MINISTRY OF EDUCATION AND RESEARCH
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DOCTORAL THESIS

Web-based monitoring platform for Digital Twin-enabled robotic manufacturing systems

Platformă informatică pentru monitorizare via internet a funcționării sistemelor de producție robotizate

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Chapter I. Monitoring manufacturing systems

Section 1. Introduction

In the era of Digital Transformation (Kraus et al., 2021; Nadkarni et al., 2021) businesses are embracing and implementing computer-based technologies to build or enhance processes employing continuous, agile approaches. Innovation is essential for companies to adapt and cope with the demands of change as the world evolves quicker than ever before, primarily due to technological advances. In modern manufacturing, the joining of Information Technologies (IT) and Operational Technologies (OT), also known as the OT/IT Convergence (Patera et al., 2021), is having a revolutionary effect.

Industry 4.0 is an umbrella term that promotes key enabling technologies for the ongoing industrial revolution, including the Industrial Internet of Things (IIoT), Cyber-Physical Production Systems (CPPS), Digital Twin (DT), Cloud Computing, Machine Learning (ML) technologies, among others. Web Services, MQTT, and APIs are prevalent methods in modern manufacturing processes for achieving interoperability, which is the capability of devices and systems to communicate with one another. CPPS refers to the interconnected machines in a factory, in which the state and actions of one machinery affect the others. The manufacturing system's performance and condition can be assessed by employing sensors to collect and process data on each device and system.

Cloud computing is a model of service delivery and access where dynamically scalable and virtualized resources are provided as a service with high reliability, scalability, and availability over the Internet. The deployment of edge computing technologies is advancing concurrently with the advancement of IIoT and is one of the most rapidly expanding sectors of industrial automation. Edge computing moves probing closer to the source, while reducing latency and ensuring reliable collection of real-time data. Consequently, new IIoT systems are shifting from centralized cloud-computing which are ideal for non-real-time application that require vast amounts of storage and high-processing power, to distributed intelligent edge computing, suitable for real-time services as they exhibit low latency.

1.1. Web-based monitoring and control of industrial processes

The next generation factory floor features collaborative robots, CNC machinery, enhanced service robots and HMI technology. Availability and maintainability are critical for all machinery. The modern manufacturing architecture must consider the concurrency and synchronization requirements of interconnected CPSs. Concurrent CPSs must be fault and failure tolerant with diagnostic subsystems designed for real-time localization and repair. Another important aspect in CPSs is reliability, which refers to the probability of a system performing its required functions, without failure, for a specified duration when used under specified conditions.

IoT's primary application is the ability to remotely manage and monitor machines. In industrial automation, remote monitoring and visualization of data are crucial for operation, maintenance planning, incident analysis, and optimization. Remote equipment control is necessary in situations where machines are inaccessible or pose risks to human safety. The COVID-19 pandemic has emphasized the importance of remote access and control of critical processes and accelerated the development of cybersecurity technologies and services that protect factory floor assets using industrial Ethernet and Internet connections.

1.2. Condition monitoring for Predictive Maintenance

A robot’s repetitive operations must be performed precisely over time, posing a challenge for robot manufacturers who must ensure accurate fault detection and diagnosis. Research has been conducted on robot hardware, transmission faults, data acquisition, and anomaly detection algorithms. Common causes of accuracy loss include issues in the transmission system, faulty rolling bearings, and gear problems such as backlash, scuffing, and abrasive wear.

Maintenance refers to the technical and administrative procedures, including supervisory actions, that are used to keep an item in a functional state or restore it to that state for the duration of its design life or longer. There are four strategies for maintenance: run-to-failure, preventive (time-based), predictive (condition-based), and proactive. Condition Monitoring (CM) is a maintenance method that monitors operational assets, detects signs of degradation, diagnoses faults, and predicts remaining operational time. It aims to predict the health of a machine or system and can be performed online or offline (Wang et al., 2018). Techniques such as vibration, acoustic emission, wear particles, and temperature monitoring can be used. The CM process typically includes five steps: data acquisition, data analysis, feature extraction, decision making, and condition diagnosis.

1.3. Production monitoring and scheduling for Key Performance Indicators

In the manufacturing industry, a production Key Performance Indicator (KPI) is a metric used to evaluate the performance of the production process. Examples include the machine uptime rate, cycle time, throughput rate, and production attainment. Production Analytics software is a platform that provides real-time visualization and analysis of machines, equipment, and production data, allowing manufacturers to identify and address production losses. However, traditional manufacturing can face challenges in data processing, such as outdated equipment with limited computational capabilities and lack of standard interfaces and protocols between machines.

Section 2. Objectives of the Doctoral Thesis

Supervisory Control and Data Acquisition (SCADA) is a system of software and hardware components that enables industrial organizations to manage processes locally or remotely, to monitor and process real-time data, and to directly interact with devices via HMI software. SCADA systems are typically deployed to control and maintain efficiency, distribute data for informed decision-making, and communicate system faults to reduce downtime. Bridging the gap between OT and IT is one of the many roles of a SCADA system. The key capabilities of a SCADA system: to provide user-friendly HMI on the factory floor, to make OT data instantly available to operators, to enable remote monitoring and control. Businesses such as Microsoft Azure (Microsoft Azure, 2022) and Ignition (Inductive Automation, 2022) offer powerful and dedicated solutions to enable the digital transformation and the shift to intelligent manufacturing but are also costly.

The main goal of the thesis is to present the development of a web-based monitoring platform for DT-enabled robotic manufacturing systems. The underlaying purpose is to gain a comprehensive understanding of the smart manufacturing ecosystem and the interdependencies among its key enablers. Therefore, the following research objectives can be identified:

1. **Explore the latest research in the field of Industry 4.0** and present the State of the Art of its key enablers, specifically: the IIoT, CPS, DT, Robotic Cloud Computing, intelligent robotic systems, and ML. Despite the rapid emergence of innovative solutions and the rapid obsolescence of research, it is essential to have a fundamental understanding of the function and challenges of each core component.

2. **Develop a monitoring framework by identifying essential signals from the robot system, creating a robust data acquisition system, and developing a web-based monitoring system with advanced capabilities.** An analysis of the functions the framework must perform will determine the most suitable and freely available development resources, which later can be easily adopted and built upon by future researchers.

3. **Develop a DT-enabled robotic system that combines the CPS, DT, and IIoT paradigms, to form an intelligent robotic system.** Studies rarely address transdisciplinary research on complex robotic systems. Therefore, a holistic approach of developing the DT-enabled robotic deburring application will put into practice multidisciplinary abilities and may expose various challenges such as incompatibility between two components due to a lack of standardization or faults in conceptual approaches.

4. **To enable the digital transformation, people will require a diverse set of skills, therefore, it is important to investigate the impact Industry 4.0 has on society and education.** It is anticipated that there will be a shift in the capabilities of the workforce, and employers will be required to provide workers with training to accommodate to the transition. A survey of literature should identify the methodologies employed to foster a growing attitude and to reduce the gap between the education of engineering graduates and the skillset expectations of the workplace. Even though robots are widely mentioned in the Industry 4.0 literature, there is a scarcity of studies on teaching approaches for industrial robots employed in modern manufacturing.

The Doctoral Thesis is structured as follows:

- Chapter 2 introduces the State of the Art of Industry 4.0’s key enablers and their application in modern robotics.
- Chapter 3 presents the development and validation of the proposed web-based monitoring platform.
- Chapter 4 outlines the creation of a DT-enabled robotic deburring system with web-based monitoring capabilities.
- Chapter 5 examines the application of the web-based monitoring platform in the context of Education 4.0.
- Chapter 6 draws the concluding remarks and the original contributions.

Chapter II. Industry 4.0. Modern Robotics

2.1. Main objective and original contributions synopsis

The main objective of this chapter is to present the State of the Art of Industry 4.0's key enablers, specifically:

- Industrial Internet of Things (IIoT).
- Cyber-Physical Systems (CPS), Virtualization, and Digital Twins (DT).
- Robotic Cloud Computing.
- Intelligent Robotic Systems.
- Reinforcement Learning (RL).

This chapter provides for each key enabler a brief introduction, presents the specific characteristics, terminology, methods, and technologies, and highlights the challenges and recent advances. While there are a handful of literature evaluations on the role and characteristics of Industrial Robots in Smart Manufacturing, these are rarely extensive, and with the rapid development of related technologies, they quickly become obsolete.

Specific sub-objectives of this chapter:

- Balance the information: present ontologies to limit complexity and categorize methods and technologies.
- Identify the key enablers of Industry 4.0, the current innovative technologies and future research directions.
- Present the core components of Cyber-Physical Production System (CPPS) and their role in process planning, monitoring, sustainability, and security.
- Introduce Cloud Computing technologies and identify the innovative solutions applied in robotic systems.
- Highlight the essential elements of Human-Robot Collaboration systems (HRC).
- Outline the fundamental RL techniques for robotic assembly.
- Explore the social associations between the advanced technologies present in smart manufacturing (e.g., human-robot collaboration) and educational demands.

In this summary, only the key introductory elements and final conclusions have been extracted from the complete body of material.

Original theoretical contributions:

- Presented the State-of-the-Art technologies that shape the CPS and DT paradigms, as well as their specific characteristics and current challenges.
- Introduced the innovative technologies in Cloud Computing and outlined their strengths and weaknesses.
- Provided a comprehensive review of advanced solutions for HRC and addressed current the State-of-the-Art technologies.
- Presented a detailed overview of cutting-edge RL solutions applied in robotic assembly.

Section **1. Introduction to Industry 4.0 and Industrial IoT**

2.2. Introduction

The first three industrial revolutions were brought about by mechanization, the use of electrical energy, and the development of information technology. The Fourth Industrial Revolution was coined "Industry 4.0" by the German Federal Government and the core concept was originally presented at the Hannover exposition in 2011. One of the objectives of the initiatives is to establish intelligent factories where production methods and technologies are improved and transformed by the most recent developments in CPPS, networks and communication, cloud computing, and IoT technologies. Nevertheless, the Industry 4.0 concept comprises all enterprise functions and services, not just the manufacturing aspect.

The objective of this section is to provide a brief introduction to Industry 4.0 and its key enables, specifically the IoT and the IIoT.

Smart factories are advanced manufacturing organizations and factories that have implemented automation and digitalization to optimize productivity and streamline processes. Koren et al. (Koren et al., 2018) state that Reconfigurable Manufacturing Systems (RMS) are the latest development in manufacturing systems. In Industry 4.0 factories, machines can make autonomous decisions based on ML algorithms, real-time data acquisition, analytics results, and past successful behaviors.

The Industry 4.0 paradigm has the following dimensions:

- Strategy and organization
- Smart factory (equipment and IT systems, digital modelling)
- Smart operation (integration of value chain)
- Smart products (physical components)
- Data-driven services (ICT functionalities, prediction, and optimization)
- Human resources (employee skills, continuous education)

In the context of Industry 4.0, software tools play a crucial role in the operation of smart factories. Enterprise Resource Planning (ERP) systems are commonly used to manage a wide range of business activities, with SAP being the leading solution. Manufacturing Execution Systems (MES) handle production reporting, scheduling, dispatching, product tracking, maintenance operations, performance analysis, workforce tracking, and resource allocation. Supervisory Control and Data Acquisition (SCADA) systems and machine/device controllers such as Programmable Logic Controllers (PLCs) are used for process level controls on the operative level. The IoT connects industrial assets and machines to enterprise information systems and business processes, while ensuring reliability, sustainability, and productivity **(Stan et al., 2016)**. New IoT systems are shifting from *centralized cloud-computing* (ideal for non-real-time application that require vast amounts of storage and high-processing power) to *distributed intelligent edge computing* (suitable for real-time services as they exhibit low latency).

Although enormous efforts have been devoted to the design and development of IIoT technologies, the constantly evolving IIoT landscape and the introduction of new requirements and technologies provide new challenges or necessitate a reevaluation of established, widely accepted solutions.

Section 2. Cyber Physical Systems and Digital Twins

2.3. General aspects

CPS are systems that integrate computation, networking, and physical processes. They are characterized by the close connection between computational entities and the physical world. CPS used in the industrial domain (Fig. 2.1) are referred to as industrial CPS or CPPS, which are specialized forms of CPS that depend on recent and future advances in computer science, information and communication technologies, and manufacturing science and technology.

The objective of this section is to provide a comprehensive overview of the current advancements and developments in the fields of CPS, CPPS, and DT.

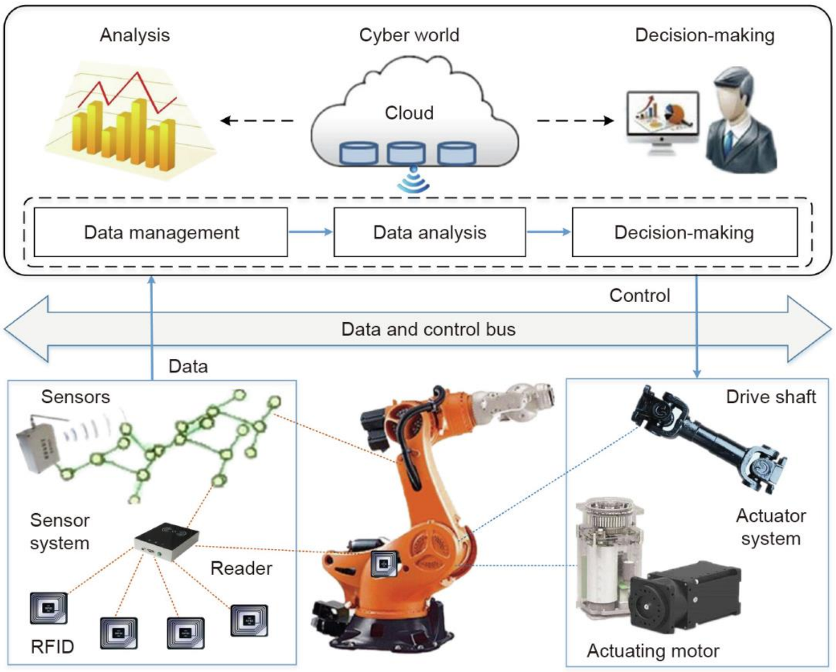


Fig. 2.1. Sensors and actuators can be considered the core elements of CPS (Tao et al., 2019).

The DT information encompasses a variety of categories, including physics-based models and data, analytical models and data, time-series data and historians, transactional data, visual models, and computations (Fig. 2.2). A study by Talkhestani et al. (Ashtari Talkhestani et al., 2019) suggests that a DT should possess three key characteristics: synchronization with real assets, active data acquisition, and the ability for simulation. Ugarte et al. (Ugarte Querejeta et al., 2020) analyzed the use of DT to facilitate a DevOps approach in CPPS, leading to a fully integrated and automated production process with the aim of continuous improvement. A DT is a formal digital representation of an asset, process, or system that captures its attributes and behaviors, and is designed for communication, storage, and processing. A discrete DT represents a single entity, while a composite DT is a collection of discrete DTs that represent an entity with many distinct elements or components.

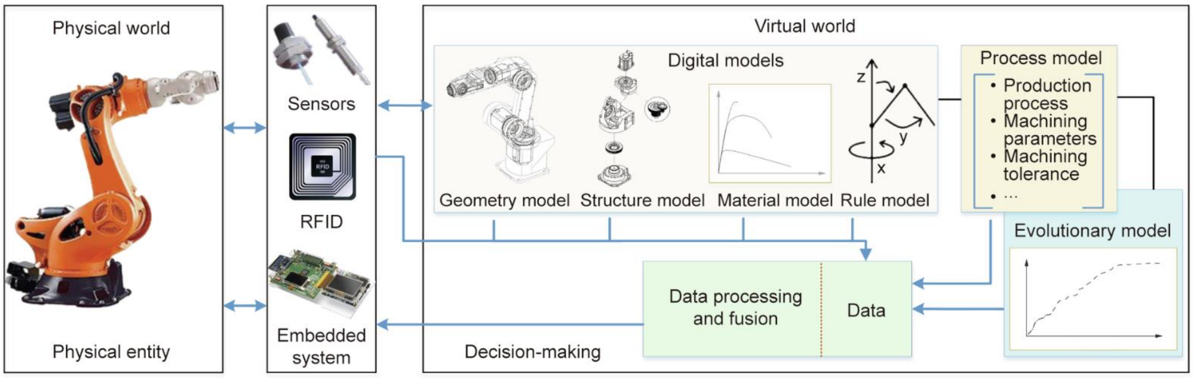


Fig. 2.2. Models and data can be regarded as the core elements of a DT (Tao et al., 2019).

Section 3. Edge, Fog, and Cloud Computing in Robotics

2.4. General aspects

Industry 4.0 is the concept of highly automated and flexible smart factories, utilizing connected and intelligent machinery for autonomous decision making. To achieve this, networks must provide guarantees for synchronization and robust security. Service-Oriented Architectures (SOAs) and Semantic Web Services (SWSs) can be employed to enable mass customization and reconfigurability. Supply chain integration is necessary for the successful implementation of Industry 4.0, with Semantic Web standards and technology playing a key role.

The objective of this section is to provide a brief introduction to Cloud, Edge, and Fog Computing and describe their current state.

Cloud-based manufacturing and Cloud robotics can aid in the realization of Industry 4.0, utilizing technologies such as cloud computing. The previous efforts to decentralize factory automation systems used SOA for CPS and IoT devices, but these approaches proved to be inefficient for real-time problems. Edge computing architectures have recently emerged as a more viable solution for decentralizing factory automation systems. By placing data processing and control functions at the edge of the network, edge computing enables real-time data analysis, low network traffic, and reduced operating costs. Cisco refers to the integration of cloud computing with edge computing as fog computing. The fog network serves as a layer between the cloud and the edge, providing the benefits of both. It enables low latency processing of large volumes of data, and bridges centralized and decentralized storage services. Consequently, edge and fog computing are alternative options for industrial automation, providing benefits such as cost-effectiveness and real-time data analysis and control.

Section 4. Robotic Systems for Smart Manufacturing

2.5. General aspects

The primary characteristic of a newly introduced type of industrial robot is its capacity to work safely alongside humans. Safety measures such as integrated sensors, passive compliance, and overcurrent detection are incorporated into the new generation of robots (Fig. 2.3). Human-robot collaboration (HRC) is the method that studies the interaction between a human and a robot during the execution of a mutual goal. A robot can safely work with humans physically or remotely to perform a task. Conventionally, it is called collaborative robot and it is built with specific technologies to comply with the ISO specification for designing and manufacturing collaborative robots (International Organisation for Standardization, 2019).

The objective of this section is to present the current state of Industry 4.0-driven robotics, with an emphasis on industrial robots, specifically articulated robots, employed in machining and assembly manufacturing.

The Industry 4.0 revolution called for the next generation of industrial robots which are designed to be more efficient and to collaborate with humans and other robots or machines allowing them to be self-aware and self-adaptable on new products and manufacturing processes (Lee et al. 2015). Nowadays, most cobots have embedded built-in features that ensure the safety ISO requirements, such as tactile sensors to detect contact. Although the CPPS are key enablers of Industry 4.0, *the cobots* and *the HRC systems* have emerged as the most exciting and promising examples of robots in modern manufacturing.

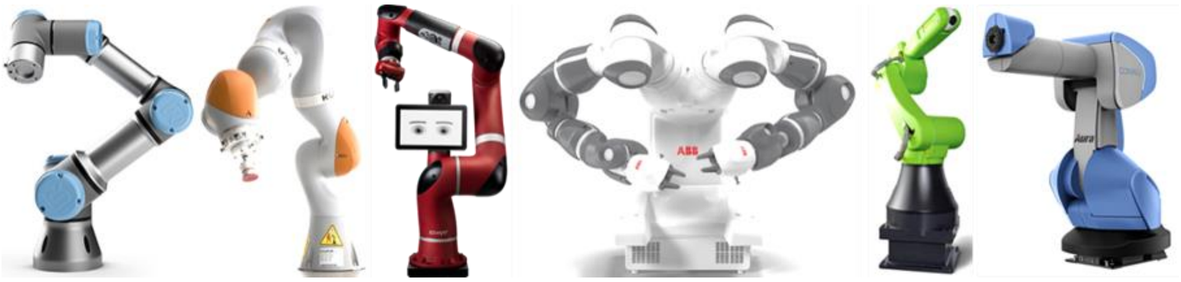


Fig. 2.3. Collaborative robots – the next generation of industrial robots.

The main challenges in HRC include its safety and developing intuitive programming techniques for non-experts. To achieve safety, various mechanical, sensory, and control features can be integrated, and coordination and collision prevention must be implemented. Additionally, HRC requires the development of novel programming techniques, such as walk-through programming or learning by demonstration.

Section 5. Machine Learning for Assembly Robots

2.6.General aspects

Artificial Intelligence (AI) is a field of study that aims to make machines function effectively and with forethought in their environment. IoT devices are intelligent machines, while AI is the collective property of a machine to perform functions such as learning or decision-making. Reinforcement Learning (RL) is a potential approach for devising difficult-to-engineer adaptive solutions for complex and distinct robotic jobs **(Stan et al., 2020)**.

The objective of this section is to provide a comprehensive introduction to RL, highlight recent remarkable advancements, and examine their potential impact on the development of robotic systems. An overview of the current state-of-the-art RL methodologies is presented, along with an evaluation of the current challenges and future development opportunities.

RL is crucial for transforming an industrial robot designed for a fixed and repetitive activity into a "smart manipulator" capable of learning and performing a desired task, without an explicit task-specific controller to meet the demands of custom manufacturing. Research in precise, collision-free trajectory tracking with optimal control is ongoing, especially for robot arms in tasks such as pick-and-place, peg-in-hole, fabric folding, and irregular surface monitoring while avoiding self-collisions and cooperative handling operations. RL tasks addressing the security and energy consumption of robots have also been studied.

Deep Learning (DL) has been effectively applied to numerous important domains, including computer vision, robotics, and RL. However, current limitations include scaling up to complex robot tasks, devising strong policy representations, and optimizing processing time. Despite these promising results, applications of RL to industrial robots are currently limited due to the effort required to set up the learning framework and the lack of experimental evaluation of RL-based approaches. Learning from demonstration (LfD) is a method in which agents acquire new skills by imitating an expert. LfD enables robots to learn optimal actions in unstructured environments without imposing a major burden on the operator. Imitation Learning (IL) is an alternative approach to RL for solving sequential decision-making problems. It seeks to train a policy to imitate the behavior of an expert, given just the expert's demonstrations. It has two primary methods: behavior cloning and inverse RL.

Robotic assembly is a manufacturing process in which a robot positions, matches, fits, and assembles interchangeable parts or sub-assemblies to produce a functional product. This process requires high levels of repeatability, dependability, adaptability, and sequencing. Traditional robotic-assembly systems rely on manual assembly sequences, but in smart factories, an RL-based approach is necessary for successful assembly. This approach must be able to plan correct sequences, plan individual and collision-free movements, calculate necessary forces and torques, and estimate the pose of assembly parts. Additionally, the RL model must ensure the robot is equipped with the appropriate end-effectors, presenting researchers with major challenges in the field.

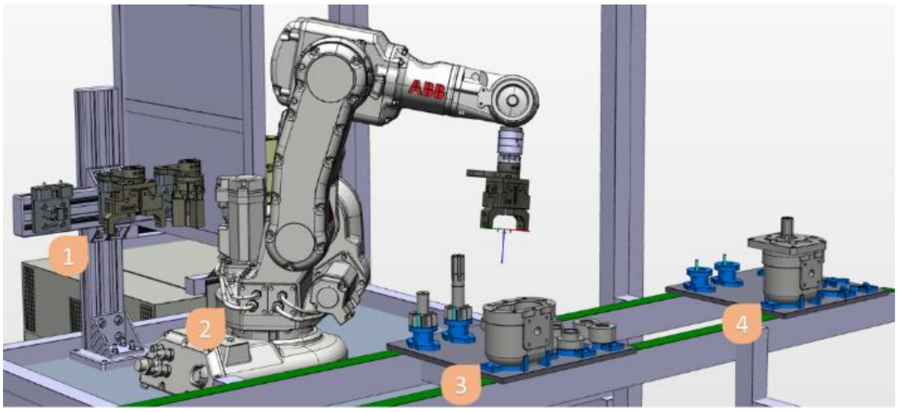


Fig. 2.4. Typical setup of a robotic assembly cell: tool storage unit (1), robot with modular gripping system (2), parts to be assembled (3), finished functional product (4).

Assembly sequence planning (ASP) has been an active research field, with algorithm-based solutions presented to improve assembly efficiency, reduce costs, and shorten development cycles. In the context of future smart factories, Watanabe, and Inada (Watanabe et al., 2020) recently proposed a computational technique for searching the optimal assembly sequence and work assignment.

Section 6. Conclusions

This closing section summarizes the conclusions and highlights the original contributions.

The Industry 4.0 paradigm and Virtualization.

Industry 4.0 is an initiative that emphasizes the extension of traditional production systems to complete integration of physical, embedded, and information technology systems, including the Internet. It highlights three implementation features: (1) *horizontal integration* through value networks, (2) *end-to-end digital integration* of engineering across the entire value chain, and (3) *vertical integration* and networked manufacturing systems. The implementation guidelines require action in several areas, including standardization and reference architecture, managing complex systems, work organization, safety and security, resource efficiency, and professional training.

The IoT connects industrial assets and machines to enterprise information systems and business processes, while ensuring reliability, sustainability, and productivity **(Stan et al., 2016)**. New IoT systems are shifting from *centralized cloud-computing* (ideal for non-real-time application that require vast amounts of storage and high-processing power) to *distributed intelligent edge computing* (suitable for real-time services as they exhibit low latency).

Reconfigurable Manufacturing Systems (RMS) are the most recent advancement in manufacturing system development that can enable Mass Customization. Key fundamental technologies for RMS are edge and cloud computing, virtualization and intelligent DT, CPS, and advanced ML techniques. The DT-driven DevOps approach of CPPS to create a fully integrated and automated production process, enabling continuous improvement has potential to become a mandatory method of designing processes in Smart Manufacturing.

Sustainability and digitization are two main manufacturing advancements that will have a substantial impact on the planning and management of future factories. Achieving energy efficiency and improving product life-cycle management are envisioned by the Industry 4.0 concept. Integrating energy management systems with CPS lead to Energy-Cyber-Physical Systems (CPES) which employ various optimization techniques to control the energy consumption of production systems. Cyber-Physical Production Monitoring Service System (CPPMSS) for collaborative production monitoring often employ web-based technologies to facilitate the collaborative work among customers, manufacturers, and equipment providers, focusing on the production and equipment status, and energy consumption monitoring.

Cloud robotics.

Cloud robotics is an intersection between robotics, cloud computing, deep learning, IoT, and other emerging technologies. Benefits of cloud computing: cost-effective scalability, high computing and storage capacity, modern data analytics and visualization services. Edge computing architectures have created a strong offering for decentralizing factory automation systems in recent years through the placement of data processing and control functions at the network's very edge. Consequently, edge computing is a major alternative for designing IoT frameworks involving industrial automation and real-time control. Benefits of edge computing: no delays in data processing which enables real-time data analysis, low network traffic, and reduced operating costs. Additionally, utilizing a decentralized network architecture known as "fog computing" serves as a bridge between the cloud and the edge, allowing for the benefits of both to be employed.

DT-based frameworks featuring cloud computing capabilities for robotic applications have become an important presence in Smart Manufacturing. Numerous studies have demonstrated that edge computing can satisfy the industry’s digital transformation requirements for intelligence, connectivity, data optimization, real-time, and security, while the fog computing can provide local computing support in the IIoT environment. This next-generation level of evolution is centered on advanced analytics, which, when applied to machine, process, and network data, provides new insights for better decision-making, and enable smart operations, resulting in impactful business outcomes and social benefit.

Intelligent Robotic Systems.

The Industry 4.0 revolution demanded the next generation of industrial robots which are designed to be more efficient, to collaborate with humans and other robots or machines, and to be self-aware and self-adaptable to new products and manufacturing processes. Although the Cyber-Physical Production Systems (CPPS) are key enablers of the Industry 4.0, the Human-Robot Collaboration Systems (HRCS) have emerged as the most engaging and promising instances of robotics in modern manufacturing. HRCS combines human dexterity and intelligence with robot precision and repeatability in a shared workspace. Advanced sensors and software enable safe physical engagement, intuitive manipulation, and collision-free operations, facilitating worker-robot collaboration. The main challenges in HRC include the safety of the HRC and the robot programming, which demands intuitive user interfaces and novel programming methods for non-expert workers.

Sensors provide the foundation for the realization of the robot's intelligence. Vision, touch, and force sensors are being employed in industrial robotics, in addition to acceleration sensors, lidars, inertial sensors, and ultrasonic sensors. DT-based methods for HRCS are advanced approaches that enable intelligent solutions for smart manufacturing. HRC design frameworks have emerged considering both the physical aspects of the human-robot interaction and the psychological and social impact, since it is particularly important to provide the human with comfort and trust in the robot's actions.

Reinforcement Learning in robotic assembly.

Continuous action domain algorithms are the most effective and appropriate for robotic manipulation. In the context of Industry 4.0, robot arm controllers must be able to optimize themselves. This capability is required to manage the many changes that occur in the manufacturing process, to ensure high accuracy and precision, and consequently to assure cost-effectiveness and product quality. Despite substantial advances of RL in simulated domains such as video games, its potential impact on real robot applications is still limited. To represent highly skilled behaviors and skills, it is necessary to learn overly complicated reward functions and methods. This opens the possibility for a trend towards exploration of sample efficient and time efficient algorithms, solving both continuous state and action space problems. Methodologies, such as data augmentation, domain randomization, and sim-to-real transfer, have emerged to improve the learning process for robots in response to the demand for massive, difficult to acquire, and expensive training data **(Stan et al., 2020)**.

DL algorithms have revolutionized numerous aspects of computer vision and have been rapidly embraced in robotics over the past decade. However, robotic perception, robotic learning, and robotic control are difficult tasks that continue to present serious challenge for conventional methodologies. Nevertheless, the employment of robotic vision in a variety of robotic assembly tasks presents potential future research opportunities that could result in improved performance and accelerated convergence compared to the current baselines.

Original theoretical contributions:

- Presented the State-of-the-Art technologies that shape the Cyber-Physical Systems and Digital Twin paradigms, as well as their specific characteristics and current challenges.
- Introduced the innovative technologies in Cloud Computing and outlined their strengths and weaknesses.
- Provided a comprehensive review of advanced Human-Robot Collaboration (HRC) solutions and addressed the State-of-the-Art methodologies employed in HRC infrastructure, safety, and robot programming.
- Presented a detailed overview of cutting-edge Reinforcement Learning solutions applied in robotic assembly.

The findings of the research were published in:

Stan, L., Nicolescu, A. F., & Pupăză, C. (2020). *Reinforcement Learning for Assembly Robots: a Review*. Proceedings in Manufacturing Systems, 15(3), 135–146, ISSN 2067-9238, Copernicus

Chapter III. The development of the web-based monitoring platform

3.1.Objectives and original contribution synopsis

The objective of this chapter is to present the core components of the proposed web-based monitoring framework employed in a robotic application, specifically:

- The framework architecture.
- The robot system and its Digital Twin.
- The web platform and its features.

In this case study, an articulated robot, equipped with specialized end-effectors must position, align, and assemble interchangeable components of a gear pump to produce a functional product. After developing the DT and the robot program, RobotStudio is employed to simulate the capabilities of the web-based platform. After simulation results demonstrate that the web-platform adheres to the implementation, the real robotic system is employed to validate the platform's effectiveness.

Consequently, the web-platform must present the following features:

- Authorized access (digest authentication) for security reasons.
- Monitor the production status (report of finished workpieces) and the total energy consumption of the robot (continuously, at predefined time intervals).
- Monitor the robot workcell signals.
- Control over the system to stop the robot in case of emergency.

Original theoretical contributions:

- The application of edge computing for data acquisition and processing in a robotic system.
- Employing a virtual robot controller for testing purposes and for replicating the functionality of the web-platform.

Original methodological contribution:

- The development of the web-based monitoring platform for robotic systems.
- The simulation procedure to demonstrate the functionality of the platform.

Experimental procedure:

- The validation of the web-based monitoring platform on a physical robotic system.

Section 1. Introduction

3.2. General aspects

As mentioned in Chapter I, sustainability is another Industry 4.0 advancement that will have a substantial impact on the planning and management of future factories, as modern manufacturing processes become characterized also by social sustainability. Environmentally and economically, the energy consumption of machines and robots is a crucial part of a production line since the energy-efficient use of industrial robots has a great impact on the production costs. Consequently, the focus of this experimental research is to analyze the energy consumption of an industrial robot and monitor it by employing robot web services. The method employed to analyze the energy consumption is based on the simulation tool integrated in ABB RobotStudio **(Stan et al., 2023)**. A more comprehensive analysis on the energy consumption of industrial robots is presented in Chapter IV.

3.3.The proposed approach

This section introduces a method for web-based monitoring of robotic manufacturing systems, as illustrated in Fig. 3.1 and further detailed in the next section. Color coded in green is the current state of the lab equipment, whereas the digital replica is grey-colored. The blue elements represent the components of the web-platform and violet represents possible applications of the web-platform.

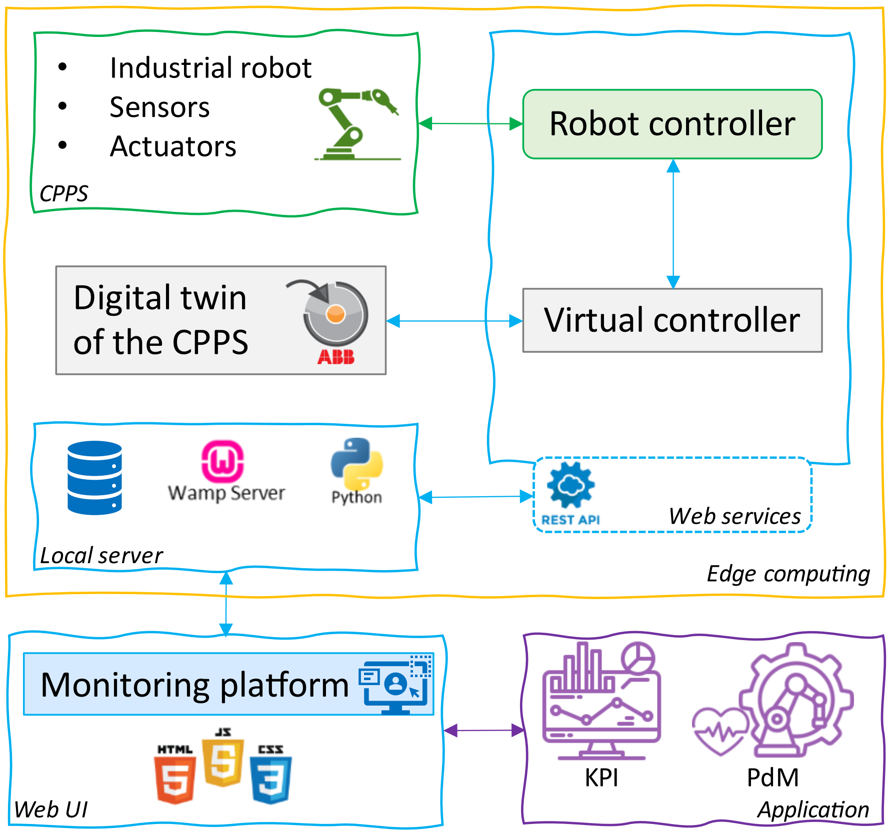


Fig. 3.1. The proposed web-based framework for monitoring a robotic manufacturing system.

3.4. Detailed overview of the articulated robot – IRB 1200/0.9

The IRB 1200 is a 6-axis industrial robot from ABB Robotics designed for flexible robot-based automation in manufacturing industries. It has a payload of 5 kg, a max vertical reach of 900 mm, a repeatability of ±0.06mm, and is equipped with the IRC5 Compact (IRC5C) controller and RobotWare software (RW v6.08) for robot control. RW v6.08 supports every feature of the robot system, including motion control, communication, application program development and execution. The robot can be supplied with optional software for application support, such as gluing and welding, and communication capabilities.

3.5.General security requirements

The ABB IRC5 devices employ TCP and UDP as Internet transport protocols, allowing for connection to a standard network and reducing expenses. Interconnection of control systems with "office" systems, such as ERP, allows for new applications. However, direct connection of control systems to the plant network raises security concerns, and it is crucial to implement preventative measures to protect against them. The main computer of the IRC5 robot controller and OPC servers are important assets to safeguard, and it is advised to protect the factory control network using a firewall or other security mechanism.

3.6. Theoretical and practical considerations

Table 1 summarizes the key characteristics of the proposed framework. This case study focuses on a production system in which a robot assembles components transported to its workspace by a conveyor. The programming of the robot is based on sensor signals, and the assembly order is predetermined. Therefore, the web-platform must be able to communicate with every device in the production system. This criterion is accomplished, since the web-platform can communicate with every robot, sensor, and actuator that is controlled by the robot controller. The two-way communication enables the web-based framework to acquire data from the robot controller and have control over it, such as stopping the robot in an emergency. The web-based framework must collect data on an hourly basis, while system control must be close-to-immediate, with no significant delays. The robotic process is entirely automated, and the DT includes robust simulation features, such as checking the toolpath against collisions and calculating the energy usage. To compute the energy consumption, the DT must combine kinematic and mathematical models with an established behavior control module. Finally, since only real-time communication and no complex processing is necessary, it is sufficient for the web-based framework to provide edge-computing capabilities.

Table 1. Characteristics of the framework.

Integration level	Connectivity mode	Update frequency	CPS intelligence	DT simulation capabilities	Digital model	Computing level
Robot	Uni-directional	Daily	Human triggered	Static	Geometry, kinematics	Edge
Production System	Bi-directional	Hourly	Automated	Dynamic	Control behavior	Fog
Factory environment		Immediate real time	Autonomous (Ai-driven)	Predictive, prescriptive	Multi-physical behavior	Cloud

***Section* 2. Development of the web-based framework**

3.7. Overview of the web-based monitoring framework

The data is collected and stored on a local server in JSON format, and the web-based GUI is created using HTML5, JavaScript, and CSS3 as well as the *Bootstrap 4* (Bootstrap v4.6, 2022) framework for the front-end development and the *Highcharts* (Highcharts, 2022) library to create the interactive charts that display the information stored on the server. The REST API paradigm is employed to communicate with the robot controller.

To develop the web-platform, the following elements were created (also depicted in Fig. 3.2):

1) A relation between the real and the virtual robot controller.
2) A communication link between the controller and the webserver.
3) A utility class to facilitate the controller-webserver communication (refer to RWS.py)
4) A utility service to collect and store data (refer to microservice.py)
5) Web GUI that enables a user to monitor a selection of sensor signals from the workcell (The Dashboard).
6) Visualization charts that enable a user to monitor the workcell productivity and the energy consumption of the robot (The Control Charts).

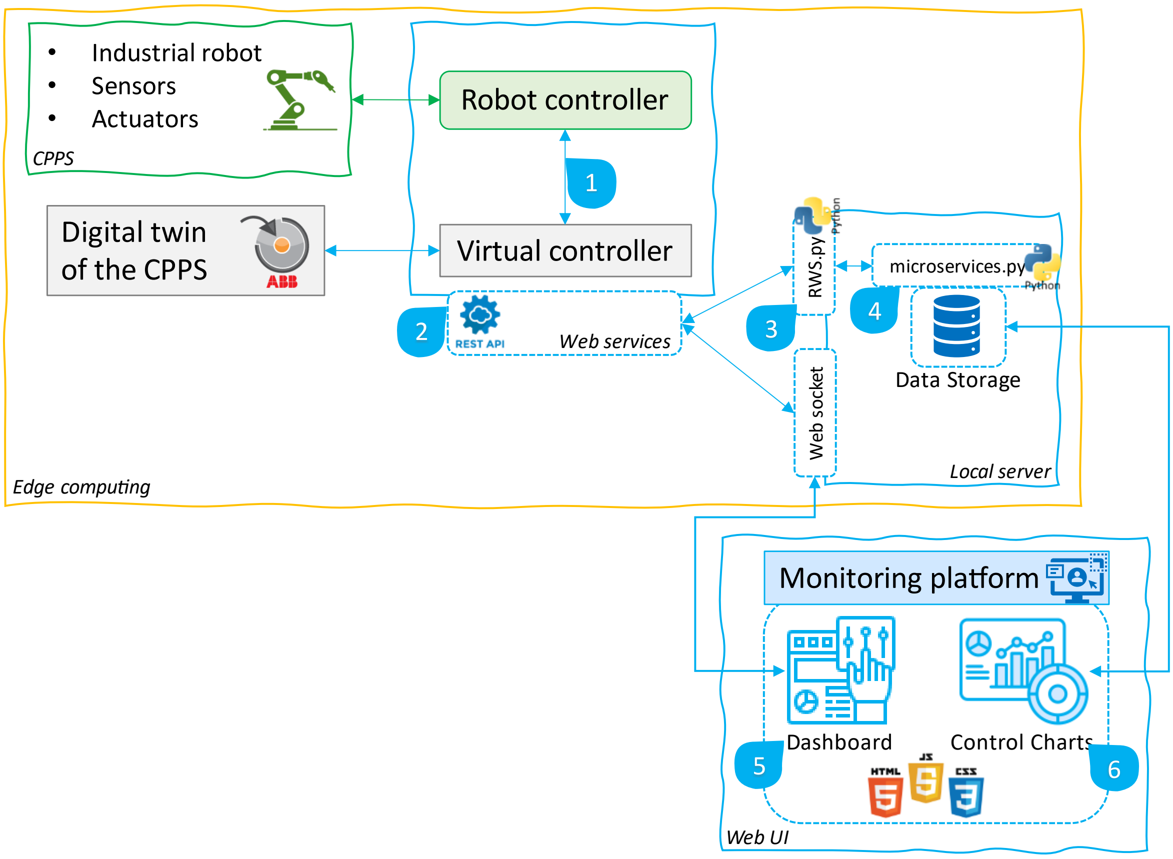


Fig. 3.2. The web-based monitoring framework.

3.7.1. The relation between the real and the virtual robot controller

The IRC5 controller features the following communication technologies: robot web services, a programming interface based on HTML5 for communicating with robots from any device, regardless of operating system, and socket messaging, which enables machine-to-machine communication via the exchange of TCP/IP messages over a network. *The virtual controller* can be described as a software that emulates the real robot controller to allow the same software that is controlling the robots, to run on a PC for offline programming, simulation, and analysis purposes. Whether virtual or real, the IP address of the controller can be discovered using the Bonjour discovery tool.

3.7.2. The communication link (server-robot) via web services

The web platform was designed to access information from the virtual robot controller using web services that adhere to the architectural form of RESTful APIs (RESTful API, 2022) using the HTTPS protocol, returning messages consisting of XML and JSON data. The Robot Web Services (RWS) (ABB Robot Web Services, 2022) consists of several services and each service may have additional services or one or more resources. Fig. 3.3 illustrates the RWS resource map and highlights the main services employed in this work.

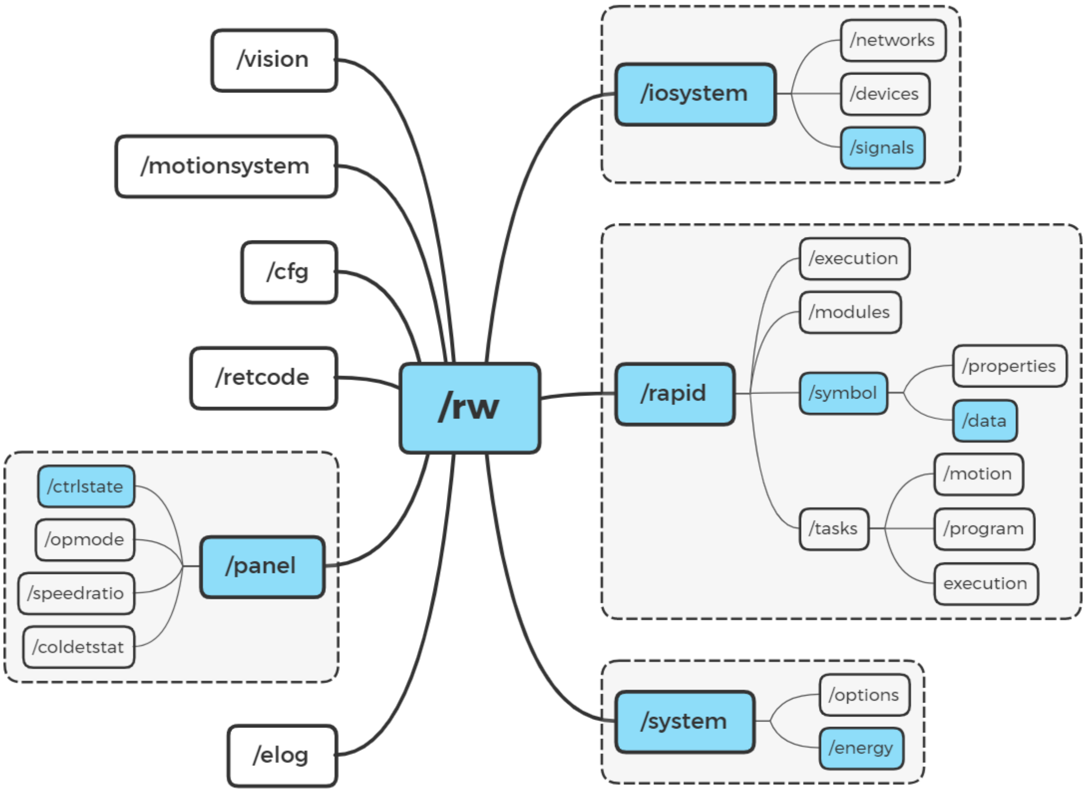


Fig. 3.3. RobotWare Services resource map.

3.7.3. The utility class to facilitate the controller-webserver communication

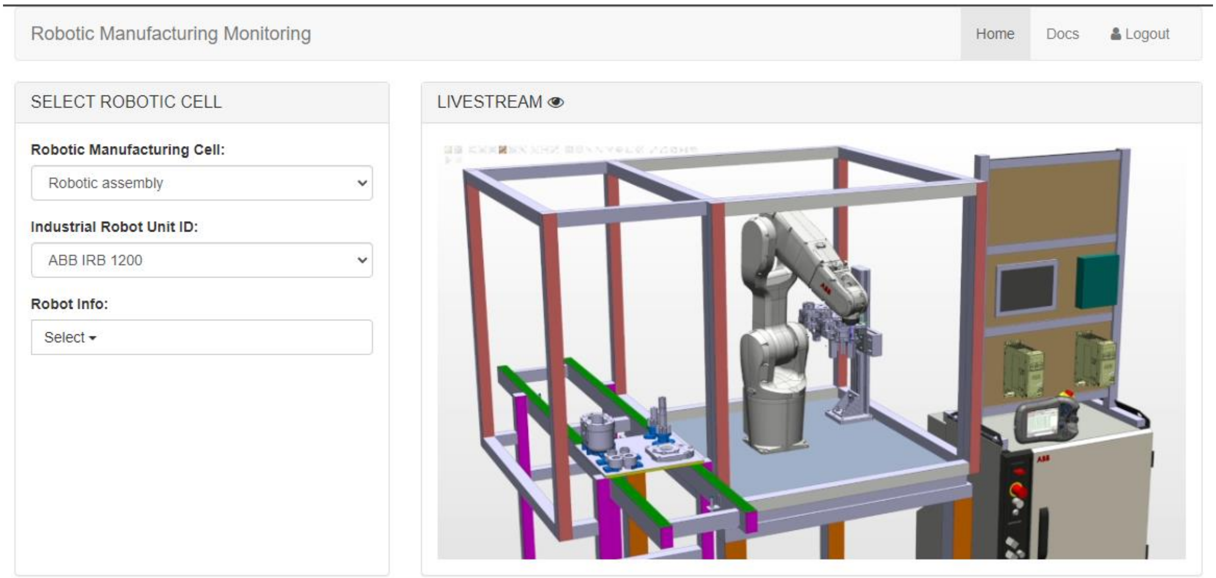
The utility class for facilitating communication with the robot controller was implemented in Python 3. The RWS class enables the creation of a persistent session connection to a controller, by providing the IP address of the robot, a username, and a password. The default authentication method for RWS is digest, and a login with a username and password is mandatory. Class functions allow for changing and reading RAPID variables, and for reading energy measurements.

3.7.4. The utility service to collect and store data

Similarly, the utility service to collect the data from the robot controller and store it in JSON files was implemented in Python 3.

3.7.5. The Web GUI: the Dashboard and the Control Charts

The GUI which allows for connection to the robot controller is presented in Fig. 3.4. Additionally, Fig. 3.5 illustrates the Dashboard which allows for the monitoring of a predefined set of signals.

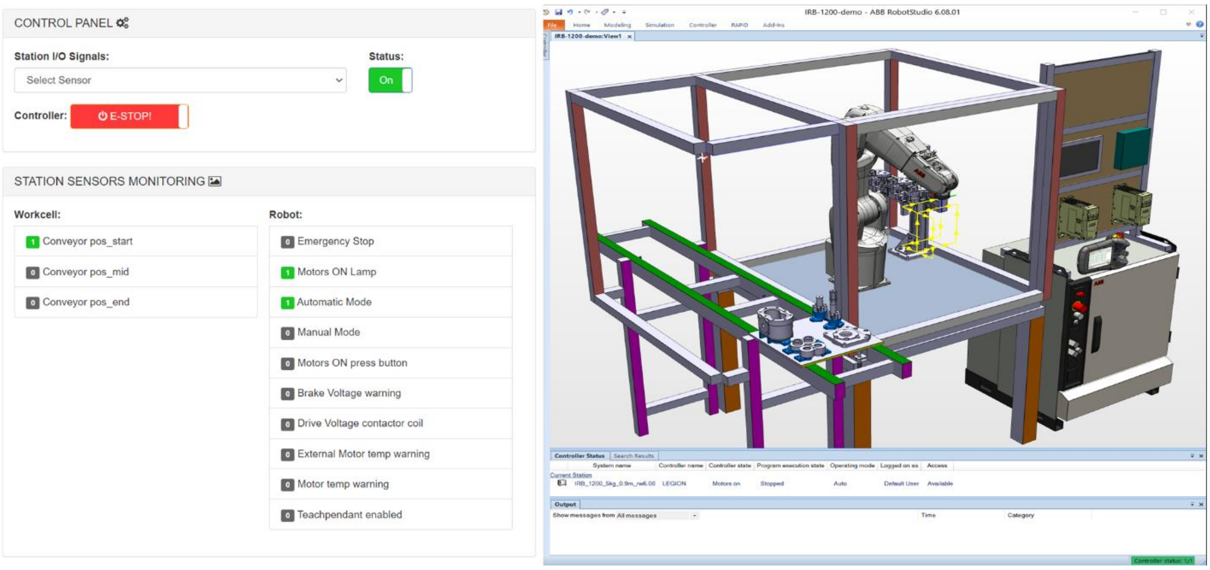


Robotic Manufacturing Cell: Robotic assembly

Industrial Robot Unit ID: ABB IRB 1200

Robot Info: Select

Fig. 3.4. Web UI options to connect to a robot controller and the Livestream panel.



Station I/O Signals: Select Sensor

Status: On

Controller: E-STOP!

Workcell:

1 Conveyor pos_start
0 Conveyor pos_mid
0 Conveyor pos_end

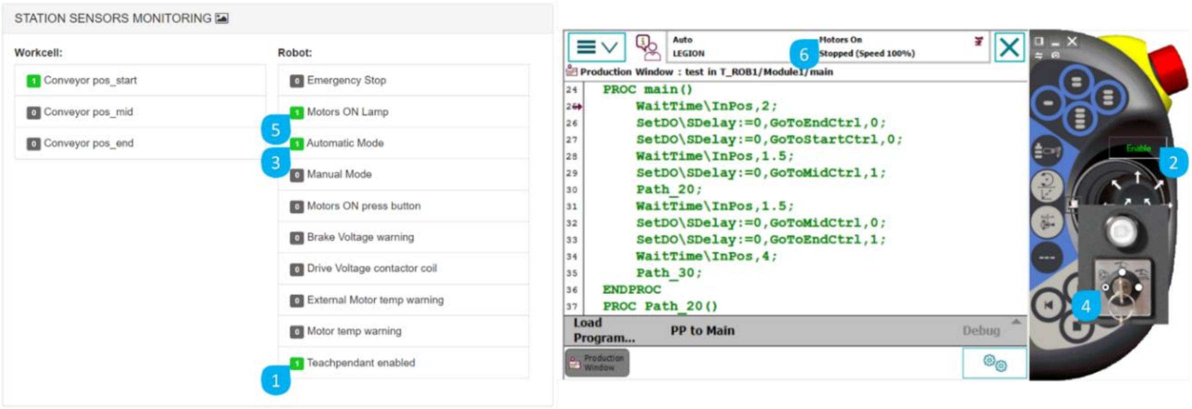
Robot:

0 Emergency Stop
1 Motors ON Lamp
1 Automatic Mode
0 Manual Mode
0 Motors ON press button
0 Brake Voltage warning
0 Drive Voltage contactor coil
0 External Motor temp warning
0 Motor temp warning
0 Teachpendant enabled

Fig. 3.5. The Dashboard: Control Panel & Sensors Monitoring Panel (left side). The Digital Twin in Robot Studio (right side).

3.8. Simulation procedure to demonstrate the functionality of the platform

The automatic mode is a method of operation in which the robot performs in accordance with the task program, without manual operator control. Fig. 3.6 demonstrates one of the monitoring capabilities of the web-framework: a signal (1) on the Dashboard indicates that the teach pendant is active (2), while other signals (3, 5), indicate that the robot control is in the Automatic Mode (4) and the motors are on (6), as stated on the teach pendant interface.


STATION SENSORS MONITORING

Workcell:
1 Conveyor pos_start
0 Conveyor pos_mid
0 Conveyor pos_end

Robot:
0 Emergency Stop
1 Motors ON Lamp
1 Automatic Mode
0 Manual Mode
0 Motors ON press button
0 Brake Voltage warning
0 Drive Voltage contactor coil
0 External Motor temp warning
0 Motor temp warning
1 Teachpendant enabled

Auto
LEGION
Motors On
Stopped (Speed 100%)

Production Window : test in T_ROB1/Module1/main

```
PROC main()
    WaitTime\InPos,2;
    SetDO\SDelay:=0,GoToEndCtrl,0;
    SetDO\SDelay:=0,GoToStartCtrl,0;
    WaitTime\InPos,1.5;
    SetDO\SDelay:=0,GoToMidCtrl,1;
    Path_20;
    WaitTime\InPos,1.5;
    SetDO\SDelay:=0,GoToMidCtrl,0;
    SetDO\SDelay:=0,GoToEndCtrl,1;
    WaitTime\InPos,4;
    Path_30;
ENDPROC
PROC Path_20()
```

Fig. 3.6. The teach pendant is enabled, and the robot is in automatic mode.

For testing purposes and to replicate the functionality of the two control charts, RobotStudio was employed to continuously simulate the robotic process, while the *microservices* script ran in the background to collect and store data from the virtual controller every hour. Fig. 3.7 depicts the interactive chart that displays the energy consumption of the robot. An expected level and two control thresholds for when the consumption exceeds or falls below the desired range are defined. If the productivity of the workcell is constant but the energy consumption exceeds the thresholds, this may indicate a problem with the robot. Fig. 3.8 illustrates the productivity control chart for the workcell. When both productivity and energy consumption reach zero, it indicates that the robot system was inactive for that time frame, which could be due to a variety of factors, such as a significant breakdown or a scheduled maintenance window.

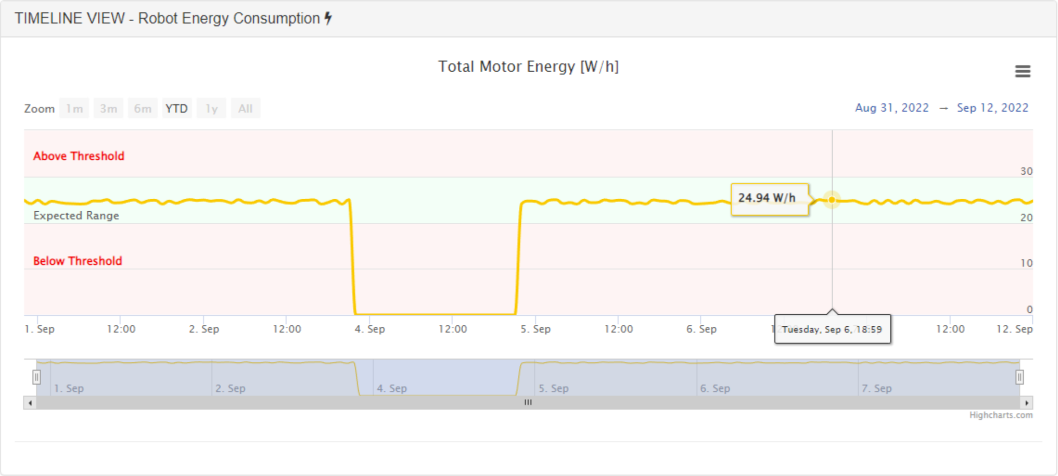


Fig. 3.7. The Robot Energy Consumption chart.

The records presented in Fig. 3.7 and Fig. 3.8 are for demonstration purposes only. As the virtual controller executes the robot program, the microservices script collects data on finished parts and energy consumption, while the visualization charts display it on the web-platform. A control script has been devised to periodically change the clock on the test machine to gather data hourly, without wasting resources. This process ensures that the robot will not operate continuously for six hours without influencing the outcome of the test.

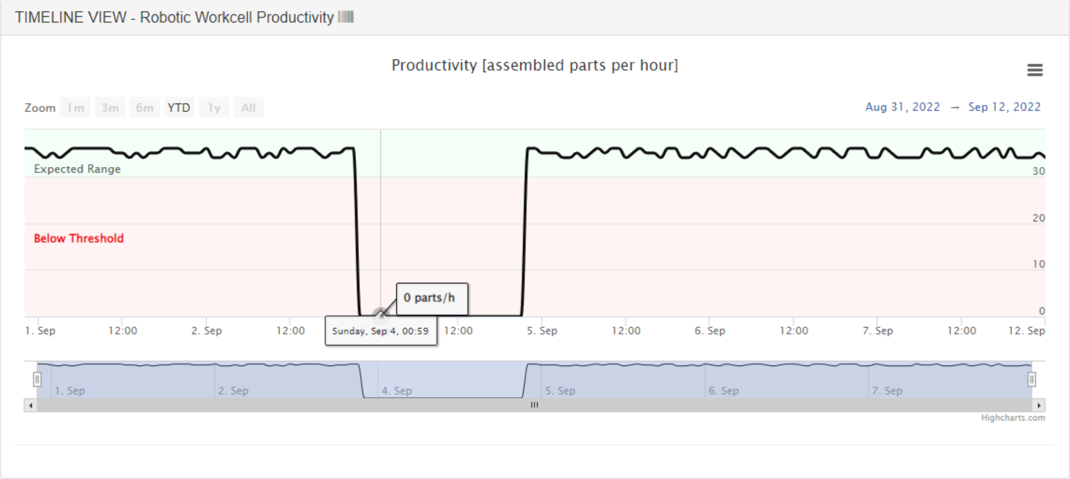


Fig. 3.8. The Robotic Workcell Productivity chart.

Section 3. Experimental validation

Experiments were conducted to evaluate the effectiveness of the proposed approach. The web-platform's signal monitoring capability was validated by ensuring that sensor changes in the robot controller were reflected in near-real time on the web-platform. Additionally, the ability of the web-based framework to collect and present data in a timely manner was verified.

3.9. The experimental setup

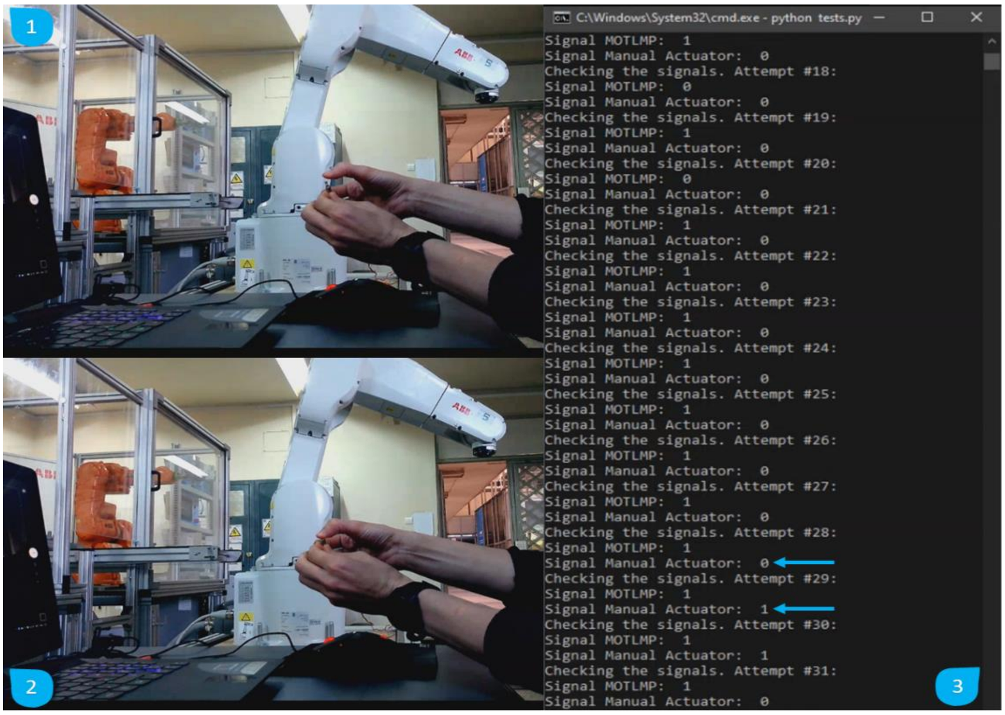
Fig. 3.9. The experimental setup consisting of an articulated robot IRB 1200, featuring the connection between the IRC5 controller (1) and the laptop running RobotStudio (2)

The experimental platform consisted of the main components as shown in (Fig. 3.9):

- Physical robotic workcell, employing an ABB IRB 1200 6-DOF articulated arm with a handling capacity of 6 kg, a reachability of 0.9 m, and a position repeatability of 0.03 mm.
- Robot controller IRC5, running RobotWare v6.08
- Virtual controller, running in RobotStudio with similar RobotWare software version.
- Digital model of the robotic workcell, created in RobotStudio.

3.10. Signal acquisition from the robot controller

A test button was utilized to evaluate the signal delay and responsiveness of the web platform. The test button was physically connected to the controller and a digital signal was assigned to it. By utilizing the robot web services, it was determined that when the test button is pressed, the signal collected from the robot controller changes from 0 to 1 (Fig. 3.10) within a timeframe of ~100ms, depending on the processing capabilities of the machine running the script (CPU: Intel I7-7700 @2.80GHz, SSD Samsung 970 EVO 1TB).



```
Signal MOTLMP:  1
Signal Manual Actuator:  0
Checking the signals. Attempt #18:
Signal MOTLMP:  0
Signal Manual Actuator:  0
Checking the signals. Attempt #19:
Signal MOTLMP:  1
Signal Manual Actuator:  0
Checking the signals. Attempt #20:
Signal MOTLMP:  0
Signal Manual Actuator:  0
Checking the signals. Attempt #21:
Signal MOTLMP:  1
Signal Manual Actuator:  0
Checking the signals. Attempt #22:
Signal MOTLMP:  1
Signal Manual Actuator:  0
Checking the signals. Attempt #23:
Signal MOTLMP:  1
Signal Manual Actuator:  0
Checking the signals. Attempt #24:
Signal MOTLMP:  1
Signal Manual Actuator:  0
Checking the signals. Attempt #25:
Signal MOTLMP:  1
Signal Manual Actuator:  0
Checking the signals. Attempt #26:
Signal MOTLMP:  1
Signal Manual Actuator:  0
Checking the signals. Attempt #27:
Signal MOTLMP:  1
Signal Manual Actuator:  0
Checking the signals. Attempt #28:
Signal MOTLMP:  1
Signal Manual Actuator:  0
Checking the signals. Attempt #29:
Signal MOTLMP:  1
Signal Manual Actuator:  1
Checking the signals. Attempt #30:
Signal MOTLMP:  1
Signal Manual Actuator:  1
Checking the signals. Attempt #31:
Signal MOTLMP:  1
Signal Manual Actuator:  0
```

Fig. 3.10. The test button is connected to the robot controller and a thus assigned to a digital signal.

3.11. Online energy analysis vs simulation results

As a software employed heavily in industry, RobotStudio offers two methods to analyze the energy consumption of the robot: online and simulation mode. In the simulation mode, the total motor power and the total motor energy are derived from an ABB robot working under normal conditions. In contrast to this, in the online mode, the signals for total motor power and total motor energy are read directly from the robot motor drives (Fig. 3.11). As with any simulation model that employs approximations, the energy data recorded from the simulation is slightly understated, as electromechanical losses in robot drives and operating condition impacts are likely to be neglected by the software model. In future work, the errors of the simulation mode could be further evaluated.

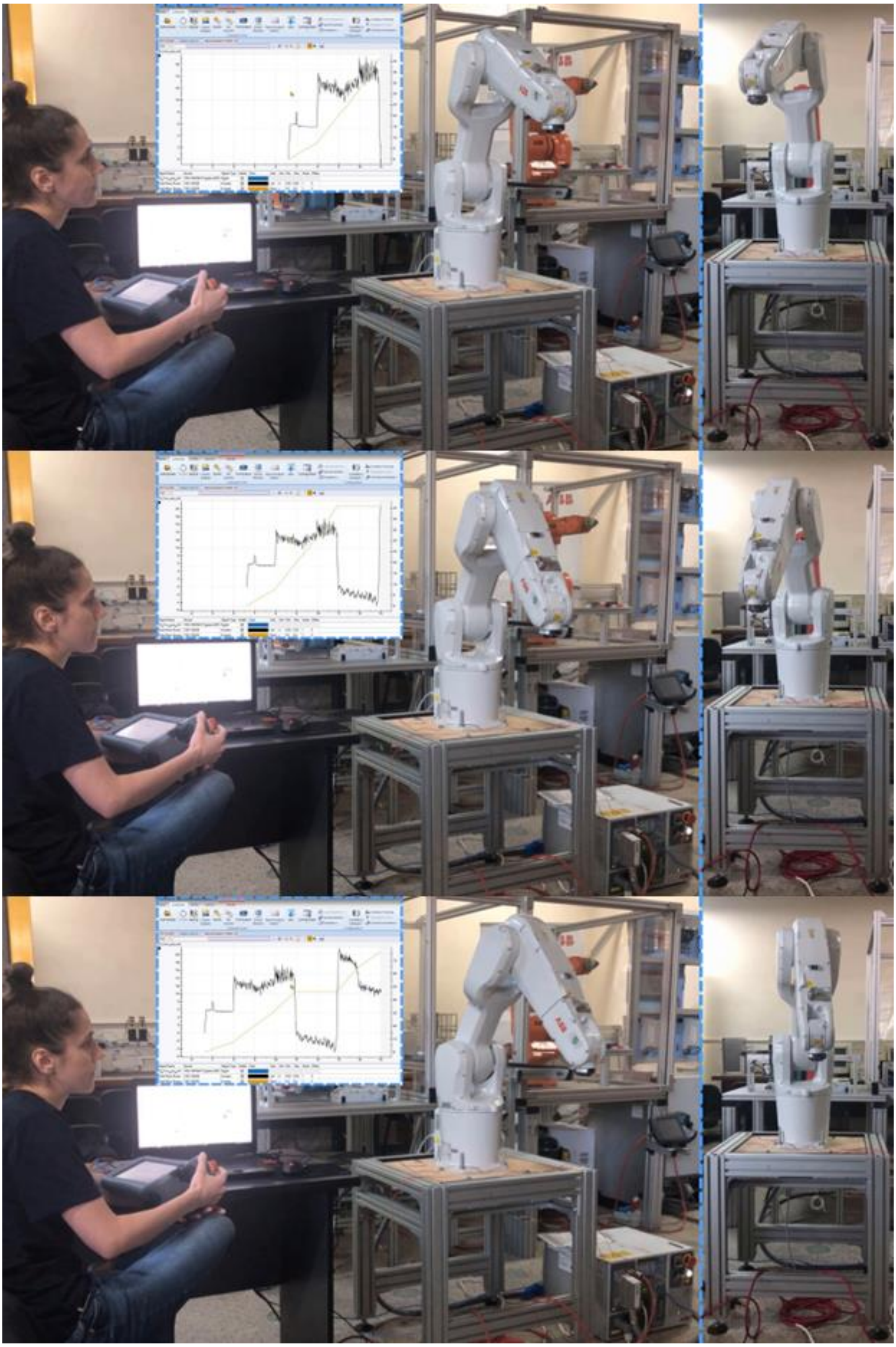


Fig. 3.11. RobotStudio energy analysis from the moving robot

Section 4. Conclusions

This chapter offered a straightforward overview on the development of the web-based monitoring platform for a robotic assembly application. The simulation results have proven the web-platform’s functionality and its smooth integration with the robotic system.

- The access to the web-platform must be authorized. Using the HTTP protocol and cryptographic hashing to avoid replay attacks, the digest authentication method upholds the security of the system when logging in.
- The interactive control charts facilitate the monitoring of the workcell output and the robot’s energy usage.
- The Dashboard GUI enables the monitoring of the robotic system based on sensor signals. The simulation demonstrated that the sensor changes are immediately signaled.
- The simulation also revealed that it is possible to stop the robot from executing the RAPID program in the event of an emergency.

Future work may be directed on numerous challenging areas:

- The web-based platform may be extended to include more than one robotic system, granting it the ability to monitor factory floor production, with focus on various aspects:
    - Human-Robot Interaction – aiming to facilitate the cooperation between humans and robots in industrial environments.
    - Collaborative Robotics – aiming to serve multi-robot systems that can work together to achieve a common task.
- Cybersecurity: improving the security of web applications for industrial robots, protecting against cyber threats and ensuring the confidentiality of sensitive data.
- When the demand for processing capacity increases, the framework can be expanded to fog or cloud computing, which will also offer further analysis capabilities.

Original theoretical contributions:

- The application of edge computing for data acquisition and processing in a robotic system.
- Employing a virtual robot controller for testing purposes and for replicating the functionality of the web-platform.

Original methodological contribution:

- The development of the web-based monitoring platform for robotic systems.
- The simulation procedure to demonstrate the functionality of the platform.

Experimental procedure:

- The validation of the web-based monitoring platform on a physical robotic system.

The findings of the research and the proposed method were submitted for publishing:

Stan, L., Nicolescu, A. F., & Pupăză, C. (2023). *Remote-monitoring-and-control-via-robot-web-services*, UPB. Scientific Bulletin, Status: Accepted, Publication in progress. Scopus

Chapter IV. The development of a Digital Twin for robotic deburring with web-based monitoring capabilities

4.1. Objectives and original contribution synopsis

The objective of the approach presented in this chapter is to bring together the DT of a robotic workcell with the proposed web-based platform to monitor the production process.

The case study requirements are summarized below:

- The workpiece is a large plastic component (1800 mm x 900 mm), with poor part-to-part tolerances, presenting injection molded burrs (defects).
- Deburring systems employing active force control are expensive and highly complex, therefore a cost-effective solution should be employed.
- Generating numerous passes for the entire workpiece dependent on burr height and tool cutter radius would increase machining time and decrease robot energy efficiency, therefore a more efficient deburring method should be implemented.

The proposed application employs an articulated robot with an automatic system for changing end-effectors, a passive force control tool with radial compliance, and a vacuum end-effector for manipulating the workpiece. Due to the size of the workpiece, the deburring workcell employs a standard “tool in hand" configuration: during the deburring process, the workpiece is fixed, and the robot manipulates the deburring tool.

The original contributions of the work can be grouped in the following categories:

Practical industrial engineering contributions:

- The application of a cost-effective deburring solution based on an end-effector with passive control and radial compliance.
- The development of a vision-based deburring algorithm to increase the manufacturing process efficiency.

Methodological contributions:

- The development of a DT using ABB RobotStudio for a robotic deburring manufacturing process, along with the design of a web platform that employs robotic web services to establish a connection to the virtual robot controller.
- The seamless integration of the web platform to monitor the robotic deburring workcell and to display the energy consumption of the robot and the production data.
- The employment of a Telegram bot with a set of specific rules for triggering alerts and notifications.

Robot programming contributions:

- The OLP of an industrial robot to deburr a large plastic workpiece along with:
  - the energy consumption analysis of the robot
  - the signal-based offline simulation of the robotic workcell

Section 1. Case study: robotic deburring application

4.2. Introduction

In typical applications, robotic machining systems have only been employed for machining procedures that do not entail large machining loads or demand high path accuracy. Industrial robots are typically used for low-force procedures such as grinding, trimming, polishing, drilling, or milling. Due to their cost effectiveness, adaptability and multifunctionality, industrial robots have gained significant interest in both academia and production **(Ivan et al., 2015)**.

Burrs are process-related defects (Aurich et al., 2009) on machined workpiece edges that have unpredictable geometries and thicknesses. *Precision deburring*, in which small burrs are removed with cutting tools contouring machined workpiece edges, can be distinguished from *heavy deburring*, which involves the removal of larger burrs such as cast flashing. Due to the necessity for using more tools, workcells are typically constructed with a "*part-in-hand*" configuration, where the robot manipulates the workpiece, and the deburring tools are fixed. The "*tool in hand*" configuration is preferred for larger workpieces, where the robot manipulates the tools.

In general, emphasis is placed on ensuring optimal contact conditions between the deburring tool and the contouring edges, adapting tool position and stiffness to burr presence and thickness, and preventing tool breakage in the event of unpredicted workpiece deviations. Robotic deburring tools and workpiece holders are designed with adaptive compliance systems to ensure constant contact and pressure between the tool and workpiece, regardless of burr shape or robot positional inaccuracy, and to avoid machining vibrations. Active and passive compliance methods are commonly used, such as advanced hybrid force/position or impedance control systems and passive spring-damper systems. Robotic tools with compliance systems improve performance by mitigating the effects of the robot's limited motion accuracy caused by low stiffness, backlash, kinematic inaccuracies, and environmental factors.

The use of advanced tools for DT-enabled robot programming and simulation can aid in enhancing the efficiency of robotic deburring systems by predicting machining errors and providing supplementary path compensations. The integration of cloud computing with robotics enables cloud-based services to extend the functionalities of the robots and to solve the conflict between heavy computing needs and local controlling requirements. To simulate the production process, it is important to have accurate, real-time information about the physical robotic systems to ensure the simulation models reflect their current state.

In the field of industrial robotics, energy consumption issues were occasionally addressed, usually in reference to specific circumstances. Reducing the energy consumption of a single robot can be accomplished in a variety of ways, beginning with the trajectory planning phase, but long-term sustainability can only be achieved through an overall energy optimization of the entire robotic cell, based on efficient optimization procedures. Energy minimization of robots necessitates accurate monitoring, evaluation, and forecast of the energy consumption. *DT-based energy modeling and simulation* are efficient means of meeting these requirements.

Web applications enable effective and efficient manufacturing activities through remote collaborations using web services. However, there are still obstacles to overcome in terms of real-time constraint, security and privacy, processing speed, and production interruptions. Usually, to minimize latency in real-time web applications, a scene graph-based 3D model with embedded behavioral control nodes driven by real sensor data is used instead of streaming video camera images.

4.3.The proposed approach for robotic deburring

Despite the use of laser measurement systems and various control systems and error compensation techniques in robotic machining procedures, there is a lack of studies on the use of radial compliance tools, particularly in situations where part tolerances are poor, and the workpiece has large dimensions. This is an important consideration in the current study case of mild deburring/deflashing. Passive force control systems do not monitor cutting forces; instead, they adapt to the contour of the part and deliver a constant force. In milling applications, the radial compliance enables the tool to rotate across 360 degrees within a compliance radius. These systems are best suited for applications with generally consistent burrs or flash, but poor part-to-part tolerances, to significantly decrease workpiece gouging **(Stan et al., 2022)**.

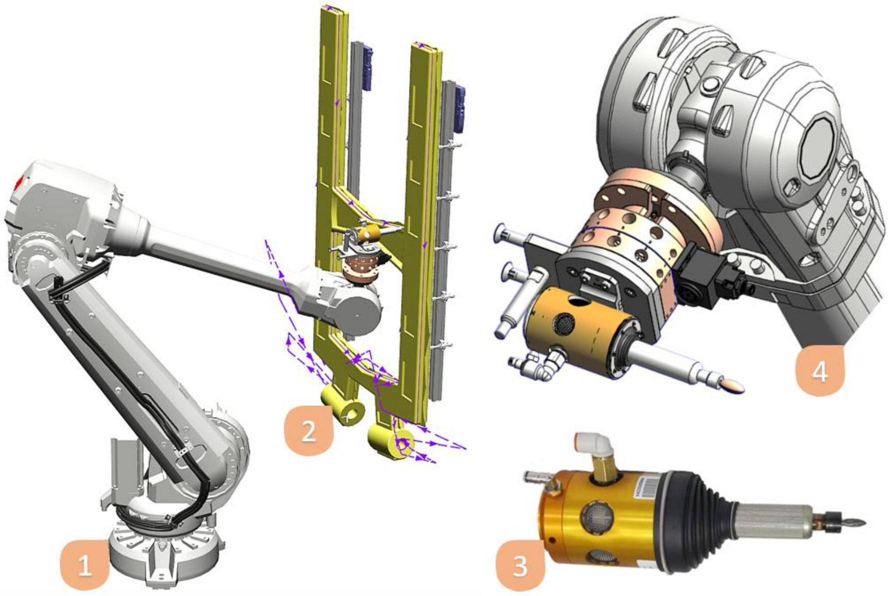


Fig. 4.1. Articulated robot (1) deburring a plastic workpiece (2) employing a passive-control tool with radial compliance (3,4).

The proposed method for robotic deburring (Fig. 4.1) in this case study employs:

- An articulated robot, ABB IRB 4600 having a handling capacity of 40kg, a max reach of 2.55m, position repeatability of 0.06mm and path repeatability of 0.28mm.
- A robot controller, IRC5 single cabinet, OmniCore V250XT.
- An automatic tool changing system ATI QC-41.
- A passive force control tool with radial compliance, ATI Flexdeburr RC300.
- due to the size of the workpiece, the deburring workcell employs a standard “tool in hand" configuration.

4.4. Robotic deburring systems

The demand for industrial robots has been increasing due to automation trends and technological advancements. The International Federation of Robotics (IFR) predicts that 500,000 units will be installed worldwide per year by 2024. The electronics industry has overtaken the automobile industry as the top consumer of industrial robots. Experts predict that companies will focus on human-machine collaboration, streamlined applications, and lightweight robots. For robots to be competitive in production, they must be reliable, sturdy, and able to comply with the environment. They should also be configurable with additional sensors, have simple programming, and have versatility to reduce the expense of special-purpose fixturing. Due to their tremendous flexibility while moving along the edges of complex-shaped components, robotic systems are considered cost-effective solutions for automating the deburring process, but they require high toolpath precision and position repeatability. Studies have been done to analyze and mitigate robotic machining inaccuracies caused by kinematic parameters inconsistencies, low stiffness, friction, backlash, limited bandwidth, and environmental factors. Intelligent solutions have been presented such as kinematic calibration methods, compliance error compensation methodologies, and external measurement systems.

The primary research focus for increasing robot stiffness is the robot component design and control parameters optimization. Various methods, such as online, offline, and hybrid compliance compensation, have been proposed to improve robot stiffness. Offline methods require knowledge of the robot's stiffness and involve adjusting the target trajectory based on estimated tool deflection. Online methods use measurements made during the robot process, such as force/torque sensors, to compensate for machining error in real-time. Vibrations caused by process forces during milling can lead to significant trajectory deviation and instability in robotic machining. Robot production errors can be corrected by calibration, but drift effects such as wear, and temperature changes must be continuously compensated. Approaches have also been presented to compensate for temperature-related deviations.

4.5. Tool compliance systems

In industrial applications, workpiece errors are compensated within the allowable tolerance mostly due to the advent of compliant tools that compensate surface irregularities while maintaining a specified force. Compliance is a tool's capacity to maintain contact and cutting force with the workpiece and can be achieved using various active and passive force control devices. Passive systems are less expensive, great for brute force deburring and where the result is only defined by a burr-free surface with loose tolerances, while active systems are best suited for applications that have very demanding surface requirements, where the expense can be justified. Passive compliant systems use controlled deflection to manage cutting forces to prevent severe chatter and part damage. These systems come in different forms such as linear, radial, rotational, or a combination of both radial and linear compliance. Radial compliance is a technique where movement of a tool is allowed in a 360-degree radius around a center position, while maintaining a constant contact force. This technique is suitable for radial brushes and removing parting lines and flash from cast parts.

Section 2. Offline simulation and validation

4.6. Development of the Digital Twin

The workcell components were designed with modern CAD tools for efficiency and dependability. The virtual model replicates the manufacturing process for design, collision detection, fault detection, testing, planning, optimization, and monitoring. For designing the DT (Fig. 4.2), ABB RobotStudio provided the necessary tools:

- To virtualize the robotic workcell.
- To generate a collision-free toolpath.
- To program the robot via OLP techniques considering sensor data and virtual models of the physical components.
- To simulate the process, analyze the motions and assess the robot energy consumption.

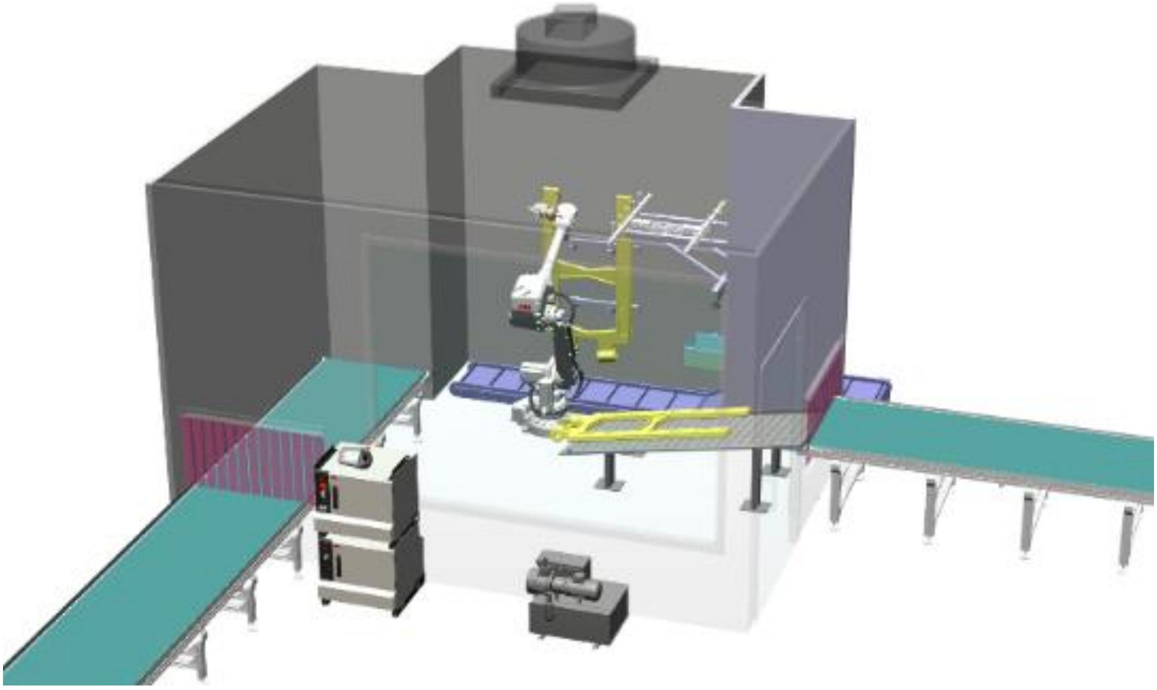
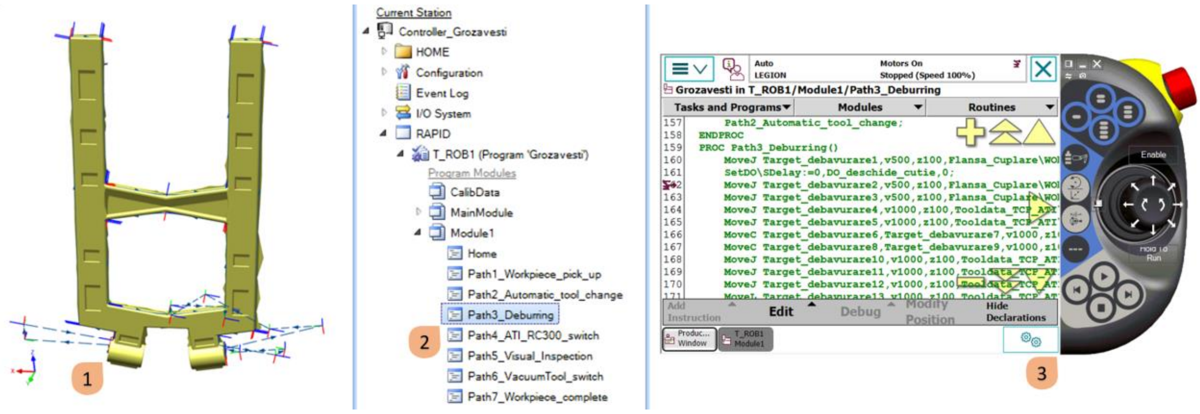


Fig. 4.2. The Digital Twin of a robotic deburring workcell

4.7. Virtual robot controller and robot programming

The virtual controller can be described as software that emulates the real robot controller to allow the same software that is controlling the robots to run on a PC for offline programming, simulation, and analysis purposes. Creating the robot program consisted of defining reachable targets, collision-free movements, and appropriate speeds. Four distinct tool center points (TCPs) were specified for the tool mounting point of the robot, the master plate of the automatic changing system QC-41, the deburring tool, and the vacuum gripper. Workcell events have been defined using I/O signals as communication channels between the controller and external devices. After validating all motions, the robot's programming was uploaded to the virtual controller. The robot deburring toolpath and robot movement routines are depicted in Fig. 4.3.



```
        Path2_Automatic_tool_change;
    ENDPROC
    PROC Path3_Deburring()
        MoveJ Target_debavurare1,v500,z100,Flansa_Cuplare\WOl
        SetDO\SDelay:=0,DO_deschide_cutie,0;
        MoveJ Target_debavurare2,v500,z100,Flansa_Cuplare\WOl
        MoveJ Target_debavurare3,v500,z100,Flansa_Cuplare\WOl
        MoveJ Target_debavurare4,v1000,z100,Tooldata_TCP_ATI
        MoveJ Target_debavurare5,v1000,z100,Tooldata_TCP_ATI
        MoveC Target_debavurare6,Target_debavurare7,v1000,z1
        MoveC Target_debavurare8,Target_debavurare9,v1000,z1
        MoveJ Target_debavurare10,v1000,z100,Tooldata_TCP_AT
        MoveJ Target_debavurare11,v1000,z100,Tooldata_TCP_AT
        MoveJ Target_debavurare12,v1000,z100,Tooldata_TCP_AT
        MoveL Target_debavurare13,v1000,z100,Tooldata_TCP_AT
```

Fig. 4.3. Robot deburring tool path (1), operations sequence (2), and robot instructions visible on the robot flex pendant (3).

The programming based on sensor signals ensures the *reliability* of the entire system and the communication integrity between the robot and the system. The layout of the workcell sensors has been modelled to both the virtual controller and the web platform, ensuring that sensor data is in sync.

4.8. Robotic manufacturing cell offline programming

Fig. 4.4 depicts the layout of the robotic deburring cell as well as the sensor configuration. The development of the DT represents the original contribution to this case study, which entailed creating the digital model of the robotic workcell, offline robot programming, workcell sensor data virtualization, manufacturing process offline simulation, and analysis.

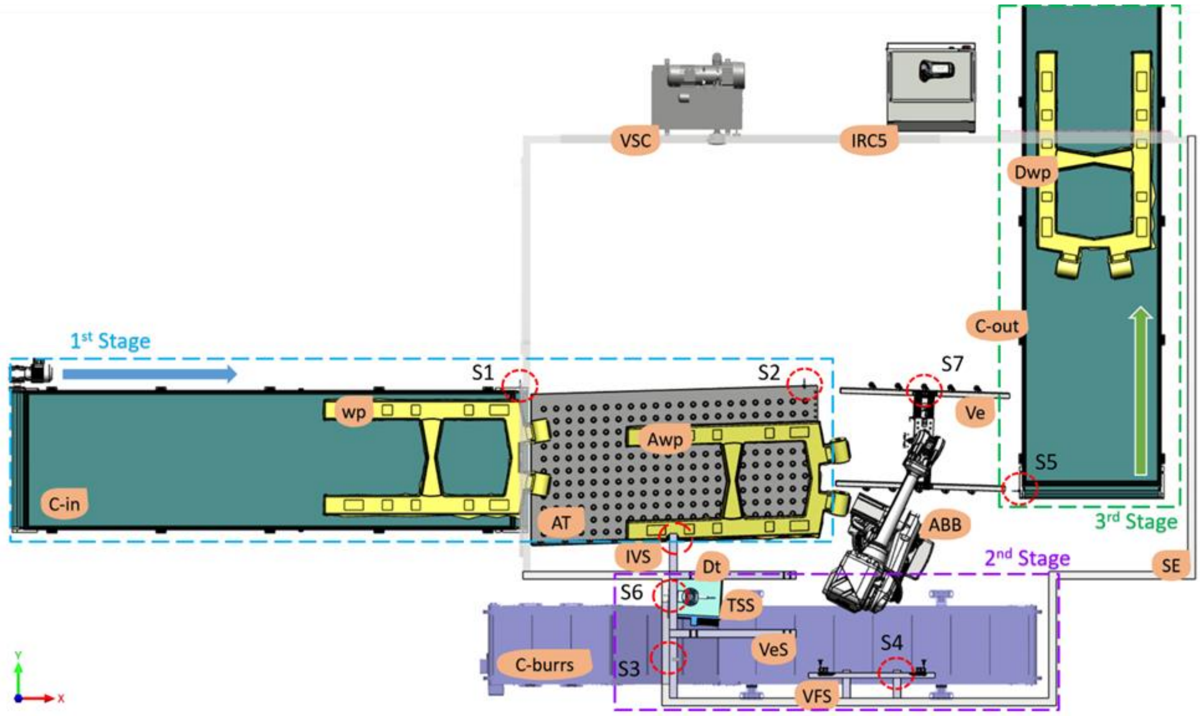


Fig. 4.4. Robotic deburring cell structure and sensors layout.

Section **3. Path planning using image processing**

4.9. General aspects

Robot programming toolpath planning systems have been developed to increase efficiency and speed. These systems aim to optimize path planning by reducing processing time and smoothing trajectories. However, most optimization methods will have a trade-off between speed and quality. Researchers have proposed various techniques for robotic deburring, including iterative techniques to detect shape deviations and adapt the deburring processes, vision-assisted robotic systems for finishing welded parts, and using machine learning and cloud computing to improve deburring operations in aircraft manufacturing industry. Most studies on robot trajectories generated from image processing do not consider the use of passively radial compliant tools or deburring large workpieces with irregular burrs. Previous deburring methods using vision systems have been proposed, but there are currently no solutions for generating the robot trajectory exclusively in variable confinement regions **(Stan et al., 2022)**.

4.10. Proposed method for deburring toolpath computation

The proposed approach uses image processing to identify and deburr partly removed burs in several iterations, depending on burr height and tool cutter radius. Due to the tool's radial compliance, residual burrs may remain after deburring. Considering the large size of the workpiece, it is more efficient to deburr only the remaining burrs, rather than re-doing the entire workpiece contour.

The vision system employed in the visual inspection procedure is a high-speed VGA camera, positioned within the ATC system’s master flange, with a compact size that makes it suitable for mounting in narrow spaces. The camera model is Cognex 8400 (integrated with image processing), with a resolution of 640x480, a maximum acquisition rate of 217 frames per second, Gigabit Ethernet communication, and Ethernet power supply. The camera was selected for its software capabilities, which include high-performance tools for object location, edge detection and inspection, part measurement, pattern matching, and filtered image processing.

Fig. 4.5. Vision system equipment: PC running ABB RobotStudio (1), robot controller (2), Cognex 8400 camera (3), the ATC system (4).

4.11. Robotic deburring algorithm for partially removed burrs

A method was developed to determine the necessary toolpath for removing remaining burrs identified through visual inspection, specifically in areas where burrs are still present. This approach ensures that only the necessary time is spent removing burrs without the need to repeat the entire deburring process. The method uses the tools provided by ABB's RobotStudio to find the areas to machine, to compute the number of iterations, and to calculate the appropriate routines for the robot to approach and retract.

4.12. Robot Energy Consumption

Reducing the energy consumption (EC) of robots is important for increasing productivity. Research focuses on hardware solutions such as lighter components and energy storing devices, as well as software solutions for motion planning and scheduling. The EC is affected by operational parameters and constrained by the workcell architecture, productivity needs, and environmental conditions during the optimization phase. As depicted in Fig. 4.6, a record of the total EC and the total absorbed power for a single work cycle has been studied for a workpiece where burrs were effectively removed in the deburring process (1), as well as for a workpiece where an additional deburring process was necessary to remove residual burrs (2). Fig. 4.6 (2) depicts the energy recorded during a work cycle of a workpiece for which the robot visual inspection detected a single region where burrs have been partially removed, and for which the proposed algorithm devised a second deburring process solely for the indicated area.

Fig. 4.6. Total energy (black) and total power (orange) of the robot during a deburring work cycle with no remaining burrs (1) and with remaining burrs (2).

It is assumed that burrs that are not completely removed during the first deburring procedure are thicker, forcing the compliant tool to deflect, and removing them properly would take numerous iterations. In the case study, the additional machining passes were computed based on tool radius, resulting in a longer deburring routine.

Section 4. Web-based platform for remote monitoring

4.13. General aspects

Effective remote robot operations in a decentralized setting require real-time monitoring and remote-control capabilities that are responsive and adaptable to unpredictability. SOA using web services allows for machine-to-machine communication via a network using HTTP and provides interoperability. A web-based solution for a manufacturing monitoring system facilitates the use of a broad variety of devices with graphical interface support **(Stan et al., 2017)**. Various systems for remote monitoring and control of robots based on Android/IOS devices and Wi-Fi communication **(Coman et al., 2019)** have been presented in the literature.

4.14. The design of the web-based platform

Fig. 4.7 depicts the key elements of the proposed web platform serving the robotic deburring application. An intelligent messaging system (Telegram bot) will generate condition-based notifications. All sensors present in the workcell have a digital counterpart in the virtual controller.

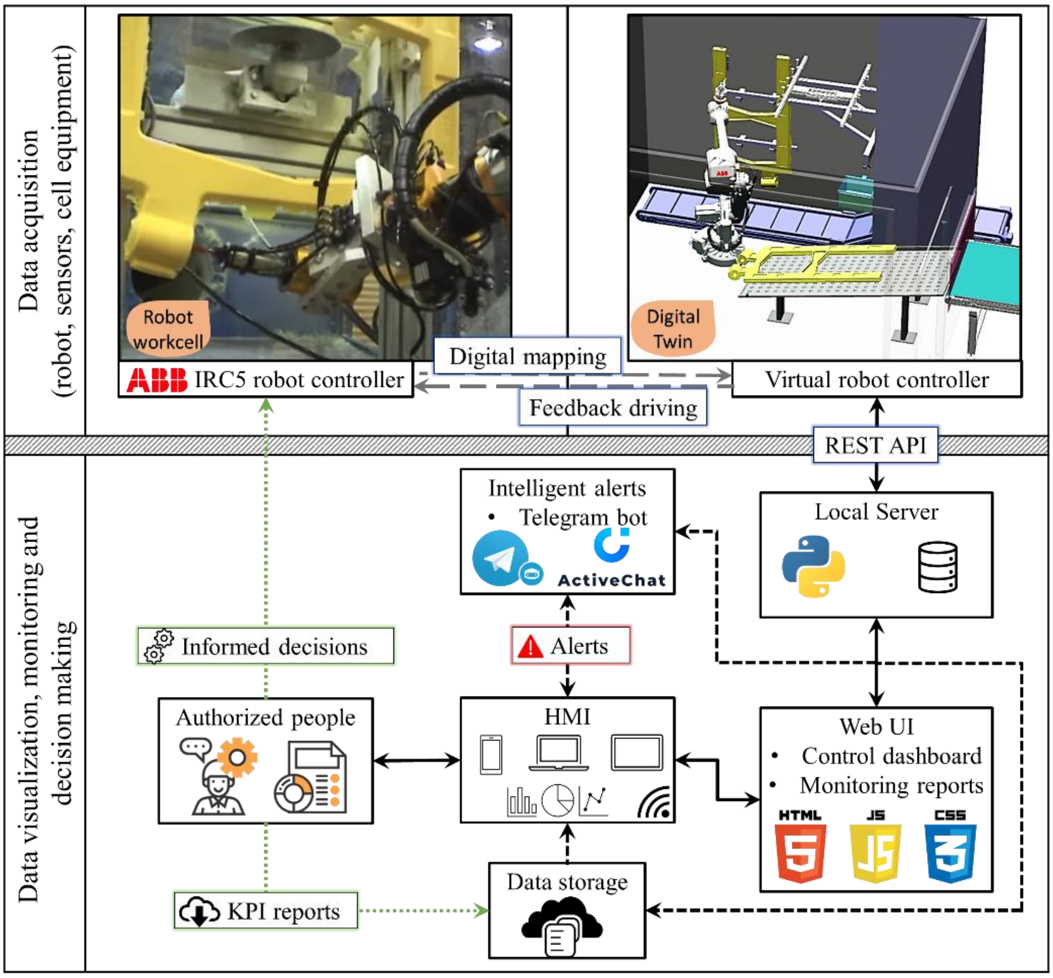


Fig. 4.7. Web-based monitoring and control platform for robotic manufacturing.

Section 5. Conclusions

This case study describes the development of a DT-enabled robotic deburring application, along with the robot offline and sensor-based programming. Moreover, the proposed web-based platform is employed to monitor the production process. The study also presents a new deburring solution based on an algorithm that generates the machining toolpath of partially removed burrs after video inspection. Additionally, a brief overview of the robot's EC, the benefits of applying the proposed deburring solution, and the monitoring capabilities of the proposed web platform on the robotic manufacturing system are presented. The main objective of the project is to employ the proposed web platform to monitor the deburring application and deliver reliable data for generating performance reports.

In this chapter, a comprehensive overview of robotic machining was presented, with a focus on recent advancements aimed at enhancing robot stiffness and control parameters through compliance compensation methods. The methods examined include kinematic calibration, laser trackers, external measurement systems, online compliance compensation systems, and various approaches to address temperature-related deviations. Additionally, an introduction to tool compliance systems was provided, which are used to compensate for surface irregularities while preserving a desired cutting force. Furthermore, a comprehensive overview of the current strategies for reducing energy consumption in robots was presented. The emphasis was placed on hardware-based approaches, software-based solutions, and algorithms designed to minimize energy use by adjusting the velocity of the robot.

This case study demonstrates the effectiveness of the proposed web-based framework by fulfilling several key requirements for successful implementation. These requirements include data collection and visualization, interoperability achieved through adherence to the Service-Oriented Architecture framework and its collection of open standards for machine-to-machine communication, and real-time monitoring through the provision of continuous updates from the sensors and robots involved. The real-time monitoring capability enables prompt decision-making and rapid response in the event of any malfunctions, therefore improving the overall efficiency of the system.

Future study may place emphasis on incorporating other technologies associated with Industry 4.0, such as cyber security and ML technologies. The web-based platform is designed to provide remote control and monitoring capabilities for FMS. The need for remote control in robotic production has become more important due to the global pandemic and is now a viable research topic. The web-based platform has potential for expansion to encompass monitoring of factory-wide processes, data collection, analysis and prognostics, provision of real-time production statistics, and serving as the operational core to improve operational performance and cost-efficiency.

The original contributions of the work can be grouped in the following categories:

Practical industrial engineering contributions:

- The application of a cost-effective deburring solution based on an end-effector with passive control and radial compliance.
- The development of a vision-based deburring algorithm to increase the manufacturing process efficiency.

Methodological contributions:

- The development of a DT using ABB RobotStudio for a robotic deburring manufacturing process.
- The seamless integration of the web platform to monitor the robotic deburring workcell and to display the robot EC and the production data.
- The employment of a Telegram bot with a set of specific rules for triggering alerts.

Robot programming contributions:

- The offline programming of the robot to deburr a large plastic workpiece along with:
    - the energy consumption analysis of the robot
    - the signal-based offline simulation of the robotic workcell

The findings of the research and the proposed approach were published in:

Stan, L., Nicolescu, A.F., Pupăză, C. et al. (2022). *Digital Twin and web services for robotic deburring in intelligent manufacturing*. Journal of Intelligent Manufacturing, 1-17, Impact factor: **7.136** (2021) Q1, WOS: 000805461000002, https://doi.org/10.1007/s10845-022-01928-x

Chapter V. Robotic web platform to introduce advanced teaching technologies

5.1. Main objective and original contribution synopsis

Even though robots are prominently featured in the literature on Industry 4.0 concepts, there is a scarcity of studies concerning education approaches for industrial robots employed in modern manufacturing.

The objective of this case study is to provide students with hands-on experience and the chance to acquire the skills necessary for the effective management of current robotic production systems. The availability of laboratory equipment allows students to deepen their understanding of industrial robots used in modern manufacturing applications.

This leads to an improvement in their knowledge of:

- Industrial robots and how robotic work cells operate and learn about their design and control principles.
- Software employed in a manufacturing setting for data acquisition from various sources (such as sensors) continuous control, operational and machine data, process data, or employed in vision guided robotics, such as video data acquisition.
- Product lifecycle management (PLM) by using data obtained from the manufacturing system to plan the required resources and analyze the productivity (based on KPIs) of the manufacturing processes.

The case study presents an application of industrial robots in manufacturing education, providing students with an interdisciplinary learning experience through problem- and project-based approaches, with a focus on the learning process and a facilitator role for the teacher.

Original theoretical contribution:

- Presented a detailed overview of advanced teaching concepts specific to engineering education in relation to modern robotics.

Original methodological contribution:

- The development of a learning framework designed to support the Education 4.0 paradigm, consisting of:
    - A web platform for robotic applications having the capability to integrate other Industry 4.0 technologies for other teaching strategies, such as cyber-physical security, Artificial Intelligence and Augmented Reality technologies.
    - A messaging system to automate alerts and reports.
    - A DT of a robotic work cell employing an articulated robot in assembly operations.

Section 1. Introduction to Education 4.0

5.2. General aspects

Continuous professional development is one of the important areas where action is required to properly implement Industry 4.0 objectives; consequently, education and training must keep pace with technological advancements. Universities are currently tasked with assuming a leadership position in establishing effective connections between research, education, and innovation **(Nicolescu et al., 2019)**.

Education 4.0 combines technology, novel instructional techniques, and best practices. Educational departments, research institutes, and universities support educators and researchers to lead educational innovation projects by creating and developing new practices, techniques, and applied technologies that fit with the institutions' goals and respond to current social settings. Remote learning programs use connectivity, digitization, and virtualization, but there is a scarcity of knowledge, design approaches, and assessment mechanisms for leveraging emerging technologies and pedagogy to deliver innovative solutions for engineering programs.

Steam-powered mechanical systems, mass production, and automation characterized the first three industrial revolutions while connectivity, digitization, and virtualization are today's prominent industrial technologies. Education 4.0 is characterized by heutagogical and cybergogical philosophies that focus on fostering autonomy, capacity, and capability for lifelong learning, and creating engaged learning in a virtual environment. The learning strategy is predominantly student-centered, and the targeted objective is the acquisition of both soft- and hard-core abilities.

Section 2. Emerging teaching concepts

5.3. Industry 4.0 education and qualification requirements

Adapting engineering education to Industry 4.0 is crucial for success. Efforts have been made by European Educational Programs to find and test innovative teaching methods and technologies to help students learn about their role in Industry 4.0 and align education with industry demands. Studies on engineering education in the context of Industry 4.0 have been published, focusing on new skills and qualifications requirements of graduates and workers, and providing roadmaps for adapting education to the needs of Industry 4.0 through curriculum modifications or new learning frameworks and methods.

The three commonly employed learning-delivery modes in Education 4.0 are face-to-face learning, remote and hybrid learning. Hybrid learning maximizes learning processes and resources by using modern student-centered models, current and upcoming technological advances, and new learning approaches such as blended learning, flipped classrooms, problem-based, challenge-based, gamification-based learning, and learning-by-doing. IoT-powered approaches such as AI and ML, Data Analytics, and Virtual Image Processing are also used to enhance the teaching-learning processes. Learning systems for virtual classrooms and collaborative platforms are emerging, either as a supplement to or as an alternative to conventional education modes and are providing synchronous online sessions to assist students learning using web conferencing technologies that include voice, text, pictures, and video, enabling students to actively engage in the sessions.

5.4. Education 4.0 teaching strategies in relation to modern industrial robots

New teaching concepts have emerged in the last three decades and several studies have identified crucial educational features and approaches for meeting the requirements of Industry 4.0. One of the emerging teaching concepts is The Teaching Factory approach, which integrates aspiring engineers in manufacturing environment in close cooperation with field specialists to acquaint them with its requirements and to increase collaboration between parties with various expertise and backgrounds. Another concept is The Project-Based Learning (PjBL) approach, which promotes student autonomy and creativity. Hassaan et al. (Hassan et al., 2015) implemented a *problem-based approach* to teach robot arm control in the context of a multidisciplinary project and competition. Tosello et al. (Tosello et al., 2019) presented a *project-based approach* to teach students in autonomous and industrial robotics for Industry 4.0 using a robot arm, a mobile robot, and a 3D vision system to complete a picking and transportation task. A teaching-focused laboratory employing a collaborative robot was presented by Poor et al. (Poor et al., 2019) for students to prepare robot applications for industry.

Although robots are prominent in the literature concerning Industry 4.0 paradigms, there is a lack of research on industrial robot-based teaching methodologies. This highlights the importance of further research in this area as it could potentially lead to more effective methods for teaching students about the integration of robots in industry and prepare them for the future of work in the Industry 4.0 era.

***Section* 3. Case study: robotic assembly application**

5.5. The proposed approach

This section introduces a project-based learning model using ABB RobotStudio for robot offline programming and data acquisition through robot web services (Fig. 5.1).

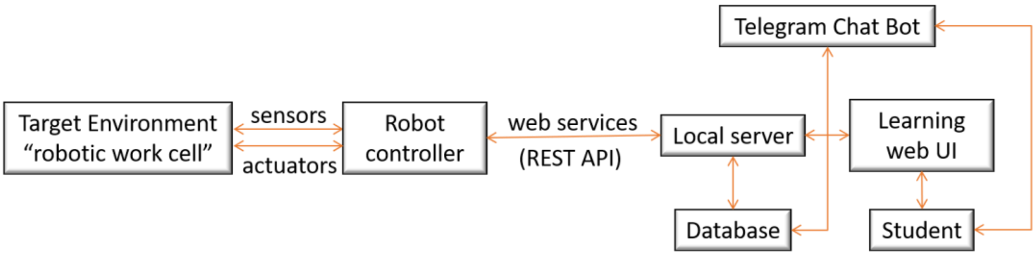


Fig. 5.1. The proposed approach for an educational web application.

5.6. Case study

The case study examines the use of robotic assembly in manufacturing, a process that uses robots with specialized tools to assemble interchangeable parts into a functional product. It requires a high level of repeatability, dependability, adaptability, and sequencing. The robotic lab enclosed work cell (6) is equipped with an ABB IRB 140 6-DOF articulated arm (1) with a 6 kg handling capacity, 0.8 m reachability, and 0.03 mm position repeatability, an IRC5 controller (5), a conveyor (4), sensors, actuators, a vacuum compressor, a Cognex camera, a tool storage system (2), effectors, and an automatic tool changer. Fig. 5.3 illustrates a student's digital representation and the laboratory's physical systems. The digital components were designed using CATIA V5, while ABB RobotStudio was utilized for offline programming and simulation of robots **(Nicolescu et al., 2019)**.

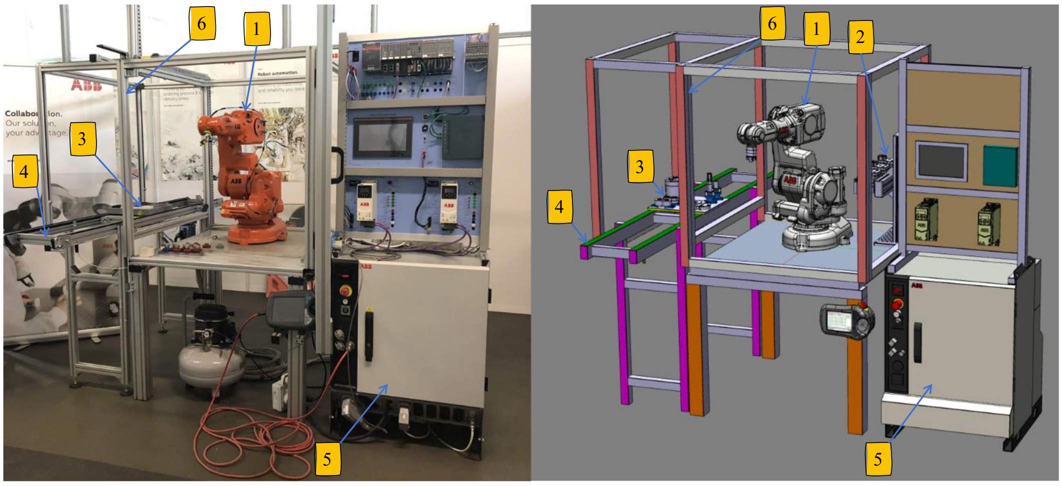


Fig. 5.2. The physical robotic cell and its digital twin developed in ABB RobotStudio.

The proposed framework's goals:

- In this educational framework, **individuals can design, program, and improve their own virtual robotic assembly manufacturing process**, facilitating the learning process, and allowing for implementation of personal ideas.
- Monitoring the performance and condition of equipment is a crucial aspect of production systems to enhance efficiency and prevent unplanned downtime. In this laboratory setting, **students can evaluate robot controller data, such as real-time energy consumption**. The robot controller also supports modern industrial I/O networks, **enabling students to experiment with sensor data monitoring and functionalities driven by KPIs**. The data collected can be analyzed and visualized on the web-platform.
- A conventional robot cell is defined by the integration of service modules with the physical components, along with the control system. In contrast, the proposed framework aims to remotely operate physical equipment through a network. **Employing web services, students can learn how to operate devices connected to the robot controller, including actuators, sensors, and cameras**.
- In the proposed approach, **students can experiment with a messaging system that enables automated triggers and delivery of customized notifications, reports, and alerts**.

Section 4. Conclusions

The proposed learning environment is based on the principles of heutagogy and cybergogy, aimed at promoting comprehension of robotic manufacturing processes, encouraging ongoing education, and fostering a mindset of growth. This will enable collaborative learning in a virtual setting and entails the following areas of development:

- CAD skills - Students will create their own solutions for various manufacturing robotic cells using CAD tools and appropriate CAD databases.
- OLP proficiency – Students will employ ABB RobotStudio to program the robots and conduct simulations to optimize the work cycle based on energy consumption, cycle duration, collision avoidance, and robot axis configurations on the tool path.
- Web services for Industry 4.0 expertise – Students can adapt their robotic work cell project to Industry 4.0 by leveraging web services and sensor data to trigger actions or present the robotic cell's energy usage and productivity based on batch production reports.

In terms of Education 4.0 specifically, the proposed learning approach is focused on the student and facilitates the employment of cutting-edge technologies in an academic setting. The approach offers students the opportunity to develop innovative solutions to modern manufacturing challenges. Future study on this educational method may place emphasis on incorporating other technologies associated with Industry 4.0 into the proposed teaching strategy, such as cyber-physical security, artificial intelligence, and augmented reality.

The original contributions of the work can be grouped in the following categories:

Original theoretical contribution:

- Presented a detailed overview of advanced teaching concepts specific to engineering education in relation to modern robotics.

Original methodological contribution:

- The development of a learning framework designed to support the Education 4.0 paradigm, consisting of:
    - A web platform for robotic applications having the capability to integrate other Industry 4.0 technologies for other teaching strategies, such as cyber-physical security, Artificial Intelligence and Augmented Reality.
    - A messaging system to automate alerts and reports.
    - A Digital Twin of a robotic work cell employing a 6-DOF robot in assembly operations.

The findings of the research and the proposed approach were published in:

Nicolescu, A.F., **Stan, L.**, & Pupăză, C. (2019) *E-Learning Platform for Robotic Applications*, 12th annual International Conference of Education, Research and Innovation, ICERI2019 Proceedings, pp. 7384-7391, WOS: 000530212403050, doi: 10.21125/iceri.2019.1760.

Chapter VI. Final conclusions

6.1. Summary of the main accomplishments

In the field of industrial engineering and automation, applications such as remote monitoring and data visualization allow for remote operation, maintenance planning, incident investigation, and optimization. IoT-enabled remote management and monitoring of devices is noteworthy when machines or equipment are inaccessible or pose a risk to human safety. Combining IT and OT has a revolutionary impact on modern manufacturing. However, challenges arise in bridging the gap between IT and OT, specifically in data transmission, storage, and analysis due to old equipment, lack of computational power, and a lack of standard interfaces and protocols between machines. **Chapter II presented the State of the Art on several key-enablers of Industry 4.0**: CPS and DT, Edge, Fog and Cloud Computing, advanced robotic systems, and RL for robotic assembly applications **(Stan et al., 2020)**.

Sustainability, like digital transformation, is an Industry 4.0 advancement that greatly impacts modern manufacturing processes. Energy consumption of machines and robots has both an environmental and economic significance in manufacturing. Therefore, research continues to focus on analyzing, monitoring, and reducing energy consumption.

The web-based platform **(Stan et al., 2023)** has been developed with the following objectives: utilizing open standards for interoperability, scalability, and collaboration; providing a user-friendly interface; enabling remote monitoring and control in near-real time; and adhering to a DevOps methodology for continuous improvement.

Noteworthy takeaways:

- Edge computing brings data acquisition closer to the source, reducing latency and increasing reliability of real-time data collection. As a result, new IIoT systems are shifting from centralized cloud computing, which is suitable for non-real-time applications with large storage and processing needs, to distributed, low-latency edge computing for real-time services. **The proposed web-platform utilizes edge computing technology by collecting and storing data on a server near the robotic system**.
- Interconnecting control systems and enterprise systems, such as ERP, enables a wide range of new applications that benefit from vertical integration from the shop floor to enterprise management. However, connecting control systems directly to the plant network poses security risks such as malware infections, denial of service, and data leakage. The need for remote access and control of critical processes has become more important due to COVID-19, which has accelerated the development of cyber security technologies and services to protect factory floor assets using industrial Ethernet and internet connection. **The proposed web-platform incorporates the IRC5 robot controller security feature, specifically the authentication system**.
- The combination of offline and sensor-based programming is a modern approach to programming industrial robots in manufacturing. Offline programming allows for the development and testing of robot programs in a virtual environment, which can save time and resources. Sensor-based programming utilizes signals from devices present in the

workcell to provide the robot with real-time information. Therefore, the web-platform must be able to communicate with every device in a production system. This criterion is accomplished, since **the web-platform can communicate with every robot, sensor, and actuator that is commanded by the robot controller**.

As presented in Chapter III, to develop the web-platform, the following elements have been created: a communication link between the controller and the webserver; a utility class to facilitate the controller-webserver communication and a utility service to collect and store data; a web GUI that enables the monitoring of a selection of sensor signals from the workcell (The Dashboard); visualization charts that enable the monitoring of the workcell productivity and of the energy consumption of the robot (The Control Charts).

The proposed web-monitoring platform's capabilities were demonstrated through a simulation procedure, and experiments were conducted on a real robotic system to validate its effectiveness. The case study focused on a robotic assembly application and proved:

- The two-way communication enables the web-based framework to acquire data from the robot controller and have control over it, such as stopping the robot in an emergency.
- The web-based framework collects data hourly, while system control is immediate.
- The robotic process is entirely automated, and the DT includes robust simulation features, such as checking the toolpath against collisions and calculating the energy usage.

Studies that address transdisciplinary research on complex robotic systems for modern manufacturing that involve various aspects, such as cost-effective robotic deburring solutions, or monitoring the energy consumption of robots via robotic web services, are relatively rare. This is likely due to the complexity and interdisciplinary nature of these systems, as well as the need for expertise in multiple fields such as robotics, industrial engineering, implementing cost-effective solutions for manufacturing, energy consumption, web services and web development. Additionally, studies of this nature often require a significant number of resources and collaboration between multiple institutions and organizations. Therefore, while such research is important for advancing the field of modern manufacturing, it is not as common as research focused on more specific aspects. To address this issue, **Chapter IV presented a holistic approach for a web-based approach to monitor a robotic application (Stan et al., 2022),** and highlighted:

- The application of a cost-effective deburring solution based on an end-effector with passive control and radial compliance.
- The offline programming of an industrial robot to deburr a large plastic workpiece, along with the offline simulation of the robotic workcell.
- A vision-based deburring algorithm, devised to improve the process efficiency.
- A brief overview of the energy consumption of industrial robots, the benefits of applying the proposed deburring solution, and the monitoring capabilities of the proposed web platform on the robotic manufacturing system.

When devising the web-based monitoring system, the biggest challenge is the seamless integration of the Industry 4.0-specific paradigms (i.e., virtualization, robot programming, image acquisition and processing, network communication), the data acquisition, and its assessment in interactive GUI elements.

Because of the increasing complexity of innovative technologies, researchers have shifted their focus to education, asserting that academic institutions must provide practice-oriented teaching approaches in learning factories to enable engineers of today to apprehend the implications of these advancements. Consequently, methods for teaching digitalization tactics in HRC and CPPS are emerging. Even though robots are prominently featured in the literature on Industry 4.0 concepts, there is a scarcity of studies concerning education approaches for industrial robots employed in modern manufacturing. **To cover this gap, Chapter V focused on the educational prospect of the proposed web-platform (Nicolescu et al., 2019)**, and introduced the following:

- An examination of the advanced techniques used in Education 4.0 to promote a positive mindset and bridge the gap between the education of engineering graduates and the skills required in the workforce.
- An investigation of the use of industrial robots in modern manufacturing through a case study, employing the proposed web-platform. In this context, the web-platform may incorporate other Industry 4.0 technologies, such as cyber security, machine learning, and Augmented Reality, to develop further teaching methodologies.

6.2. Original contributions

The doctoral thesis's original contributions can be categorized as follows:

1. **Theoretical contributions:**
    - Presented in an original and comprehensive manner the State-of-the-Art technologies that shape the Cyber-Physical Systems and Digital Twin paradigms, as well as their specific characteristics and current challenges.
    - Introduced the innovative technologies in Cloud Computing and outlined their strengths and weaknesses.
    - Provided a comprehensive review of advanced Human-Robot Collaboration (HRC) solutions and addressed the State-of-the-Art methodologies employed in HRC infrastructure, safety, and robot programming.
    - Presented a detailed overview of cutting-edge Reinforcement Learning solutions applied in robotic assembly.
    - Employing a virtual robot controller for testing purposes and for replicating the functionality of the web-platform in an original approach.
    - Presented a detailed overview of advanced teaching concepts specific to engineering education in relation to modern robotics.
2. **Methodological contributions:**
    - The development of the web-based monitoring platform for robotic systems in a step-by-step approach comprising full details of the methodology.
    - The simulation strategy to demonstrate the functionality of the platform.
    - The development of a Digital Twin using ABB RobotStudio for a robotic deburring manufacturing process.
    - The seamless integration of the web platform to monitor the robotic deburring workcell and to display the energy consumption of the robot and the production data.

- The development of a learning framework designed to support the Education 4.0 paradigm, consisting of:
    - A DT-enabled robotic application employing an articulated robot in assembly operations.
    - An adapted version of the web platform, having the capability to integrate further Industry 4.0 technologies for other teaching methodologies, such as cyber-physical security, Artificial Intelligence and Augmented Reality.
    - A messaging system based on a Telegram bot with a set of specific rules for triggering alerts and notifications.

3. **Robot programming contributions:**
    - The offline programming of an industrial robot to deburr a large plastic workpiece along with:
        - the energy consumption analysis of the robot
        - the signal-based offline simulation of the robotic workcell
4. **Practical industrial engineering contributions:**
    - The application of a cost-effective deburring solution based on an end-effector with passive control and radial compliance.
    - The development of a vision-based deburring algorithm to increase the manufacturing process efficiency.
    - The application of edge computing for data acquisition and processing in a robotic system.

6.3. Future work

Future work may be directed on numerous challenging areas:

- **The web-based platform may be extended to include more than one robotic system**, granting it the ability to monitor factory floor production of various robotic applications, to collect, and to analyze data for providing real-time production statistics. By employing web services, the web-platform can function as a communication core for numerous robotic systems, therefore, enhancing the operational performance and cost-efficiency. Specifically, the robot controllers can communicate with one another via the web platform's backend or with other devices, such as industrial cameras, enabling other advanced approaches for robotic applications, such as deburring or assembly.
- **When the demand for processing capacity increases, the framework can be expanded to cloud computing**, which will also offer further analysis capabilities such as AI-based approaches for condition monitoring.
- **In the context of education, future work may place emphasis on incorporating other technologies associated with Industry 4.0**, such as cyber-physical security, AI, and Augmented Reality.
- **The investigation of security weaknesses in networked machines and robotic systems, as well as the development of security methods and architectures**, are equally promising directions.
- In the wake of COVID-19, **enhancing the remote control and monitoring of manufacturing systems** is an important research topic for future work.

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