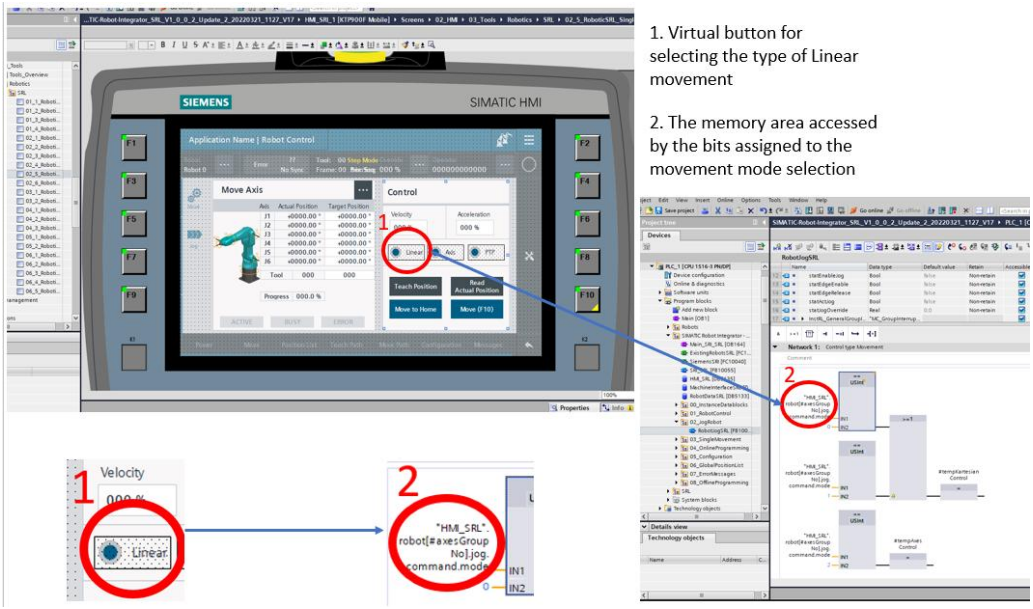


Fig. 4.5 Example of HMI Screen - Function Block Communication

4.4 Signals export from TIA Portal and import in MCD. Signal exchange limitations in the user interface

In Fig. 4.6 the pop-up box for successfully exporting signals from the Tag_table is highlighted, while on the right part of the screen the setup for importing the signals exported from TIA Portal is prepared. In the "File Type" box, only three signal types can be imported. The first option is "Simit," which allows the import of the signals exported from Simatic Simit framework [D41]. The second type, IL, corresponds to "Step 7," allowing the import of the signals exported from Step 7. The third type, also IL, represents the files exported from TIA Portal. All three file types belong to Siemens software, thus limiting the signal import from any other external programming environments at the user interface level.

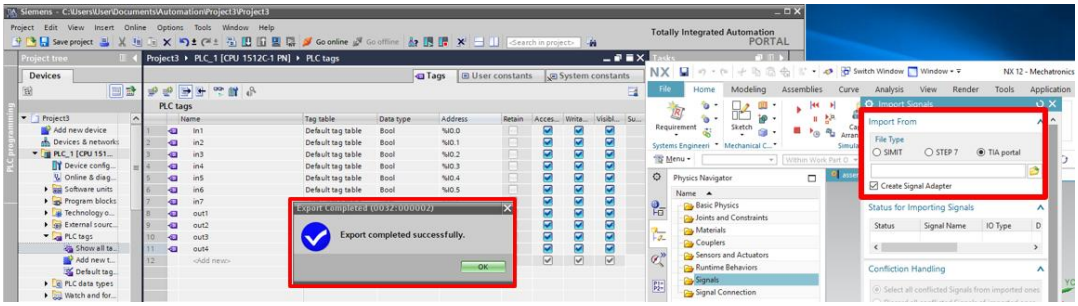


Fig. 4.6 Signal export from TIA Portal and import to MCD setup

4.5 Advanced Simulator configuration in TIA Portal and external signals in Siemens MCD. Establishing the Handshake Links between the signals acquired from PLCSIM Advanced and those generated by Siemens MCD

In Fig. 4.7 the indicator “1” is located in the Signal Mapping section, and has been set for “PLCSIM Adv file format.” Indicator “2” is in the “External Signal Configuration” section, proving that the instance “PLC_UPB” has been detected with status “RUN.” Indicator “3” represents “PLCSim Adv” displaying the instance name, status “RUN,” and the assigned IP address is 192.168.0.1.

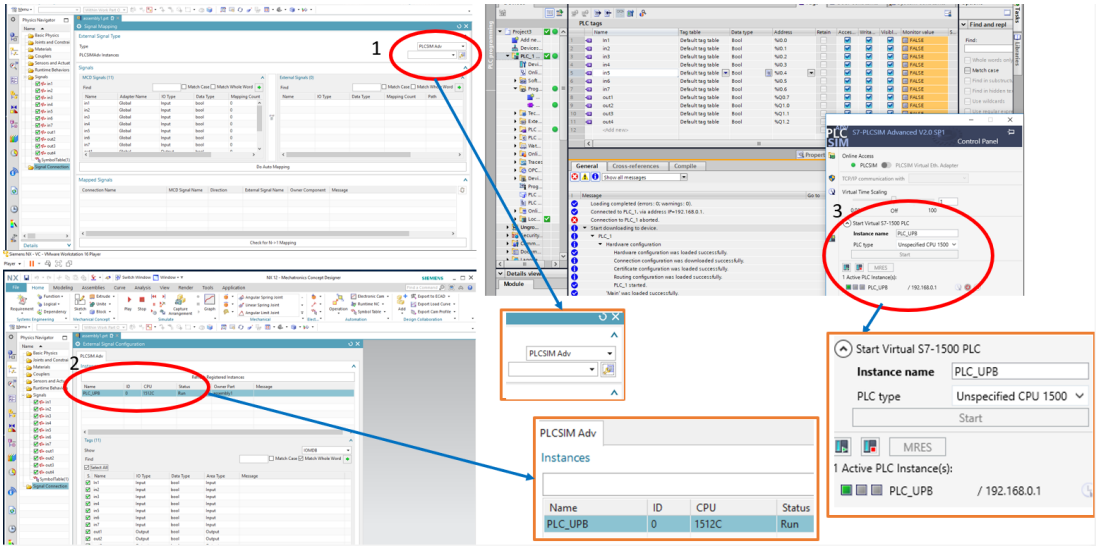


Fig. 4.7 Preparation of the communication between the working environments

In Fig. 4.8 the list of the links established between the digital outputs from MCD and the digital inputs from PLCSim Adv is highlighted. Once the links are created, they are automatically inserted into the global variable area within the MCD control. The list of the links between MCD digital outputs and PLCSim Adv digital inputs shows that, after creation, the links are automatically placed in the global variable section of MCD control. Box 1 contains the PLC labels (in1, in2). Box 2 indicates PLC status, which is online, using the IP address and the same instance name as in MCD. Box 3 represents the connected device, identified as “PLCSIM_Adv,” with the instance name “PLC_UPB_IRRI.” Box 4 defines the signal mapping between input and output signals.

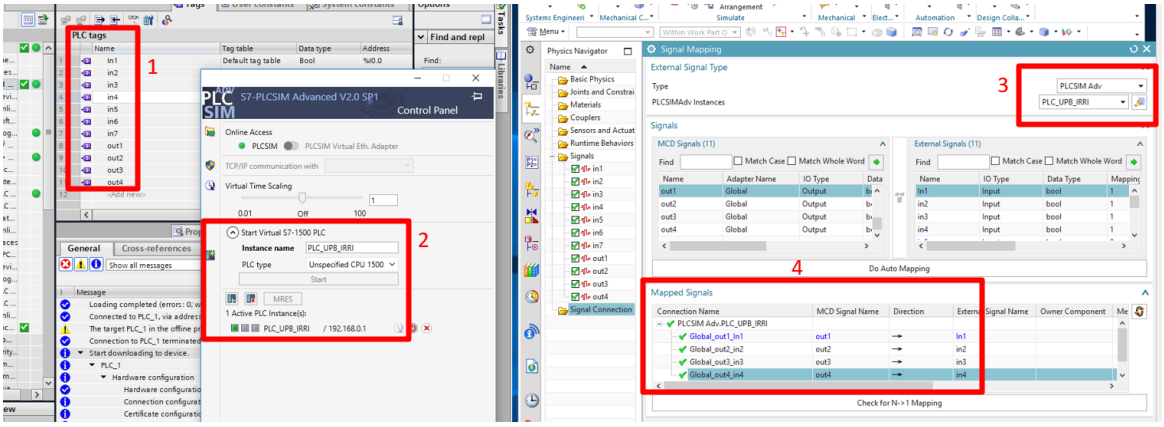


Fig. 4.8 Establishing Links Between Signals

4.6 Verification of the integration of Simatic Robot Integrator with alternative Virtual Commissioning environments

The graphic diagram illustrated in Fig. 4.9 represents a schematic representation of the integration, comprising the elements and the communication pathways, as well as the limitations that lead to incompatibilities. Factory IO is a software exclusively employed for testing PLC programming logic through Virtual Commissioning of various scenarios created by the user or selected from the scenario library.

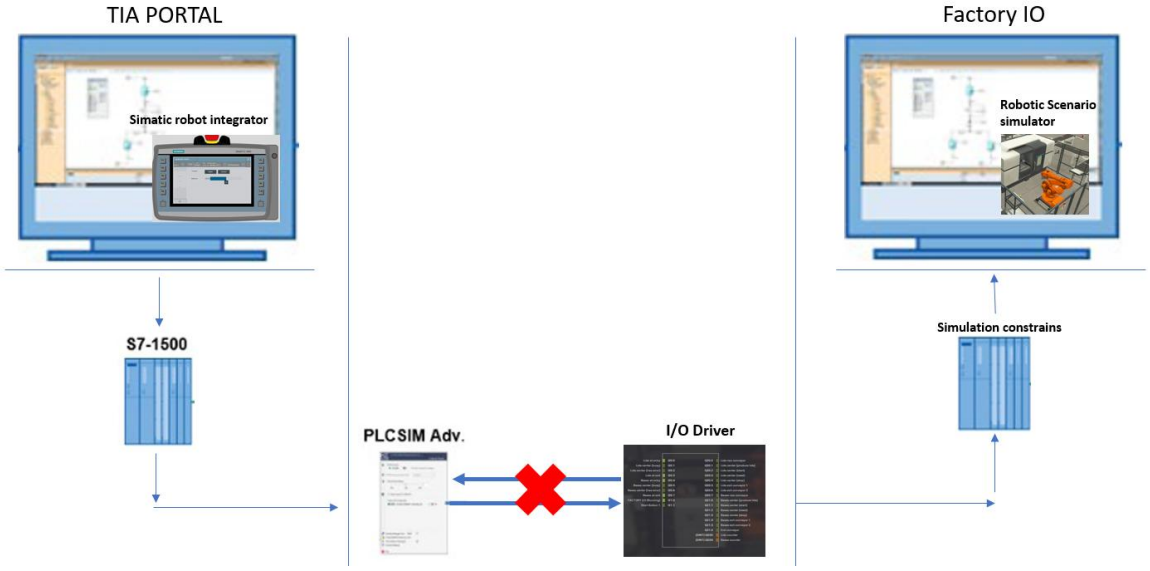


Fig. 4.9 Conceptual diagram for TIA Portal - Factory IO communication

After mapping the signals and establishing the communication, the following aspects regarding the limitations of the Factory IO user interface were observed:

1. Signals are automatically generated in the “Sensors and Actuators” interface when the sensors or the actuators are added to the scene.

2. Addresses can be assigned to each signal.
3. Factory IO is compatible with PLC simulators from various manufacturers (Schneider, Siemens, Allen Bradley, etc.).
4. For Siemens components, Factory IO can connect to physical processors from the S7-200/300/400/1200/1500 series and S7-PLCSIM [D42]. However, PLCSim Adv is not available in the drop-down list of the user interface.
5. Factory IO does not provide the ability to import signals. All the signals must be added manually, an action that is unreasonable for scenarios containing robotic cells, which can easily require hundreds of signals.

Factory IO is a Virtual Commissioning (VC) software that cannot map signals generated by movements of complex mechanical parts. CAD elements cannot be imported, and the work is limited to the built-in equipment and component library.

4.7 Conclusions

Conclusions and theoretical contributions

1. The analysis of the integrations performed confirms that Siemens ecosystem (Simatic Robot Integrator, Mechatronic Concept Designer, TIA Portal) provides native Click-to-Connect solutions, which simplify the signal exchange and reduce the manual configuration effort, but these benefits are available exclusively within Siemens environments.
2. Differences between industrial communication standards were highlighted through the interoperability testing with external platforms, such as ABB RobotStudio or Factory IO. These require additional configuration, manual signal mapping, and the development of dedicated handshake mechanisms.
3. The technical limitations of Factory IO (inability to import signals, lack of compatibility with PLCSim Advanced, limited equipment library) indicate that Virtual Commissioning solutions are not yet fully mature for complex industrial robotics scenarios, and the Factory IO platform does not provide the minimum necessary compatibility for the integration with Siemens.
4. The research contributes to the theoretical fundamentals of the Virtual Commissioning (VC) concept, demonstrating both the advantages of native platform integrations and the challenges in the interoperability between different manufacturers - insights that can guide future developments in the field.

Conclusions and practical contributions

1. A virtual Teach-pendant for SRI was designed and commissioned, implemented as an HMI screen, which can replace dedicated hardware during the testing and validation phase.

2. The integration between TIA Portal and Siemens MCD was confirmed using PLCSim Advanced 2.0, demonstrating the advantages of the integration between native manufacturer platforms.
3. Tests with Factory IO highlighted both its extended compatibility with physical PLCs and simulators from multiple manufacturers, as well as its limitations in complex robotic scenarios (e.g., manual signal mapping, inability to import CAD models).
4. The practical results reinforce the role of SRI as a rapid integration tool within Siemens ecosystem, while confirming that interoperability with non-Siemens platforms requires additional configuration and testing resources.
5. An original methodology was developed for the evaluation and the comparison of Virtual Commissioning solutions, validated through experimental tests between Factory IO and Siemens platforms. This led to the identification of the platform limitations and highlighted the advantages of the methodology.

Chapter 5. CONTRIBUTIONS REGARDING THE APPLICATION OF VIRTUAL COMMISSIONING CONCEPTS IN TIA PORTAL AND ABB ROBOTSTUDIO ENVIRONMENTS VIA OPC SERVER

5.1 Introduction

Chapter 5 presents the applied contributions regarding the functional interconnection between TIA Portal and ABB RobotStudio through an Open Platform Communications (OPC) server, demonstrating the feasibility of integrating the control and the simulation platforms from different manufacturers into a unified Virtual Commissioning system. The research focuses on the configuration and parameterization of TIA Portal for the compatibility with OPC server, the development of a bidirectional communication bridge, as well as the setup of the virtual controller in ABB RobotStudio. The stages of testing and monitoring the signals transmitted between the two environments are detailed, with attention paid to data fidelity, communication latency, and connection robustness. This approach validates a flexible integration model, also applicable to other industrial scenarios, proving the generality of the original methodology.

Figure 5.1 graphically presents the main stages and objectives achieved in Chapter 5:

- Configuration and parameterization of TIA Portal to establish compatibility with the OPC server;
- Configuration and parameterization of ABB RobotStudio to establish compatibility with the OPC server;
- Configuration, parameterization, and establishment of “handshake” communication between TIA Portal and ABB RobotStudio via the OPC server;
- Testing and monitoring of the signals transmitted from RobotStudio to TIA Portal.

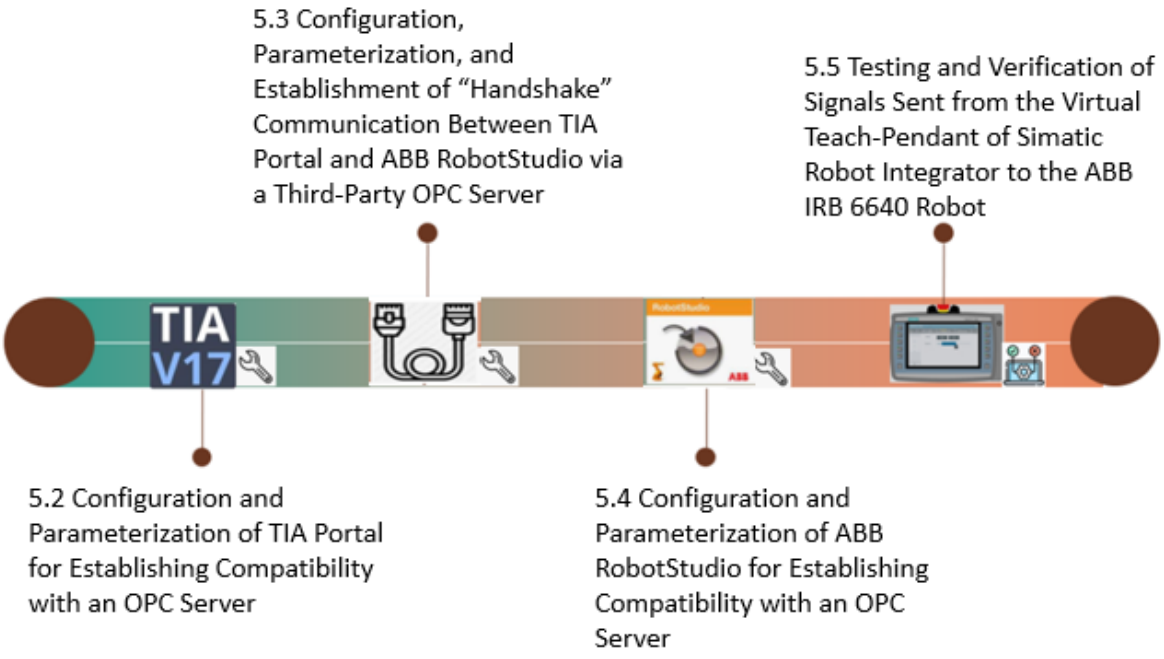


Fig. 5.1 Roadmap diagram of Chapter 5 objectives

5.2 Configuration and parameterization of TIA Portal to establish compatibility with the OPC server

Figure 5.2 graphically illustrates at a conceptual level the difference between the data exported from TIA Portal and that imported into ABB RobotStudio, including the necessary transformations to ensure data compatibility.

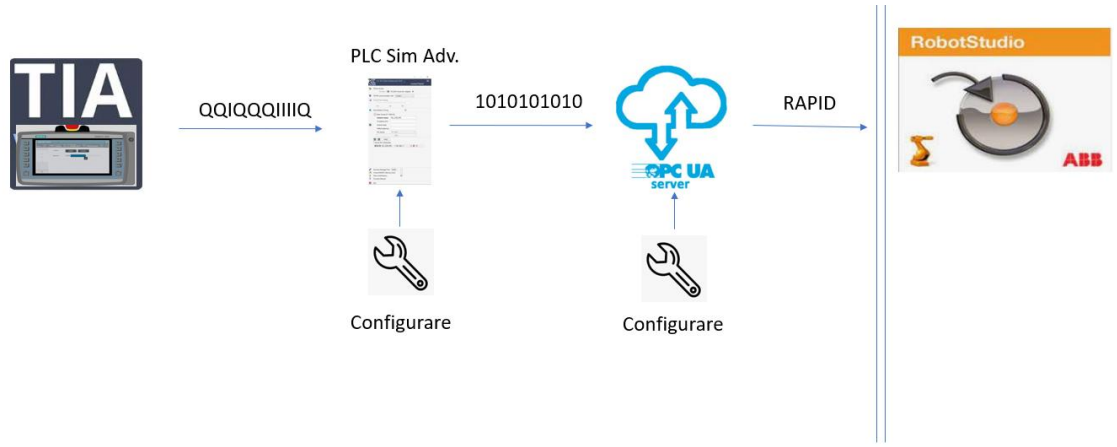


Fig. 5.2 Schematic representation for the process configuration

The procedural steps include the verification of the processor eligibility, the assignation of the addresses and ports, and the security configuration for adding signals during testing. TIA Portal must be configured to communicate via an OPC server, which

involves removing restrictions, enabling the "Support simulation during block compilation" option, and assigning IP addresses and ports. For example IP 192.168.1.1 and port 4840. OPC Server integration allows PLC variables to be exposed to external applications and systems, ensuring a standardized communication between the control equipment and higher-level software. The CPU selected for the tests was 1516-3 PN/DP V2.9, compatible with OPC UA and TIA Portal V17, supporting multiple connections and security certificate management. Implementing the OPC Server requires manually adding the signals IN1, IN2, OUT1, and OUT2 corresponding to the addresses I0.0, I0.1, Q0.0, and Q0.1. PLCSIM Advanced and the virtual Ethernet adapter enable the establishment of a "Local" TCP/IP communication (Fig. 5.3) between TIA Portal and ABB RobotStudio, with the PG/PC interface configured as PN/IE and the slot x1 assigned as subnet.

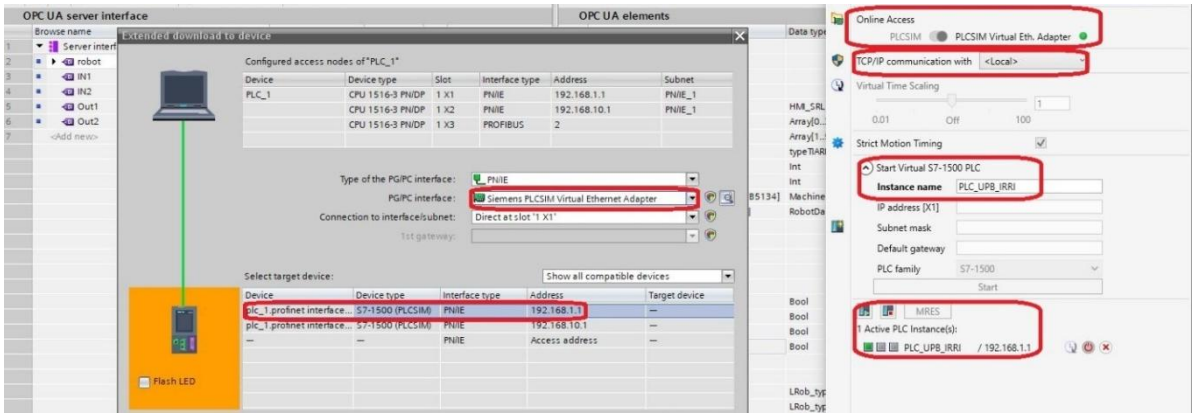


Fig. 5.3 PLCSIM Advanced set-up

5.3 Design and testing of a connection bridge using tools and software associated with the platforms

A set of tools (Fig. 5.4) was developed for the integration of a collaborative UR3e robot (simulated or real) with ROS2 Humble, the UR ROS2 driver, and MATLAB/Simulink Robotics. On a 64-bit Ubuntu Linux machine, a Docker image from Universal Robots is launched, which includes the ROS2 driver in the form of a URCap. The execution is initiated via an external command. The ROS2 driver enables the communication between ROS2 and MATLAB/Simulink, using blocks for ROS2 interfaces and decoding the messages for relevant topics: /scaled_joint_trajectory_controller, /joint_trajectory, /joint_states. Robot trajectories are transmitted via trajectory_msgs/msg/JointTrajectory messages, including joint positions, velocities, accelerations, and mechanical stress. For simulation or real control, the user connects to the Docker environment through VNC or another remote access tool. The trajectories can be defined directly via joint angles or via the gripper's position employing the inverse kinematics method and a rigidBodyTree generated in MATLAB. Additional files, including URDFs for tools can be loaded from available archives. The Polyscope 5.12

program executes the external control command, and the robot starts from the initial position defined in the initial_positions.yaml parameters.

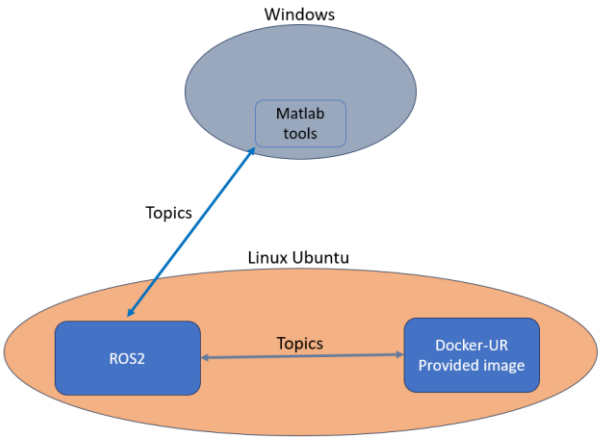


Fig. 5.4 The diagram of the created connection bridge

5.4 Configuration and parameterization of ABB RobotStudio to achieve the compatibility with the OPC Server. Configuration of the virtual controller

The diagram (Fig. 5.5) illustrates the configuration and the preparation stages for the communication at the level of each component. The flowchart of the integration can be observed..

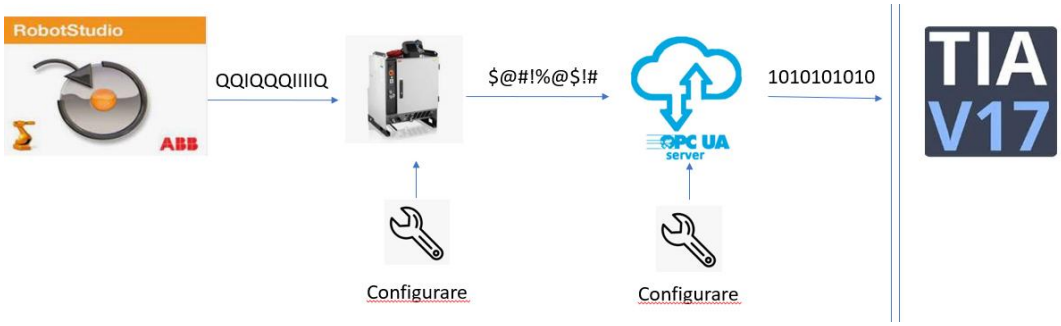


Fig 5.5 Diagram for RobotStudio configuration

The virtual controller must be configured right after the definition of the station and the of the robot. In the “Communication” category of the controller parameters, the 616-1-PC Interface option was selected, required for OPC client communication from RobotStudio to the TIA Portal server [E50][E51]. To establish the communication, the OPC Client smart component was added in RobotStudio, and the address “opc.tcp://localhost:4840” was assigned [E52].

The RSConnectDIO and RSConnectGIO blocks enable bit-to-bit and byte-to-byte communication respectively, linking the signals between the virtual controller and the simulator [E53]. Configuring the RSConnect blocks involves assigning the network card address (192.168.0.244), the PLC rack (0) and the slot (1), as well as the definition of the addresses for each input bit (M0.1, M0.2, etc.) and the output bit (M1.0, M2.0, etc.), with the configurations that must correspond to the NETtoPLC interface.

5.5 Testing and monitoring the signals transmitted between RobotStudio and TIA Portal

To establish the communication and to visualize the signal exchange, port 102 is used, and the selected network adapter is the virtual Ethernet card generated by PLCSim Advance. The PLCSim address must be automatically detected in the list of available adapters, which requires the simulator to be online. After setting the adapter and meeting the detection conditions, monitoring is started, and the signals, such as bits M1.0 and M0.1, are transmitted to TIA Portal in “online” mode (Fig. 5.7).

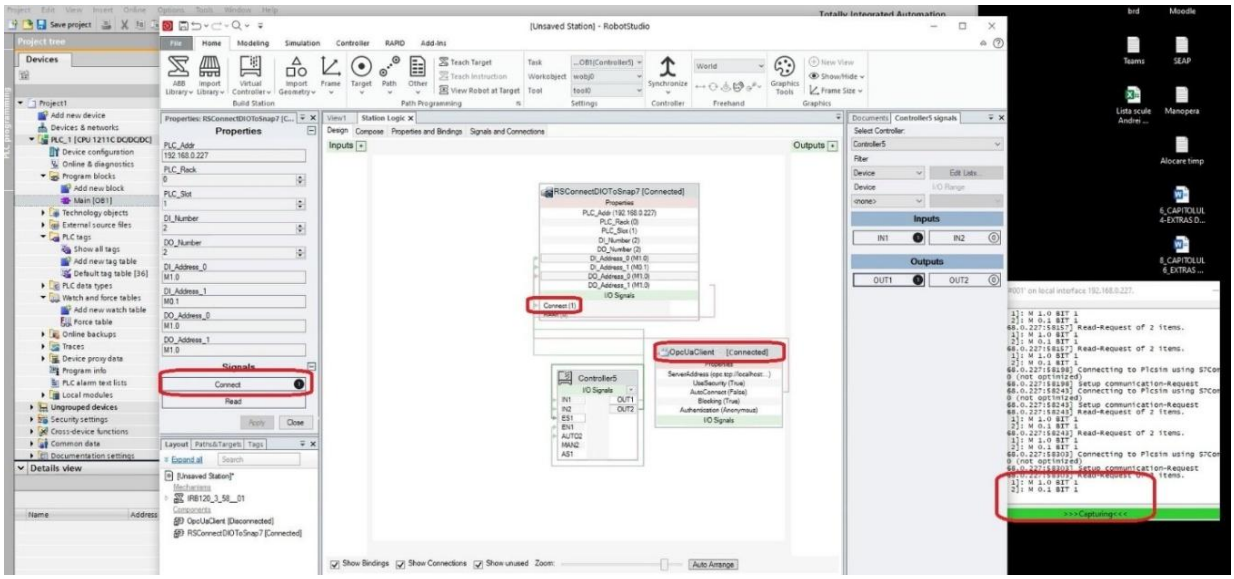


Fig. 5.7 Testing the communication conditions of the simulator

5.6 Conclusions

Conclusions and Theoretical Contributions

1. Communication based on the OPC standard was implemented, confirming its essential role as a common interface for the integration of the automation platforms from different manufacturers, confirming the scientific literature findings on the interoperability and openness of industrial systems.

2. The configuration and parameterization of TIA Portal and ABB RobotStudio environments highlighted the importance of adhering to the specific technical requirements of each platform to ensure the compatibility, demonstrating that the interoperability depends not only on the protocol, but also on the employed software and of the hardware architecture.
3. Data transfer analysis showed that latency and signal transmission fidelity are critical factors in the Virtual Commissioning processes, confirming that industrial simulation requires both open standards and the optimization of the software and hardware resource configurations.
4. The limitations identified in configuring RobotStudio controller and managing signals via OPC underlined the need for continuous development of the integration solutions, providing the fundamentals for future research areas aimed to extend the interoperability in hybrid industrial scenarios.

Conclusions and practical contributions

1. The technical feasibility of the functional integration between TIA Portal and ABB RobotStudio via an OPC server was demonstrated, establishing a “Handshake” type communication and the monitoring of the bidirectional signals.
2. The practical implementation highlighted a series of best practices:
   - the eligibility of TIA Portal processors for OPC transfer is a mandatory condition;
   - the OPC server must be fully enabled, and the protections disabled to allow data exchange;
   - the PLCSim Adaptor Ethernet virtual card is a requisite in Siemens simulations;
   - RobotStudio controller requires additional configurations and the use of external software components (“smart components”) to manage inputs and outputs.
3. The tests demonstrated the robustness of the connection, but also potential limitations: RobotStudio interface may generate errors and blockages in the case of complex transfers, requiring monitoring measures and data flow optimization.
4. The practical contribution of this work consists in providing a flexible integration model for Virtual Commissioning, with possible extension to other industrial environments, reinforcing the utility of the OPC protocol in automation projects.

Chapter 6. VIRTUAL COMMISSIONING OF COLLABORATIVE ROBOTS: BLOCKCHAIN INTEGRATION

6.1 Introduction

Chapter 6 explores another research area in Virtual Commissioning (VC) of robotic systems, focusing on collaborative robots (cobots) and the integration of blockchain

technology into distributed industrial control architectures. It analyzes Schneider Electric platforms, including EcoStruxure Cobot Expert and Machine Expert Virtual Commissioning, evaluating the software interoperability between different vendors and the capabilities for programming, simulation, and integration of collaborative robots. The chapter highlights the hardware and the software limitations, such as the limited selection of the components and difficulties in integration outside the native ecosystem, as well as the challenges of an efficient and secure communication between components. It emphasizes the need for a unified programming environment able of managing multiple types of collaborative robots through a single interface.

6.2 EcoStruxure Cobot and Machine Expert

Cobot Expert platform provides graphical tools and drag-and-drop functionalities for programming and managing collaborative robot tasks, including kinematic planning and trajectory optimization [F60-61]. It is compatible only with the Lexium series, which limits its applicability in multi-vendor environments. The software supports Virtual Commissioning (VC), reducing the configuration time, and integrates Machine Expert for machine control, performance monitoring, and predictive maintenance, complying with ISO 10218 and ISO/TS 15066 standards. Key functionalities include offline programming and simulation, optimization of robotic programs, scalability and flexibility, as well as task testing in virtual simulations [F62–65].

Machine Expert enables programming and configuration of automation systems at the machine level, integrating logic control, motion control, HMI interfaces, and industrial networks, compatible with the Modicon M241, M251, M262 series, and PacDrive LMC [F66-67]. It supports IEC 61131-3 languages, OPC DA/UA communications, SQL databases, Python scripting, and source code version control. The platform (Fig. 6.1) includes optional modules for configuring motion axes, safety logic, and a Virtual Commissioning environment through Expert Twin, which creates Digital Twins for simulation and testing [F68-69].

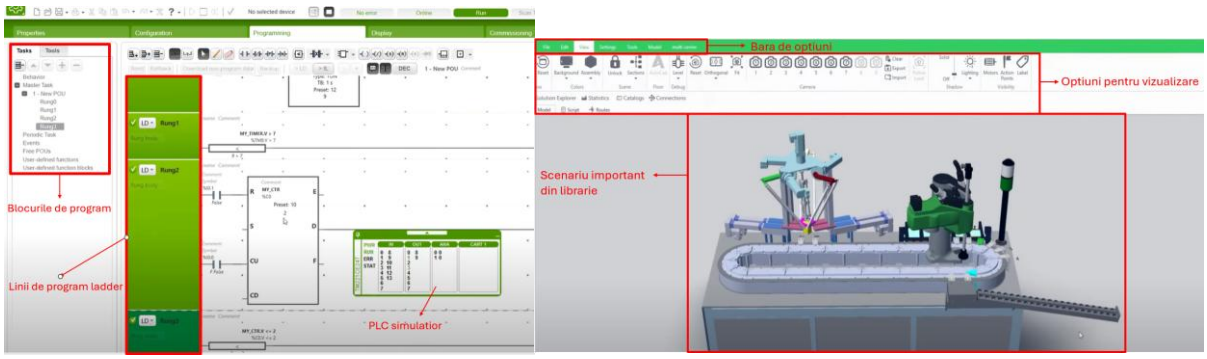


Fig. 6.1 EcoStruxure Machine Expert Twin Interface

From a hardware perspective, Lexium collaborative robots use standard, compact controllers (≈300×200×50 mm) without a dedicated teach pendant, with control performed via a tablet compatible with Machine Expert. The tablet can be docked in a docking station

with integrated safety functions, and the system also includes a Mini-control interface for basic operations. This configuration allows easy integration into the existing ecosystem and optimizes the Virtual Commissioning (VC) of Lexium robots.

6.3 Blockchain Technology in Industrial Robotics

Blockchain technology can support traceability, autonomous coordination, and immutable maintenance records for industrial robots through smart contracts and secured logging. Robots integrated into blockchain networks can validate component provenance, share tasks, and ensure compliance in regulated industries, while also enhancing cybersecurity through verified identification and secure firmware updates. Although challenges exist regarding the latency, scalability, and integration, pilot projects using ROS 2 and Hyperledger Fabric demonstrate the feasibility of converging blockchain with robotics.

Schneider Lexium collaborative robots do not provide native support for blockchain or other IIoT technologies; however, academic studies show that ROS 2 can be integrated with smart contracts for secure data control and logging [F70–71]. Other examples include ABB, which applies blockchain for energy transactions and supply chain transparency via ABB Ability [F72], and Stäubli, which monitors robot fleets and supports predictive maintenance through the SCOPE platform. Currently, Lexium relies on traditional control and programming methods with PLCs. The blockchain implementation requires external middleware rather than proprietary APIs.

6.4 Proposal for the implementation strategy

In an original implementation proposal (Fig. 6.4) a virtual robotic cell composed of a Lexium RL3, a Schunk end-effector, and a cobot support was developed. The main steps were: the selection of the experimental hardware and software base, parameterizing the Digital Twin in Twin Expert, and writing the cobot program and trajectory in Cobot Expert; integrating the PLC and cobot in Machine Expert; designing the PLC program for cobot control; converting FBD code into Ladder; configuring the hardware and software of the PLC, cobot, and gripper; managing and parameterizing the signals; and identifying platform limitations. This approach allows the evaluation of Schneider Electric platform limits for Virtual Commissioning (VC) and the identification of the necessary configurations.

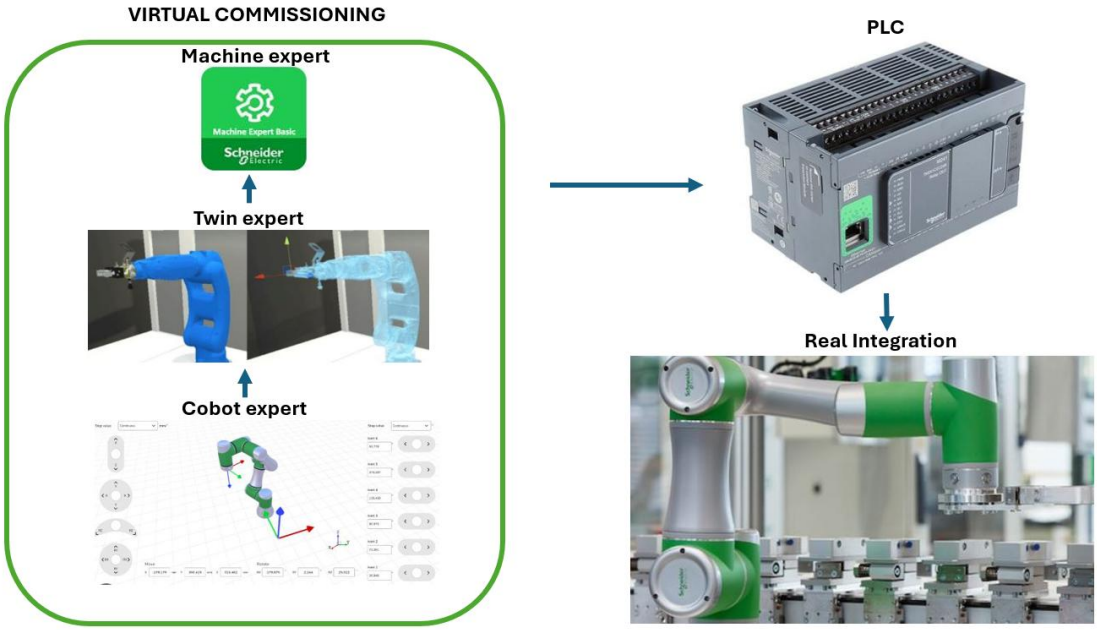


Fig. 6.4 Conceptual model for applied Blockchain technology

The equipment employed was: Lexium RL3 Cobot, Lexium Controller LXMRL07C1000, Cobot Expert v1.7.0.48, Machine Expert Basic Trial with Twin Expert.

In Machine Expert, a virtual TM241CE24R processor was configured with the necessary signals for the virtual robot operations. Expert Twin was launched, the RL3 cobot was selected, and a virtual mounting support was added. The Schmalz vacuum gripper was chosen from the available library. The end-effector library is limited, and manual customization requires advanced knowledge.

In Cobot Expert, the robot trajectories were defined, setting operational parameters such as payload, speed, acceleration, mounting orientation, and center of gravity. The main program controls the movement and trajectory of the cobot. The programming environment combines graphical elements with manual coding, allowing adjustment of robot behavior and trajectory definition.

The PLC program was developed in Machine Expert to manage the robotic cell and to integrate it with the main production line. Communication between the PLC and the cobot is realized via the MODBUS protocol, using the Twin Expert module to integrate the trajectory and the logic defined in Cobot Expert.

Key observations and limitations in Machine Expert Simulator

• Communication flow restrictions during configuration. Although the physical robot can be connected directly to Cobot Expert via the “Click to Connect” function, and Cobot Expert can interface with Twin Expert, a direct connection between the real cobot and Twin Expert is not ensured. This limitation requires that all configurations, even previously saved ones, pass

through Cobot Expert, adding unnecessary complexity and reducing efficiency in implementing or updating robot programs.

• Model compatibility issues between platforms. Users can import pre-defined Digital Twin models for the cobot, gripper, or other standard components, such as conveyors, into Machine Expert. However, fully customized models configured in Twin Expert cannot be imported directly into Machine Expert. The model must be manually reconstructed in Machine Expert, limiting the flexibility and continuity of the workflow between the platforms.

• Virtual PLC program performance. The PLC program developed in Machine Expert successfully controls the virtual application in real time, operating with precision and stability. The simulation runs without errors and is robustly optimized, indicating that the platform is highly suitable for creating and testing control logic in a real-time virtual environment before the real physical implementation.

6.5 Conclusions

The case study presented a Virtual Commissioning (VC) environment implemented using industrial software provided by Schneider Electric, such as Machine Expert and Cobot Expert. The research highlights and further addresses several limitations and gaps in actual VC solutions for collaborative robots within the Schneider ecosystem, despite the company's strong position in the industrial automation sector.

Key observations:

- The hybrid programming environment, which combines graphical programming elements with written code, is accessible even to users with limited programming knowledge.
- Trajectory and motion programming are simplified through visual drag-and-drop tools.
- The requirement to use two separate software environments (Twin Expert and Machine Expert) for modeling and implementation affects the workflow continuity.
- Optimal performance is achieved within the Schneider ecosystem; operating outside increases the project complexity.

Major limitations identified in the integration of VC using the Schneider Machine Expert and Schneider Cobots Expert platforms:

- The integrated library contains a limited number of robots and end-effectors (only a few available options).
- Limited flexibility for customized or different robotic components.
- Real robots cannot communicate directly with Twin Expert; an intermediate connection via Cobot Expert is required.
- Digital Twin models created entirely in Twin Expert cannot be imported in Machine Expert, requiring manual reconstruction.
- The configuration of customized components requires advanced programming knowledge.

Advantages of VC integration using Schneider Machine Expert and Schneider Cobots Expert platforms

- Easy integration with other Schneider tools such as Machine Expert, Modicon PLCs, and Twin Expert, providing unified automation control.
- Predefined robot and component models enable rapid prototyping.
- Integrated simulation tools allow real-time preview and validation of cobot behavior.
- Support for standard IEC 61131-3 languages (ST, FBD, LD, etc.), supporting standardization.

Chapter 7. FINAL CONCLUSIONS, ORIGINAL CONTRIBUTIONS, DISSEMINATION OF THE RESEARCH RESULTS AND FUTURE RESEARCH AREAS

7.1 Final conclusions

The doctoral Thesis achieved a Virtual Commissioning (VC) environment using industrial software platforms available from leading industrial companies such as ABB and Siemens.

The main contributions of the Thesis include solution identification for controlling the most commonly used industrial robots from ABB and Fanuc, employing the actual most important unified interface, Simatic Robot Integrator. It also highlights the actual limitations and gaps in the field of Virtual Commissioning for industrial robots. To address these gaps, the Thesis proposed an original Virtual Commissioning approach using concurrent working environments from ABB and Siemens. The Thesis also underlines the absence of significant categories of dual-gantry robots from the portfolios of the major manufacturers, such as ABB and Güdel, within Virtual Commissioning environments when an ABB controller is used. The research further demonstrates that these limitations underscore the intense competition among the main providers of Virtual Commissioning. The work solves, in an original manner, the challenge of the robot control, overcoming these limitations.

The final outcome of the theoretical and applied research is a stable and reliable solution for carrying out VC activities for industrial users. It enables the integration of products developed by ABB and Siemens. The applicability of this original solution is extremely broad for industrial users, compared to other hybrid integration solutions available on the market, such as Beckhoff and Virtual Universe PRO. Users can equally benefit from the developed hybrid solution without investing in high-cost licenses for NX MCD or other software products that enable the connection of ABB RobotStudio with TIA Portal.

The hybrid solution developed in the Thesis also opens new research perspectives at minimal investment cost, due to the open-source solutions provided by ABB and Siemens.

The limitations of the doctoral Thesis are as follows: the dedicated configuration for transmitting data from the interface to the robot could be improved to enhance ease of use; communication requires user programming and networking skills; the absence of a "Click-to-Connect" shortcut, which could automatically link output bits to input bits in the blocks. The approach can be further developed to be less dependent on changes to the robot, PLC, or control interface.

Additionally, some guiding elements within the interface are needed to help the end user to set tasks and send or receive data.

Future research could focus on the development of an application that operates as a "Click-to-Connect" interface, enabling data processing and exchange between software environments from different manufacturers, such as ABB or Fanuc. This endeavor would require source blocks to facilitate communication. The goal is to create an application that, with minimal configuration and parameterization tasks, provides a link through which jobs and responses can be sent and received.

ORIGINAL CONTRIBUTIONS OF THE DOCTORAL THESIS ALIGNED WITH THE SPECIFIC OBJECTIVES

The specific objectives of the doctoral Thesis, derived from each main objective are tuned with the author's original contributions. They are all presented in Tables 7.1-7.7.

Table 7.1 Specific objectives and contributions for MO1

MO1. Analysis and synthesis of the current state of the research for VC purposes	
SO1.1 Research on the scope and on the importance of implementing Virtual Commissioning in production processes	✓ The integration of VC into production processes has been studied;
SO1.2 Synthesis of the current state of the research in the field of Virtual Commissioning	✓ Research areas for improving Virtual Commissioning have been identified; ✓ Methods previously used to enhance Virtual Commissioning have been analyzed.
SO1.3 Summary of recommended devoted Software for Virtual Commissioning	✓ An original analysis of dedicated platforms offered by concurrent providers was conducted.

Table 7.2 Specific objectives and contributions for MO2

MO2. Establishing the key functionalities of the current software platforms which will be employed in the Thesis	
SO2.1 Selection of the robot model for which Virtual Commissioning (VC) will be performed	✓ General industrial robots (IR) architectures were analyzed, and the type of robot to be employed was identified; The model and the size type of the IR from a specific manufacturer were selected.
SO2.2 Establishing the Software Platforms in accordance with the specific objective OS1.3	✓ An analysis of software programs provided by different companies was conducted;
SO2.3 Selection of the Software Platforms for which the communication for VC will be performed	✓ An analysis of the communications capabilities in different software systems was conducted; ✓ An analysis of the procedures for establishing the communication was carried out;

Table 7.3 Specific objectives and contributions for MO3

MO3. Identification of the gaps in actual research studies and unsolved issues in the field of Virtual Commissioning (VC)	
SO3.1 Selection of the main industrial publications addressing VC limitations	✓ An original analysis of the limitations of the main platforms for VC concept integration was conducted.
SO3.2 Establishing the Methodology for applying the VC Concept	✓ Data transfer pathways between platforms were clearly identified.

Table 7.4 Specific objectives and contributions for MO4

MO4. Virtual concept of the control via a teach-pendant device for simulating robots in SRI through graphical model parameterization in the HMI screen interface	
SO4.1 Selection of the robot types available in Simatic Robot Integrator libraries	✓ The three types of robots available in the interface were analyzed in respect to: traditional manufacturers, robot architecture, and user defined robots;

SO4.2 Implementation of the HMI screens to replace the Physical Control Interface of Simatic Robot Integrator	✓ Graphical screens such as JOGframe, Tool Overview, and Soft End Config were created.

Table 7.5 Specific objectives and contributions for MO5

MO5. Establishing the communication and parameterization in Simatic Robot Integrator of the control code from TIA Portal with CAD models simulated in Siemens MCD	
SO5.1 Signals export from TIA Portal and import to MCD, indicating the limitations in the User Interface of the signal imports	✓ The Advanced Simulator in TIA Portal and the external signals in Siemens MCD were configured.
SO5.2 Establishing Handshake links between the signals retrieved from PLCSim Advanced and signals generated by MCD	✓ Verification and testing of the signal exchange were carried out.
SO5.3 TIA Portal configuration and parameterization to ensure the compatibility with the OPC Server	✓ The processors suitability was established, including IP and port allocation and protection configuration for testing purposes; ✓ Maximum accessibility level was activated and final protection was removed; ✓ Accessibility of OPC server and Simatic server were enabled, along with IP and port allocation;
SO5.4 Design of a connection bridge using external tools to enable the communication between RobotStudio and Simatic Robot Integrator	✓ Manual addition of signals to the OPC server within TIA Portal was performed;

Table 7.6 Specific objectives and contributions for MO6

MO6. Testing and verification of the SRI integration with Virtual Commissioning environments that are not compatible with Siemens
SO6.1 Verification and testing the integration between SRI with Factory IO

Table 7.7 Specific Objectives and Contributions for MO7

MO7. Design and testing a connection bridge using external tools to enable additional

communication between ABB RobotStudio and Simatic Robot Integrator	
OS7.1 Testing a connection bridge using external tools to enable the communication between RobotStudio and Simatic Robot Integrator	✓ ROS2 messages were sent via Simulink to the robot driver.
OS7.2 Configuration and parameterization of ABB RobotStudio to ensure compatibility with the OPC Server	✓ The virtual control station was configured to enable the communication;
OS7.3 Parameterization and configuration of the input and output adapter blocks of RSconnect	✓ The communication block of the OPC client's intelligent component was added and configured;
OS7.4 Establishing the communication between TIA Portal and RobotStudio via the communication blocks in RobotStudio	✓ The signals sent from RS to TIA were tested and monitored;

7.2 Original contributions

The research and the doctoral Thesis development have generated a series of the author's original theoretical, methodological, and practical applicable contributions, which can be grouped as follows:

Theoretical contributions related to Chapters 1 and 2

- Coherent and comprehensive synthesis of the actual development platforms limitations for Virtual Commissioning (VC) provided by Siemens and ABB.
- Application of the general theory of Virtual Commissioning to the software platforms offered by Siemens and ABB.
- Identification and resolution of all issues arising from different programming languages employed for the industrial robot control.
- Mechanical design and 3D modeling of the robotic cell and its components employed in the case study.
- Electrical, pneumatic, and programming logic design for actuating the entire robotic cell used in the case study.
- Mathematical synthesis of the programming logic conversion for industrial control, from function blocks to ladder diagrams.
- The analysis of the complete integration confirmed that Siemens ecosystem (Simatic Robot Integrator, Mechatronic Concept Designer, and TIA Portal) provides native Click-to-Connect solutions that simplify the signal exchange and reduces manual configuration effort; however, these benefits are exclusively within Siemens environments.

- Highlights of the differences in industrial communication standards by testing the interoperability with external platforms such as ABB RobotStudio or Factory IO, which require additional configuration, manual signal mapping, and dedicated handshake mechanisms.
- Demonstration of the technical limitations of Factory IO, including the inability to import signals, lack of compatibility with PLCSim Advanced, and a limited equipment library. These findings show that Virtual Commissioning procedures are not yet fully mature for complex industrial robotics scenarios, and Factory IO does not provide the minimum compatibility required for the integration with Siemens.
- New theoretical fundamentals of the Virtual Commissioning (VC) concept were established, demonstrating both the advantages of native platform integrations and the challenges of the interoperability between different manufacturers, providing guidance for future developments in the field.
- The implementation of OPC-based communication confirmed its essential role as a common interface for integrating automation platforms from different manufacturers, confirming the finding from the scientific literature on the interoperability and industrial system openness.
- Configuration and parameterization of TIA Portal and ABB RobotStudio highlighted the importance of meeting the specific technical requirements of each platform to ensure the compatibility, showing that the interoperability depends not only on the protocol, but also on the employed software and hardware architecture.
- Data transfer analysis demonstrated that latency and signal fidelity are critical factors in the Virtual Commissioning processes, confirming that industrial simulation requires both open-source standards and optimization of the software and hardware resource configurations.
- Limitations identified in RobotStudio controller configuration and OPC signal management emphasized the need for the continuous development of the integration solutions, providing the necessary fundamentals for future research areas, aimed to extend the interoperability in hybrid industrial scenarios.

Methodological contributions related to Chapter 3

- Mathematical synthesis of the programming logic conversion for industrial control from function blocks to ladder diagrams.
- Identification of the peculiarities and challenges of unifying industrial robot control.
- Formulation of the compatibility limits for the simulation environments using Digital Twins for industrial robot cells.
- Development of an original methodology for evaluating and comparing Virtual Commissioning solutions, validated through experimental tests between Factory IO and Siemens platforms, which highlighted both the advantages and the limitations of a platform dedicated solely to Virtual Commissioning simulation.

Practical contributions related to Chapters 4, 5, and 6

- Virtual design and implementation of a Teach-pendant control for Simatic Robot Integrator through graphical model parameterization as an HMI interface screen.
- Design and verification of the communication; parameterization in Simatic Robot Integrator interface of the control code from TIA Portal with geometric models simulated in Siemens MCD.
- Export of the signals from TIA Portal and import into MCD, highlighting the limits of the user interface for signal exchange.
- Tests with Factory IO demonstrated both its extended compatibility with physical PLCs and simulators from multiple manufacturers, as well as its limitations in complex robotic scenarios, such as manual signal mapping, inability to import CAD models, and blockages with a large amount of data.
- Configuration of Advanced Simulator in TIA Portal and external signals in Siemens MCD; establishment of the handshake links between signals retrieved from PLCSim Advanced and those generated by Siemens MCD.
- Design and testing of a connection bridge using external tools and software in respect to the main platforms.
- Validation through monitoring and supervision of the signals exchanged between RobotStudio and TIA Portal.
- Demonstration of the technical feasibility for the functional integration between TIA Portal and ABB RobotStudio via an OPC server, establishing handshake communication and bidirectional signal monitoring.
- Practical implementation highlighted several best practices:
    - Processor eligibility in TIA Portal for OPC transfer is mandatory;
    - The OPC server must be fully activated, with protections disabled to allow data exchange;
    - The PLCSim Ethernet virtual board is necessary for Siemens simulations;
    - RobotStudio controller requires additional configuration and the use of the external software components (“smart component”) for managing inputs and outputs.
- The tests proved the robustness of the connection, but also potential limitations: RobotStudio interface may generate errors or blockages during complex transfers, requiring the supervision and optimization of the data flow.
- The most significant practical contribution of the doctoral Thesis is the delivery of a flexible integration model for Virtual Commissioning, with a real potential for the extension to other industrial environments, reinforcing the utility of the OPC protocol in automation projects.

7.3 Dissemination of results: research articles published and/or presented at International Conferences

The research conducted during the doctoral studies led to the development and publication of four scientific articles, appearing both in specialized journals indexed in international databases and in the proceedings of international conferences.

Scientific Articles:

I. **Andrei, A.**, Nicolescu, A.F., Pupăză, C - *Perspectives of Virtual Commissioning using ABB RobotStudio and Simatic Robot Integrator Environments: A review.* Proceedings in Manufacturing Systems, Volume 16, Issue 3, 2022, 117-123 ISSN 2067-9238.

II. Bucur, C., **Andrei**, A., Tasu, S. - *Controlling Industrial Robots with Simulink* 2023 15th International Conference on Electronics, Computers and Artificial Intelligence (ECAI), Bucharest, Romania, 2023, pp. 1-4, BDI, 10.1109/ECAI58194.2023.10193974

III. **Andrei**, A., Nicolescu, A.F., Pupăză, C., Coman, G, Ghionea, A. - *Applicability of Virtual Commissioning Concepts in Industrial Robotics as a Solution for Compatibility Issues Between Virtual Simulation and Logic Control Software.* Appl. Sci., WOS:001429844400001, IF 2005=2.5, Q1, Engineering, Multidisciplinary, 15, 2033. https://doi.org/10.3390/ app15042033

IV **Andrei, A,** Pupăză, C., Nicolescu A.F. - *A Case Study on Virtual Commissioning of Collaborative Robots using Schneider Software Platforms - BDI "*Scientific Bulletin" Seria D: Inginerie Mecanică, ISSN (print): 1454-2358 / (online): 2286-3699, Vol. 88, Issue 1, 2026

International Conference:

- *Conference: 2023 15th International Conference on Electronics, Computers and Artificial Intelligence (ECAI). Data 29.06.2023, ora 9:00, Conference Center of the National University of Science and Technology Politehnica Bucharest.*

7.4 Future research topics

Future research will focus on the development of an application functioning as a "Click-to-Connect" interface that processes and enables data exchange between software environments from other manufacturers, such as Kuka or Fanuc. This will require the development of the source blocks to facilitate the communication. The goal is to create a general-purpose application that, with minimal configuration and parameterization effort, provides a link through which the tasks and responses can be sent and received.

In addition to this accomplishments, the author has identified several current research area, directly related to the doctoral Thesis:

- Integration of Virtual Commissioning with artificial intelligence algorithms for fault prediction and optimization of preventive maintenance in industrial robotic systems;

- Implementation of the blockchain technology to ensure immutable traceability of the safety parameters for collaborative robots, preventing undetected manipulation of critical security configurations;
- Development of a Virtual Commissioning environment integrated with generative AI simulators, able to create adjustable and predictable scenarios for testing and training robots in surgical and other highly complex medical applications;
- Development of a Virtual Commissioning framework for the simulation and the calibration of the robots in image-guided surgery, enhancing the precision, safety, and control in gentle manipulation tasks.

In brief:

The final result of this doctoral Thesis is a stable and reliable solution for performing VC activities for industrial users, enabling the integration of the products developed by ABB and Siemens.

The applicability of this approach is extremely broad for industrial users, compared to other hybrid integration solutions available on the market, such as Beckhoff and Virtual Universe PRO. Users can equally benefit from the developed hybrid solution without investing in high-cost licenses for NX MCD or other software products that enable the connection of ABB RobotStudio with TIA Portal.

The hybrid solution developed in the doctoral Thesis also opens new research perspectives at minimal investment cost, due to the open-source solutions provided by ABB and Siemens.

The strategy developed in the Thesis can be applied as a methodology for unifying platforms and programming languages offered by other major industrial robot and control system manufacturers, such as KUKA, Fanuc, Yaskawa, Allen Bradley, and Schneider, completed by the necessary devoted configuration and parameterization for each employed platform

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