

METHODOLOGY FOR COORDINATING HETEROGENEOUS INDUSTRIAL ROBOTS AND OTHERS PERIPHERAL DEVICES IN PRODUCTION SYSTEM

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The integration of heterogeneous industrial robots and peripheral devices in modern production systems introduces challenges related to interoperability, synchronization of operations and unified process control. This paper presents a methodology for coordinating industrial robots from different manufacturers together with additional technological devices within a single robotic workstation. The proposed approach is based on a PLC-centric control architecture enabling centralized coordination of technological operations and structured exchange of control and status signals between devices using industrial communication networks. The methodology defines system architecture, communication principles and a signal-based coordination model for synchronization of robotic and technological operations. The concept is demonstrated on a robotic workstation integrating ABB and KUKA robots, a vision inspection system, a conveyor and pneumatic devices. In addition, a digital shadow of the robotic workstation is implemented using OPC UA communication via PLC and connected with a virtual model in Tecnomatix Process Simulate for monitoring of selected process data.

KEYWORDS

heterogeneous industrial robots, peripheral devices integration, robot coordination methodology, PLC-based control, PROFINET communication, production systems automation

1 INTRODUCTION

In recent years, the development of modern manufacturing systems has been significantly influenced by trends in industrial digitization and automation. Industrial robots are a key component of today's production lines, and their use is gradually expanding from simple handling operations to the execution of complex technological processes. In the environment of modern production systems, workstations are therefore increasingly emerging where multiple robotic systems collaborate with other peripheral devices, such as camera systems, pneumatic modules, sensors, or technological fixtures. The integration and coordination of such heterogeneous devices within a single manufacturing process presents a significant challenge in terms of the design of the control architecture, communication mechanisms, and the overall organization of the manufacturing system.

These trends are closely related to the Industry 4.0 concept, which emphasizes the interconnection of physical manufacturing equipment with digital control and monitoring systems. Modern manufacturing systems are often interpreted as cyber-physical manufacturing systems enabling the integration of manufacturing technologies, data flows, and control systems within a unified digital architecture [Monostori 2014]. Standardized communication protocols and industrial communication networks play a significant role in such systems, ensuring reliable data exchange between individual elements of the automation system [Wollschlaeger 2017]. At the same time, the use of digital models of production facilities, such as digital twins or digital shadows, is increasingly being developed, enabling real-time monitoring and analysis of the behaviour of technological systems [Tao 2019].

The issue of coordinating multiple robotic systems is the subject of extensive research. Several studies focus on the coordination of multi-robotic systems, analysing various approaches to the control, synchronization, and collaboration of robotic units [Verma 2021], [Ni 2026]. Similarly, Tejada et al. discuss current challenges and opportunities for the development of multi-robot systems, including their use in various industrial applications [Tejada 2025]. However, most of these approaches are primarily focused on algorithmic or distributed control architectures, which are often used, for example, in the field of mobile robotics or autonomous robotic systems.

In the context of industrial manufacturing systems, however, the coordination of technological equipment is often implemented through centralized control architectures based on programmable logic controllers (PLCs). PLC systems represent a standard platform for industrial automation and ensure the control of technological processes, communication between devices, and the synchronization of production operations. The programming of such systems is standardized, for example, by the IEC 61131-3 standard, which defines the basic principles of control logic design in industrial applications [John 2010].

In addition to the coordination of robotic systems, research also focuses on the integration of manufacturing equipment within the environment of smart manufacturing systems. For example, Cimino et al. propose an interoperable platform enabling the integration of various Industry 4.0 tools and technologies within manufacturing enterprises and emphasize the importance of a unified architecture for integrating heterogeneous devices [Cimino 2023]. Similarly, Wan et al. present a concept for a reconfigurable smart factory based on cloud robotics, which enables the coordination of robotic devices via a distributed control platform [Wan 2019]. Other works focus on big data processing architectures and analytical tools designed for monitoring and optimizing complex manufacturing systems [Zhang 2017].

Despite the existence of these approaches, most research solutions focus primarily on distributed control architectures or the integration of manufacturing systems at the level of digital platforms. In practical industrial applications, however, the coordination of robotic workstations and technological equipment often takes place via centralized control systems based on PLCs. However, there are relatively few systematic methodologies in the available literature that address the design of coordination for heterogeneous industrial robots and peripheral devices via PLC control.

The aim of this work is therefore to propose a methodology for coordinating heterogeneous industrial robots and peripheral devices in production systems based on a centralized PLC

control architecture. The proposed methodology defines a structured model for the exchange of control and status signals between individual devices, a sequential model for controlling the technological process, and a synchronization mechanism enabling the coordinated operation of robotic and technological devices within a shared manufacturing process. The proposed approach is demonstrated at a robotic workstation integrating industrial robots from various manufacturers, a camera system, pneumatic modules, and a monitoring layer based on a digital shadow of the robotic workstation.

2 OVERVIEW OF THE CURRENT STATUS OF THE ISSUE AT HAND

The coordination of multiple robotic systems and technological devices represents a significant area of research in the field of industrial automation and modern manufacturing systems. As the level of automation in manufacturing processes increases, there is a growing need to integrate various types of equipment that must work together within a single manufacturing process. Such systems often include industrial robots, manipulators, camera systems, pneumatic modules, and other technological devices that must be coordinated with one another through a suitable control architecture.

One of the significant areas of research is the coordination of multi-robot systems. Several studies analyse various strategies for coordinating robotic systems and highlight the importance of synchronizing individual robotic operations and effective communication between control units [Verma 2021], [Ni 2026]. Tejada et al. provide an overview of current approaches to multi-robot systems and discuss the challenges and opportunities for their use in various industrial applications [Tejada 2025]. However, these approaches often focus primarily on algorithmic coordination methods or distributed control architectures, which are typical, for example, in mobile robotics or collaborative robotic applications.

The concept of smart manufacturing systems and Industry 4.0 also plays a significant role in the coordination of manufacturing systems. Modern manufacturing systems are increasingly designed as cyber-physical systems, which enable the integration of physical equipment with digital models and information systems [Monostori 2014]. Within these systems, various technologies are used to enable the integration of manufacturing equipment and data flows, with interoperable platforms and standardized communication protocols playing a key role [Lu 2017], [Xu 2018].

In the field of smart manufacturing systems, research also focuses on architectures enabling the integration of heterogeneous manufacturing equipment. Cimino et al. propose an interoperable platform enabling the integration of various Industry 4.0 tools and technologies within manufacturing environments and emphasize the importance of a unified architecture for integrating heterogeneous equipment [Cimino 2023]. Similarly, Wan et al. present a concept for a reconfigurable smart factory based on cloud robotics, which enables the coordination of robotic devices through a distributed control architecture [Wan 2019]. Other works focus on the use of data architectures and analytical tools for monitoring and optimizing manufacturing processes, such as a big data analytics architecture designed for complex manufacturing systems [Zhang 2017].

In addition to production system architectures, communication technologies and control systems used in industrial automation also play a significant role. Industrial communication networks

enable data exchange between individual devices within a production system and ensure the synchronization of technological operations [Wollschlaeger 2017]. Modern production systems also utilize standardized communication protocols, such as OPC Unified Architecture, which enable interoperability between various devices and control systems [Mahnke 2009]. The control logic of technological devices is often programmed using PLC systems, whose principles are defined, for example, by the IEC 61131-3 standard [John 2010].

In recent years, the use of digital models of production equipment has also been developing, enabling the monitoring and analysis of technological processes. Digital twins and digital shadows allow for real-time monitoring of equipment operating parameters and support the integration of physical production systems with digital analytical tools [Tao 2019].

Despite the existence of the aforementioned approaches, most research solutions focus primarily on distributed control architectures, cloud platforms, or data-oriented approaches to the integration of manufacturing systems. In industrial practice, however, the coordination of technological equipment often takes place via centralized control systems based on programmable logic controllers. Systematic methodologies describing the design and implementation of coordination for heterogeneous robotic and peripheral devices via PLC control are, however, only limitedly represented in the available literature. This fact creates an opportunity for the design of the methodological approach presented in the following chapters of this work.

3 DESIGN OF A ROBOTIC WORKSTATION

The proposed robotic workstation was designed as an experimental technological cell intended to validate the methodology for coordinating heterogeneous industrial robots and peripheral devices within a single production system. The robotic workstation's design was based on the requirements of an industrial environment, where a common task is the integration of equipment from different manufacturers into a single technological process. Such systems often include multiple robotic manipulators along with other technological devices, such as conveyor systems, camera systems, or pneumatic modules, which must be coordinated with one another through a suitable control architecture.

The robotic workstation design proceeded in several stages. In the first phase, a conceptual design of the technological cell was created, with the aim of defining the basic layout of the individual devices and technological elements of the robotic workstation. Subsequently, a virtual model of the robotic workstation was created in a CAD environment, which made it possible to verify the spatial arrangement of the equipment, the working ranges of the robotic manipulators, and ensure collision-free operation of the individual technological elements. The virtual model also allowed for the optimization of the placement of technological equipment even before the actual implementation of the robotic workstation. A virtual model of the robotic workstation was created in a CAD environment to verify the spatial arrangement of the technological components and the working reach of the robotic manipulators, as shown in Fig. 1.

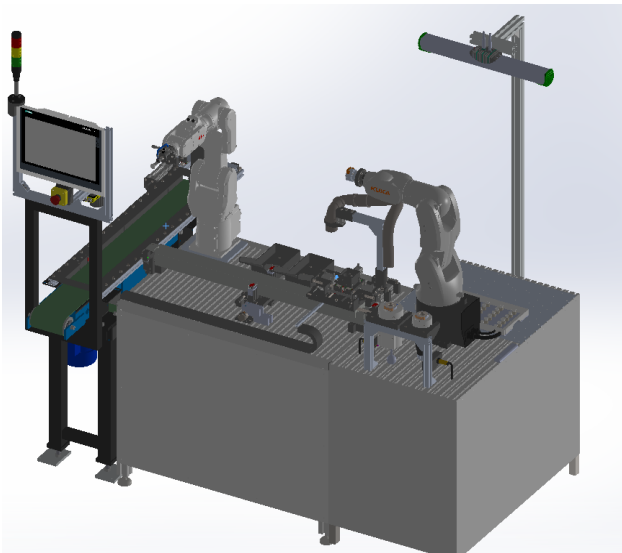


Figure 1. Conceptual CAD design of the robotic workstation created in the SolidWorks environment.

Based on the developed CAD model, the robotic workstation was physically constructed, and the individual components were integrated into a unified control architecture, as shown in Fig. 2. The design emphasizes modularity and the capability to integrate various types of equipment, enabling the robotic workstation to serve as an experimental platform for testing different approaches to the coordination of robotic systems.



Figure 2. Experimental robotic workstation integrating ABB and KUKA industrial robots within a PLC-based control architecture.

The proposed robotic workstation integrates several technological subsystems, including industrial robots, a conveyor system, a camera system, and pneumatic modules. The robotic workstation is controlled by a central programmable logic controller (PLC), which coordinates individual technological operations and facilitates the exchange of control and status signals between individual devices.

3.1. Composition of the robotic workstation

The proposed robotic workstation consists of several pieces of equipment that together form an integrated manufacturing system capable of performing handling and processing operations. The robotic workstation was designed to enable robotic systems from different manufacturers to collaborate with other peripheral devices within a single manufacturing process. The robotic workstation architecture is based on centralized control via a programmable logic controller, which ensures the coordination of individual devices and the exchange of control and status signals between them.

The basic elements of the robotic workstation are two industrial robots from different manufacturers, which perform handling and technological operations. The first robot is an ABB IRB 1100 industrial robot with an OmniCore C30 control unit, which is equipped with a suction gripper and is used primarily for handling operations and moving semi-finished products within the workspace. The second robot is a KUKA KR 3 R540 AGILUS industrial robot, which performs processing operations on semi-finished products that have been evaluated as OK. The robot is equipped with a technological fixture containing a mechanism for clamping two work heads, which enable the performance of drilling operations and the subsequent screwing of mating parts onto the semi-finished product. The use of robots from different manufacturers allows for the demonstration of the challenges of integrating heterogeneous robotic systems within a single control system.

Control of the entire robotic workstation is provided by a Siemens S7-1500 PLC, which serves as the system's central control unit. The PLC coordinates the technological process, processes signals from sensors, and facilitates the exchange of control and status signals between individual robotic workstation devices. Communication between the PLC and individual devices is implemented via the PROFINET industrial communication network, which enables deterministic data exchange between the PLC, robotic manipulators, the camera system, the 3D scanning system, and the pneumatic island.

The robotic workstation also includes a conveyor system used to transport objects between individual technological operations. The conveyor ensures the transfer of handled objects into the robots' workspace and enables the automation of material flow within the technological cell.

A Cognex In-Sight 5100C 2D camera system is used in the robotic workstation to detect and inspect the manipulated objects; it serves to identify the presence of a workpiece in the workspace and to verify its correct placement. The camera system detects whether the semi-finished product is located within the robotic manipulator's workspace, determines its position, and simultaneously performs a pass/fail inspection of its condition. The acquired information is then transmitted to the PLC control system, which uses it to determine the next steps in the manufacturing process and to execute the robotic manipulators' handling operations.

In addition, the robotic workstation is equipped with a Photoneo PhoXi L 3D scanning system, which is used to detect and locate parts intended for an assembly operation performed by a KUKA robot. The system enables the identification of the presence and position of individual components within the workspace and provides the necessary spatial information for planning the robot's manipulation trajectories. The Photoneo Bin Picking Studio software tool is used for 3D data processing and object identification; it processes the acquired point cloud and calculates grasping positions for the robotic manipulator.

Another component of the robotic workstation is a pneumatic system that controls selected technological elements of the robotic workstation. The pneumatic elements are controlled via an SMC EX260 pneumatic island, which enables the integration of pneumatic valves into the robotic workstation's control architecture and their operation via a PLC control system.

In addition to control communication, the system also implements a monitoring layer based on the OPC UA communication standard, which enables access to selected operational data from the entire robotic workstation. Through this interface, process data is transmitted from devices integrated into the robotic workstation, such as the status information of robotic manipulators, data from sensor systems, information on the status of the conveyor system, and selected operational variables of the robots. The collection and sharing of this data is handled by the Siemens S7-1500 PLC control system, which serves as the central communication hub in the proposed architecture.

The acquired data is then used to create a digital shadow of the robotic workstation in the Tecnomatix Process Simulate environment, which represents a virtual model of the physical process system. The digital model enables real-time monitoring of the movement of robotic manipulators, the progress of technological operations, and selected operational parameters of the robotic workstation.

The robotic workstation designed in this way represents a comprehensive technological system that enables the execution of coordinated operations by multiple robotic manipulators and peripheral devices within a single manufacturing process, while also providing a suitable experimental platform for implementing a methodology for coordinating heterogeneous robotic systems and peripheral devices, as well as for the integration of a digital shadow of the production robotic workstation into a digital manufacturing environment.

3.2. Robotic workstation technological process

The manufacturing process carried out at the robotic workstation consists of several sequential operations coordinated by a central PLC control system. The individual operations include handling the semi-finished product, its visual inspection, sorting of parts, and the subsequent drilling and assembly operations. An overview of the work area of the robotic workstation where these operations are performed is shown in Fig. 3.



Figure 3. Detail of the technological working area of the robotic workstation.

The process begins with the semi-finished product being fed into the work area via a conveyor system. Once the conveyor reaches its end position, the presence of the semi-finished

product is detected by an optical sensor, which sends the information to the PLC control system. Subsequently, the Cognex In-Sight 5100C camera system is activated to perform a visual inspection of the semi-finished product. The camera identifies the presence of the object, determines its position, and simultaneously performs a pass/fail inspection based on the detection of characteristic features on the object's surface.

After the visual inspection is successfully evaluated, a handling operation is performed by an ABB IRB 1100 industrial robot equipped with a suction cup gripper. The robot picks up the semi-finished product from the conveyor and moves it to a fixture mounted on a linear pneumatic mechanism. If the semi-finished product is evaluated as defective (NOK), it is automatically sorted out by the pneumatic mechanism into a separate storage area designated for defective parts. If the part is acceptable (OK), the semi-finished product is clamped in the fixture and moved to the work zone designated for performing machining operations.

Once the technological position is reached, machining and assembly are performed by a KUKA KR 3 R540 AGILUS industrial robot. The robot is equipped with a technological fixture that allows for the exchange of working tools. First, the robot grasps the drilling head and performs the operation of drilling holes into the body of the workpiece. After completing this operation, the robot sets down the drilling tool and grasps the screwing head intended for assembling the mating part.

The Photoneo PhoXi L 3D scanning system is used to identify mating parts; using the Photoneo Bin Picking Studio software tool, it analyses the acquired point cloud and identifies the position of the nearest available component. The robot then grasps the identified mating part, moves over the machined workpiece, and screws it in place.

After completing the assembly operation, the KUKA robot returns to its home position, and the finished product is moved by a handling mechanism to the output area designated for correctly manufactured parts. The robotic workstation then returns to its initial state, and the PLC control system initiates the processing of the next semi-finished product.

The sequence of individual technological operations performed at the robotic workstation is shown in Fig. 4.

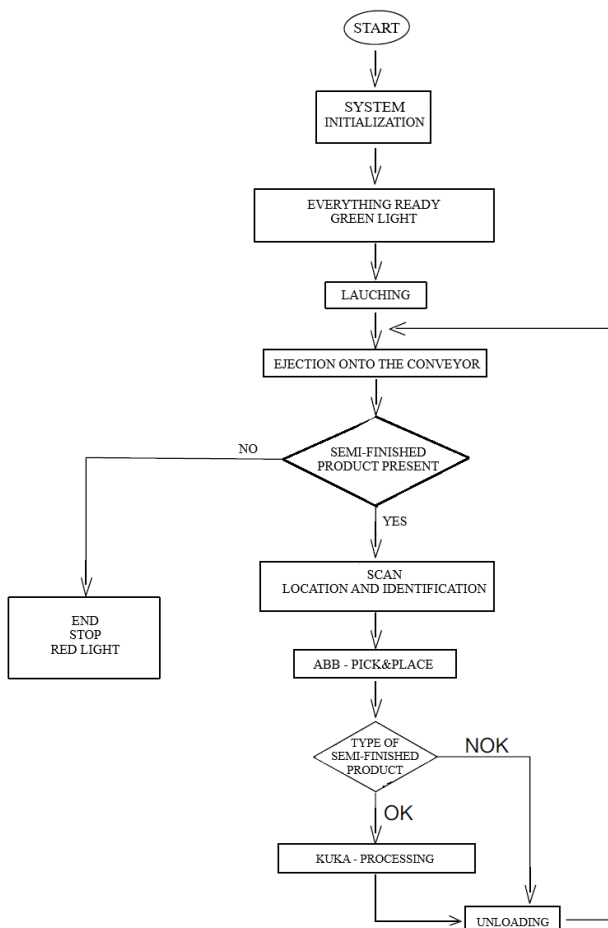


Figure 4. Sequence diagram of the technological process executed at the robotic workstation.

4 PROPOSAL FOR A METHODOLOGY FOR COORDINATING ROBOTIC WORKSTATION DEVICES

The robotic workstation described in the previous chapter consists of several heterogeneous devices that must be coordinated with one another during the manufacturing process. These include industrial robots from various manufacturers, camera and sensor systems, pneumatic components, and a conveyor system. Proper coordination of these devices is essential to ensure a smooth and safe production process.

However, integrating such devices within a single production system presents a significant technical challenge. Devices from different manufacturers often use different control architectures, communication protocols, and methods of data exchange. In practice, therefore, there is often no unified and systematic procedure that would allow for the simple interconnection of heterogeneous robotic systems and peripheral devices into a single functional unit.

For these reasons, a methodology for coordinating robotic workstation equipment based on centralized control via a PLC was proposed. The proposed methodology defines the method of interconnecting individual robotic workstation devices, the structure for exchanging control and status signals, and the principle of sequential coordination of technological operations during the production cycle.

The methodology was designed with an emphasis on ease of implementation, clarity of data flows, and the possibility of application to other types of robotic workstations consisting of equipment from different manufacturers.

The overall workflow of the proposed coordination methodology is illustrated in Fig. 5.

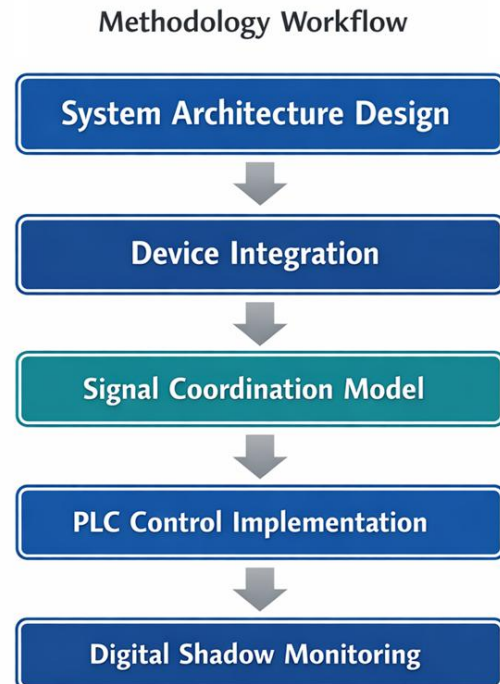


Figure 5. Workflow of the proposed methodology for coordinating heterogeneous robotic workstation devices.

The proposed methodology is structured into five consecutive steps, as illustrated in Fig. 5. The workflow starts with the definition of the robotic workstation architecture and continues with the integration of individual devices, definition of the signal coordination model, implementation of the PLC control logic, and integration of the digital shadow. Each step defines specific inputs, processing activities and outputs that serve as the basis for the subsequent step. This structure provides a systematic procedure for integrating heterogeneous robotic and peripheral devices within a common PLC-centric control architecture.

The first step defines the architecture of the robotic workstation and the relationships between its individual technological elements. The main input is the required technological process, including the required sequence of operations and the devices needed to perform them. Based on these requirements, the physical arrangement of the robots, conveyor system, vision system, pneumatic devices and technological equipment is defined, together with the role of the PLC as the central control unit. The output of this step is the defined system architecture, including the identification of the devices, their functional roles and the basic communication relationships between them.

The second step focuses on the integration of the individual devices into the defined control architecture. The input consists of the selected devices and the communication interfaces available for their integration. Each device is connected to the PLC-based control system according to its functional role and communication requirements. The integration includes industrial robots from different manufacturers, the Cognex vision system, the conveyor system and pneumatic components. The output of this step is an integrated set of robotic workstation devices accessible through the common control architecture.

The third step defines the signal-based coordination model used for synchronization between the PLC and the connected devices. The input is the set of control and status signals

identified during the device integration phase. For robotic operations, the coordination model is based on the READY, BUSY and DONE status signals. The PLC uses these signals to determine whether a device is ready to receive a command, whether the requested operation is in progress, and whether the operation has been completed. The output of this step is a defined signal-handshake structure that forms the basis for sequential coordination of the manufacturing process.

The fourth step consists of implementing the coordination logic in the Siemens S7-1500 PLC. The input is the defined robotic workstation architecture and signal coordination model. The PLC program processes input signals from sensors and individual devices and generates control signals according to the defined sequence of technological operations. The production cycle is divided into sequential process steps, with the transition to the next step depending on the corresponding status or completion signals. The output of this step is the implemented PLC control sequence coordinating the operation of the robotic and peripheral devices within the manufacturing cycle.

The fifth step extends the control architecture with a monitoring layer based on the digital shadow concept. The input consists of selected process variables available in the PLC control system, including device status information, process state variables and selected robot data. These variables are made available through the OPC UA communication interface and transferred to the virtual robotic workstation model developed in the Tecnomatix Process Simulate environment. The received data are used to update the corresponding elements of the virtual model and to visualize the current state of the physical robotic workstation. The output of this step is a digital representation of the workstation that reflects selected process states and robot movements based on data obtained from the physical system.

The resulting methodology therefore establishes a continuous workflow from the initial definition of the robotic workstation architecture to device integration, signal-based coordination, PLC implementation and monitoring of the physical robotic workstation through its virtual representation.

4.1. Data flow structure

The proposed coordination methodology is based on a centralized control architecture in which a Siemens S7-1500 programmable logic controller serves as the main control unit. The PLC ensures the coordination of individual technological devices in the robotic workstation, the processing of input signals from sensors, and the generation of control signals for individual devices involved in the production process.

Communication between the individual devices in the robotic workstation is implemented via the PROFINET industrial communication network, which enables deterministic and reliable data exchange between the control system and the connected devices. Through this network, ABB IRB 1100 industrial robots with OmniCore C30 control units and KUKA KR 3 R540 AGILUS robots, the Cognex In-Sight 5100C camera system, the Photoneo PhoXi L 3D scanner, and the SMC EX260 pneumatic island are integrated into the control architecture.

The PLC control system collects status information from the robotic workstation equipment and simultaneously controls the course of the technological process via control signals. Thanks to centralized control, it is possible to ensure the synchronization of individual operations and the coordination of robotic manipulators and peripheral devices within a single technological cycle.

The system architecture also includes the implementation of a monitoring layer based on the concept of a digital shadow of the robotic workstation. The digital shadow is implemented via the OPC UA communication protocol, which enables the transfer of selected process data from robotic workstation devices to the monitoring application. In this case, the PLC serves as a central communication hub that collects status information from robotic workstation devices and makes it available via the OPC UA interface.

The transmitted data includes, for example, status signals from robotic manipulators, information from sensor systems, the status of the conveyor system, and selected operational variables of the robots, such as the positions of individual joints or the status of the operation being performed. This data is then used to update the virtual model of the robotic workstation created in the Tecnomatix Process Simulate environment, which represents a digital shadow of the physical process system.

Through the digital shadow, it is possible to monitor the progress of the process, the movement of robotic manipulators, and selected operational parameters of the robotic workstation in real time. The architecture implemented in this way also demonstrates the possibilities for integrating robotic workstation control systems with digital manufacturing tools in an Industry 4.0 environment.

The overall architecture of the robotic workstation control system is shown in Fig. 6.

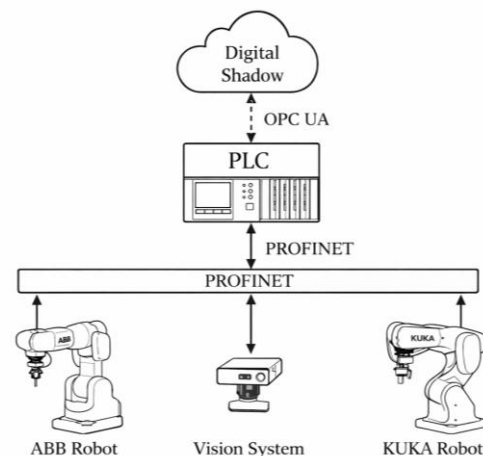


Figure 6. PLC-centric communication architecture of the robotic workstation integrating industrial robots, vision systems and digital shadow monitoring

4.2. Control signal exchange model

The coordination of individual devices within the proposed methodology is based on a signal-handshake model managed by the PLC. The purpose of this model is to provide a structured sequence for initiating, executing and completing individual operations within the production cycle. The handshake principle enables the PLC to determine the current state of the connected devices and to initiate the subsequent process step only after completion of the preceding operation.

At the beginning of the production cycle, the PLC initializes the connected devices and verifies that the required conditions for operation are fulfilled. When the robotic workstation is ready, the READY state indicates that the system is prepared to execute the next operation. After receiving the start command from the operator, the PLC initiates the corresponding process sequence. During execution of an individual operation, the system remains in the BUSY state. Once the operation has been

successfully completed, the DONE state is generated. The PLC evaluates this state and automatically proceeds to the next predefined process step.

The coordination sequence can therefore be represented by the states READY → COMMAND → BUSY → DONE → READY, where each state represents a defined stage of the technological operation. The DONE state does not terminate the complete production cycle; instead, it confirms the completion of the current operation and allows the PLC to continue with the next operation according to the predefined sequence.

In addition to the normal operating sequence, an ERROR state is used to indicate an interruption or condition preventing further execution of the production process. Such a state may occur, for example, when no further workpiece is available or when the safety system interrupts the operation. In this case, the PLC interrupts the current sequence and prevents further operation until the corresponding condition is resolved and the system can be initialized again.

The described signal-handshake model provides a common coordination principle for devices from different manufacturers. Instead of requiring direct communication between the ABB and KUKA robot controllers, the PLC evaluates the status of individual devices and determines when the next operation can be initiated. This approach enables the individual devices to remain functionally independent while their operations are coordinated within a common production sequence.

The principle of control signal exchange between the PLC and individual robots is illustrated in Fig. 7.

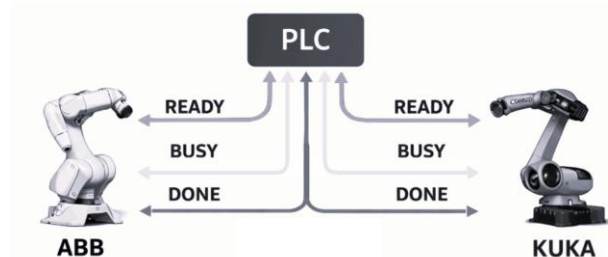


Figure 7. Signal-based coordination model between PLC and ABB and KUKA robots using READY–BUSY–DONE states.

Variable	Description	System response
READY	Workstation/device is initialized and ready for operation	PLC can initiate the next operation
COMMAND	PLC issues a command to start the required operation	The corresponding device starts the operation
BUSY	Current operation is being executed	PLC waits for completion
DONE	Current operation has been completed	PLC proceeds automatically to the next process step
ERROR	Production sequence is interrupted by an abnormal condition	PLC interrupts the sequence and prevents further operation

Table 1. Description of the signal-handshake states used for device coordination

4.3. Sequential coordination of the technological process

The sequential coordination of the manufacturing process is carried out via a PLC control program, which ensures the step-by-step execution of individual operations in the production cycle. The control system processes input signals from sensors and based on these, activates the individual operations of the robotic manipulators and peripheral equipment on the robotic workstation.

The process begins with the detection of a semi-finished product in the workspace of the conveyor system. After the semi-finished product is brought into the inspection position, the Cognex In-Sight 5100C camera system is activated, which performs a visual inspection to verify the presence of the semi-finished product and evaluates its condition in OK/NOK mode. Based on the result of this inspection, the PLC control system determines the next steps in the manufacturing process.

If the part is correctly positioned, the ABB IRB 1100 industrial robot is activated to perform the handling operation. The robot grasps the semi-finished product using a suction cup gripper and moves it to a technological fixture designed for performing further operations. If the part is evaluated as defective, the control system ensures its automatic removal from the production process via a pneumatic mechanism to a designated location.

After placing the OK-type semi-finished product into the technological position, the machining and assembly phase is performed by the KUKA KR 3 R540 AGILUS industrial robot. The robot is equipped with a technological fixture that allows for the exchange of working tools. In the first phase, the robot performs the operation of drilling holes into the body of the semi-finished product, using a drill head stored in the tool magazine.

Next, the Photoneo PhoXi L 3D scanning system is activated; using the Photoneo Bin Picking Studio software tool, it identifies the location of available mating parts intended for assembly. The KUKA robot then grasps the identified mating part and performs the operation of screwing the mating part onto the machined part.

After completing the assembly operation, the robot returns to its home position, and the PLC control system activates the mechanism to move the finished product to the robotic workstation's output area. The next production cycle is then initiated.

This principle of sequential coordination allows the PLC control system to ensure the synchronization of the operations of individual robotic workstation devices and to coordinate the operations of robots from different manufacturers within a single technological process.

4.4. Integration of the digital shadow of the robotic workstation

Part of the implementation of the proposed coordination methodology involves creating a digital shadow of the robotic workstation, which enables real-time monitoring of the technological process and visualization of the status of individual robotic workstation devices. The digital shadow is a virtual representation of the physical system that is continuously updated based on process data obtained from the robotic workstation's control system.

The virtual model of the robotic workstation was created in the Tecnomatix Process Simulate environment, which enables the modelling of manufacturing systems, the simulation of robotic operations, and the visualization of technological processes.

The model contains virtual representations of robotic manipulators, technological equipment, and the workspace that correspond to the physical configuration of the experimental robotic workstation.

The connection between the physical robotic workstation and its virtual model is implemented via the Siemens S7-1500 PLC control system, which serves as the central communication hub in the proposed architecture. The PLC collects status information from the robotic workstation equipment and makes selected process variables available to external applications via the OPC UA communication interface.

The transmitted data primarily includes status information from robotic manipulators, information from sensor systems, results of visual part inspection, the status of the conveyor system, and the current phase of the technological process. The transmitted data also includes selected operational variables of the robots, such as the positions of individual joints of the robotic manipulator or the status of the operation being performed.

This data is subsequently used to update the virtual model of the robotic workstation in the Tecnomatix Process Simulate environment, ensuring synchronization between the physical system and its digital representation. The digital shadow thus enables real-time monitoring of robotic manipulator movements, the progress of technological operations, and the current status of the manufacturing process.

The implemented digital shadow also provides an additional monitoring layer on top of the robotic workstation control system and demonstrates the possibilities for integrating robotic workstations with digital manufacturing tools. This approach is in line with Industry 4.0 concepts, where the interconnection of physical manufacturing systems with digital models that enable the monitoring and analysis of manufacturing processes plays a crucial role.

4.4.1. OPC UA data model for the digital shadow of robotic workstation

To ensure communication between the physical robotic workstation and its digital model, a data model based on the OPC UA communication standard was implemented. This model enables the structured provision of selected process variables from the PLC control system to external applications used for monitoring and visualizing the technological process.

In the proposed architecture, the Siemens S7-1500 PLC control system acts as an OPC UA server, making available selected process variables representing the current status of individual devices in the robotic workstation. These variables are subsequently used in the Tecnomatix Process Simulate environment to update the virtual model of the robotic workstation, thereby ensuring synchronization between the physical system and its digital representation.

The architecture of the digital shadow of the robotic workstation and the data flow between the physical system, PLC, and the virtual model are illustrated in Fig. 8.

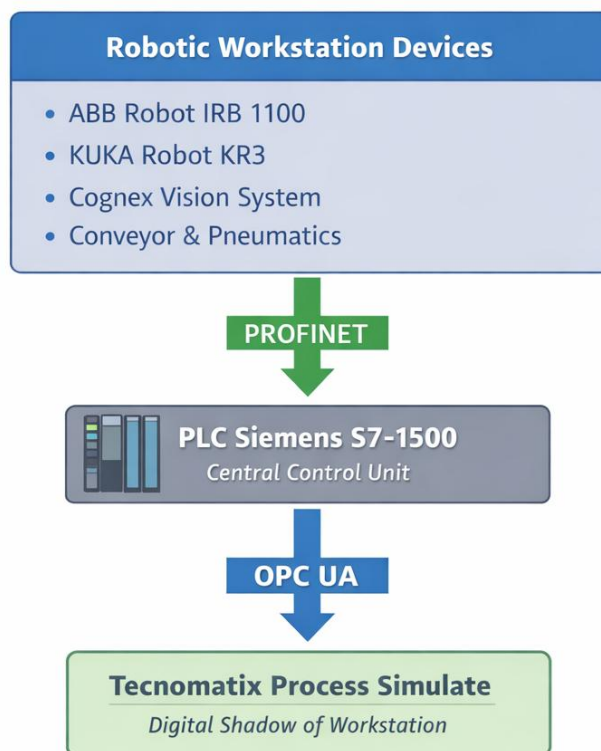


Figure 8. Architecture of the digital shadow of the robotic workstation showing data flow from devices through PLC via OPC UA to Tecnomatix Process Simulate.

The digital shadow data model contains variables representing the status of individual pieces of equipment and the progress of the manufacturing process. The main categories of transmitted data include:

- RobotABB_JointPositions – current values of the joint variables of the ABB IRB 1100 robot
- RobotKUKA_State – status of the operation being performed by the KUKA KR 3 R540 AGILUS robot
- VisionInspection_Result – result of the visual inspection of the part in OK/NOK mode
- Conveyor_Status – status of the conveyor system and presence of a workpiece in the work zone
- ProcessStep – current phase of the technological cycle controlled by the PLC system

These variables are transmitted via OPC UA communication to the Tecnomatix Process Simulate environment, where they are used to update the status of the digital model of the robotic workstation. Based on the received data, it is possible to monitor the movement of robotic manipulators, the progress of technological operations, and the current state of the manufacturing process in the digital model.

The defined data model includes variables describing the state of robotic manipulators, sensor systems, conveyor operation, and the current phase of the technological process. The main variables used within the OPC UA data structure are summarized in Table 2.

Variable	Data Type	Description
ABB_JointPositions	REAL[6]	Joint values of ABB IRB 1100 robot
KUKA_State	INT	Current operation state of KUKA robot
VisionInspection_Result	BOOL	Result of visual inspection (OK/NOK)
Conveyor_Status	BOOL	Status of conveyor system
ProcessStep	INT	Current phase of the technological process

Table 2. OPC UA variables used for digital shadow implementation

The data model defined in this way enables the integration of the robotic workstation control system with digital manufacturing tools and lays the foundation for implementing a digital shadow of the production system, which can be used to monitor, analyse, and optimize manufacturing processes.

5 DISCUSSION

The proposed methodology for coordinating heterogeneous robotic systems was implemented in a robotic workstation consisting of industrial robots from various manufacturers and several peripheral devices. Within the proposed architecture, a programmable logic controller (PLC) serves as the central control unit, ensuring the coordination of individual technological operations and the exchange of control signals between robotic workstation devices. This approach enables centralized control of the technological process and ensures the synchronization of activities among individual devices involved in the production cycle. The implementation of the methodology at a functional robotic workstation also demonstrates the feasibility of coordinating heterogeneous robotic systems and peripheral devices through a PLC-centric control architecture.

The issue of coordinating multiple robotic systems is often addressed in the technical literature in the context of multi-robotic systems or distributed control architectures. For example, Verma and Ranga analyse various strategies for coordinating robotic systems and emphasize the importance of synchronization mechanisms and effective communication between individual robotic units [Verma 2021]. Similarly, Wan et al. present the concept of a reconfigurable smart factory in which robotic systems are integrated via network technologies and cloud services [Wan 2019].

Compared to the approaches mentioned above, the proposed methodology focuses primarily on the practical integration of heterogeneous robotic systems within a PLC-centric architecture, which is widely used in industrial manufacturing systems. This approach provides a comparatively straightforward architecture for interconnecting robots from different manufacturers and peripheral devices through a common PLC-based control layer. The proposed methodology thus reflects the real-world requirements of industrial applications, where PLC systems often serve as the fundamental control element of technological robotic workstations.

Although PLC-based coordination architectures are commonly applied in industrial automation, for example in robotic machine tending or robot-CNC integration applications, the proposed methodology extends this concept towards the coordinated integration of multiple heterogeneous devices

within a single manufacturing robotic workstation. In contrast to typical robot-machine communication scenarios, the presented approach integrates industrial robots from different manufacturers together with machine vision systems, a 3D scanning system, pneumatic devices and a digital shadow environment connected through OPC UA communication. The contribution of the work therefore lies not in the introduction of a new control principle, but in the development of a structured and practically validated methodology for the integration and coordination of heterogeneous industrial technologies within a unified PLC-centric architecture.

From the perspective of the Industry 4.0 concept, the ability to integrate various devices via standardized communication technologies is also significant. As noted by Lu [Lu 2017] and Xu et al. [Xu 2018], interoperability and data exchange between devices are key elements of modern smart manufacturing systems. In the proposed methodology, this principle is implemented with the PROFINET industrial communication network for control communication between individual robotic workstation devices and through the OPC UA protocol for data transfer to the digital shadow of the robotic workstation.

An important aspect of the proposed methodology is its practical applicability in an industrial setting. Unlike many research approaches that focus primarily on simulation or theoretical models of robot coordination, the proposed methodology is based on the use of commonly available industrial automation components, such as PLC control systems, standardized communication networks, and industrial robotic systems. The aim of the presented work was not the quantitative evaluation of system performance, but the development and practical verification of a methodology for coordinating heterogeneous robotic systems within a PLC-centric control architecture. This approach enables the implementation of the methodology in real production systems without the need for fundamental changes to the existing control architecture.

Another significant feature of the proposed solution is its modular nature. The methodology allows for the relatively simple integration of additional devices or robotic systems into the existing control architecture. Such an approach is particularly important in modern manufacturing systems, where it is often necessary to expand or reconfigure production robotic workstations depending on current production requirements.

The implementation of a digital shadow of a robotic workstation via the OPC UA protocol also demonstrates the possibilities for integrating a physical manufacturing system with its virtual representation in a digital manufacturing environment. Real-time monitoring of process data from individual robotic workstation devices enables better visualization of the technological process and provides a foundation for further data analysis or optimization of production operations.

Despite the aforementioned advantages, it should be noted that the proposed methodology was demonstrated on a specific robotic workstation, and its implementation may require modifications depending on the configuration of the specific production system. In the future, it would be possible to extend the methodology, for example, to include the coordination of a larger number of robotic systems, the integration of higher control levels of production systems, or the implementation of advanced analytical tools for processing production data.

6 CONCLUSIONS

The article addressed the design of a methodology for coordinating heterogeneous industrial robots and peripheral devices within advanced manufacturing systems. The main objective of the work was to develop a systematic procedure enabling the integration of robotic systems from different manufacturers, along with other technological equipment, within a single robotic workstation.

The proposed approach is based on a PLC-centric control architecture, which ensures centralized coordination of individual devices within the manufacturing system. The methodology defines a structured model for the exchange of control and status signals between robotic workstation devices and the principle of sequential coordination of technological operations during the production cycle. The synchronization of individual devices is implemented via a signal-handshake model based on the READY, BUSY, and DONE status signals, which enables reliable coordination of robotic manipulators and peripheral devices.

The proposed methodology was demonstrated at a robotic workstation integrating ABB IRB 1100 and KUKA KR 3 R540 AGILUS industrial robots along with other technological devices, such as the Cognex In-Sight 5100C camera system, the Photoneo PhoXi L 3D scanning system, and the SMC EX260 pneumatic island. The implementation of the methodology enabled the coordination of handling and technological operations performed by individual robotic systems within a single production cycle.

The proposed methodology was practically implemented and validated on a physical robotic workstation under laboratory conditions. The validation confirmed the successful integration and coordination of heterogeneous industrial devices, including ABB and KUKA robotic systems, machine vision technologies, pneumatic components and conveyor transport. The conducted tests verified the functionality of the proposed PLC-based coordination architecture, the signal-handshake communication model and the synchronization of technological operations within the production cycle. Furthermore, the OPC UA communication interface successfully enabled real-time data transfer between the physical robotic workstation and its digital shadow implemented in the Tecnomatix Process Simulate environment.

The proposed solution also included the implementation of a digital shadow of the robotic workstation via the OPC UA communication protocol. Process data obtained from the robotic workstation equipment is transferred to a virtual model created in the Tecnomatix Process Simulate environment, which enables monitoring of the technological process and synchronization between the physical robotic workstation and its digital representation.

The proposed methodology represents a practically implementable approach for the integration of heterogeneous robotic systems and peripheral devices in modern manufacturing robotic workstations. In the future, it would be possible to extend the methodology, for example, to include the coordination of a larger number of robotic systems, the integration of higher control levels of production systems, or the implementation of advanced analytical tools for processing production data.

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