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Creating a web-oriented human-machine interface for a SCARA robot physical model based on industrial Internet of Things technologies

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Abstract. Loading and unloading operations are one of the key links in many production processes in modern industry. Improving the accuracy, productivity, and velocity of control is essential for increasing the efficiency of loading and unloading processes. This can be achieved by integrating production processes into the web through the implementation of the "Industry 4.0" concept. The aim of this work was to develop a web interface for a system that simulates loading and unloading operations based on a SCARA robot, which ensures effective monitoring and control of the technological process. To determine the architecture of proposed system, modern approaches to the development of automated control systems using the "Industry 4.0" concept were analysed. To select the tools for creating the system components, technologies for software development that are suitable for this task were analysed and identified. A comprehensive control and monitoring system for the SCARA robot was developed using a web interface based on the "Industry 4.0" concept. The developed web interface demonstrated an effective approach to building interactive control systems, improving productivity and convenience for operators. The practical significance of the results lies in the creation of a unified solution for monitoring and controlling robotic complexes, which can be adapted and implemented on various production and educational platforms. Additionally, the developed solution can be used in the educational process for laboratory practice in normative disciplines

Keywords: automation; industry 4.0; internet of things; MQTT; OPC UA; PLC; web-based SCADA

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Introduction

In the industrial sector, increasing attention is being paid to automation and optimisation of production and logistics processes. SCARA robots play a key role in improving loading and unloading operations, providing high precision, productivity, and safety. This application opens up new opportunities for creating modern intelligent control systems. The necessity for efficient monitoring and management of complex technological complexes drives the continuous development of human-machine interfaces and web technologies that provide operators with full real-time control over technological processes.

The current stage of industrial development is characterised by profound transformations caused by the implementation of innovative technologies and changes in global economic conditions. One of the key trends is the transition to the concept of "Industry 4.0," which involves the integration of digital technologies into all aspects of the production process. It was noted in the study by M. Vlasenko & Yu. Khlaponin (2024), that the concept of "Industry 4.0" is based on technologies such as the Internet of Things (IoT), big data, artificial intelligence (AI), and machine learning (ML), which together form the foundation for the smart factories of the future.

It was emphasised in the study by A. King (2021) that one of the main drivers of the development of the "Industry 4.0" concept is the growing need for product personalisation and the associated shortening of production cycles, which requires enterprises to be more flexible and responsive. This stimulates the implementation of additive technologies (3D printing), robotic production lines, and predictive maintenance systems. In this context, supervisory control and data acquisition (SCADA) systems play a particularly important role, as they allow operators and managers to obtain a complete and up-to-date picture of production processes in real time. As noted in the study by F.J. Folgado *et al.* (2024), SCADA systems are used in almost all industries, including automotive, chemical manufacturing, energy, transport, agriculture, and others.

The study by S. Ardi *et al.* (2024) emphasised the feasibility and advantages of using SCADA systems, particularly the potential to improve production efficiency, ensure better equipment protection, and increase workforce productivity. The authors also highlighted the importance of early detection of abnormal operating modes and rapid notification of personnel through the integration of process data from sensors and enhanced communication capabilities. Modern visualisation systems integrate data from various sources, including IoT sensors, enterprise resource planning (ERP) systems, and manufacturing execution systems (MES), presenting them in a clear and intuitive format. The authors examined these advantages of SCADA through the example of implementing the Wonderware InTouch system in the automotive industry. This system offers a wide range of visualisation capabilities for unloading operations, including the creation of detailed schematic diagrams, interactive control panels, and real-time reports.

Another powerful SCADA system often used for visualising logistics processes is Siemens WinCC. This system is distinguished by its high scalability and reliability, making it an ideal choice for enterprises of various sizes. As noted in the study by D. Mencia *et al.* (2023), WinCC offers advanced 3D visualisation capabilities, which are especially useful for simulating complex loading and unloading operations using robotic systems such as SCARA robots. Another important aspect of analysing existing visualisation systems is the comparison between local and cloud-based solutions. Local visualisation systems, such as the previously mentioned Wonderware InTouch and Siemens WinCC, have certain distinctive features. As it was noted in the study by C. Bayılmış *et al.* (2022), local visualisation systems provide maximum speed in data processing and information display, which is critically important for emergency response. It was also stated, that local systems ensure complete control over data security, which is especially crucial for enterprises with high confidentiality requirements.

On the other hand, cloud visualisation systems, such as Amazon AWS IoT SiteWise or Microsoft Azure IoT Central, offer a range of unique advantages. The primary benefit of cloud solutions is their scalability and flexibility. Cloud systems also provide easy data access from anywhere in the world, which becomes increasingly important in the context of business globalisation and the spread of remote work practices. Moreover, cloud platforms often offer built-in analytics and machine learning tools that can be used to optimise logistical processes. However, when choosing between local and cloud-based solutions, it is essential to consider the specifics of their operation. The study conducted by O.A. Lawrence & M. Tariq Iqbal (2020) pointed out that for enterprises with mission-critical processes, where even a brief loss of connection can lead to significant losses, local systems remain the preferred choice. Conversely, for companies seeking maximum flexibility and minimal IT infrastructure costs, cloud solutions may be the optimal choice. It is also important to consider the growing trend of using mobile applications for process visualisation. According to the study by I. Qasim *et al.* (2020), many modern systems, both local and cloud-based, offer mobile interfaces that allow operators and managers to access key information and manage processes from mobile devices. This is especially useful for large warehouse complexes, where the speed of response to changing situations can significantly enhance operational efficiency.

Summarising the analysis of existing unloading operation visualisation systems, it can be concluded that the market offers a wide range of solutions capable of meeting the needs of enterprises of various scales and specificities. From powerful SCADA systems to specialised logistics platforms, from local solutions to cloud services – each approach has its advantages and limitations. In the context of developing a web interface for a visualisation system for a SCARA robot-based loading and unloading operations modelling complex, the analysis of existing solutions allows defining key requirements and best practices. In particular, it is important to ensure a balance between information display detail and interface simplicity, implement capabilities for qualitative visualisation of SCARA robot operations, provide for integration with other enterprise systems, and ensure access to information from various devices, including mobile ones. Therefore, the objective of this study was to develop an architecture for a web-oriented human-machine interface for a SCARA robot, based on industrial Internet of Things technologies and modern web frameworks. The proposed architecture is intended to serve a dual purpose – enabling its application both in industrial manufacturing and in educational settings for remote monitoring and control of a laboratory testbed.

Materials and Methods

The SCARA robot control system was based on the Siemens S7-1200 programmable logic controller (PLC), manufactured by Siemens (Germany), which provided reliable and efficient management of all stand components. Specifically, the CPU 1215C model (6ES7215-1AG40-0XB0) was used, which was optimally suited for robot control tasks and real-time data processing. Figure 1 shows a stand with a SCARA robot.

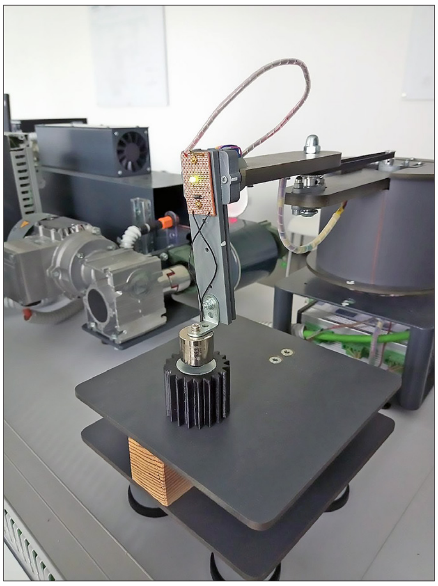

Figure 1. Stand with SCARA robot

Source: authors' photo

The SCARA Robot Test Stand was designed by LLC "Donenergoprommontazh" on the order of SE "Siemens Ukraine" for Kryvyi Rih National University, taking into account the requirements of compactness, functionality, and ease of use in laboratory conditions. All stand components are placed on a robust metal frame with overall dimensions of 275x350x190 mm.

The stand design includes the following main elements:

- frame: provides structural stability and reduces the impact of external vibrations;
- electrical Cabinet: sized 25x40 cm, located in the lower part of the frame. It is equipped with PLC, power supplies, and other electrical equipment;
- SCARA robot: mounted on the upper part of the frame, with a work zone optimised for demonstration and studying operational principles;
- test object zone: designed for placing loads and simulating various operational scenarios.

The stand features a visualisation system interface based on SIMATIC WinCC, which provides displaying current and target positions of robot mechanisms, control modes (manual, automatic, stop), monitoring the magnetic gripper state and other system parameters, real-time technological process visualisation. Although the existing HMI system provides basic control and monitoring functions, it has certain limitations, particularly the lack of remote access and limited analytics capabilities. With the formulated list of software and technical solutions, it was possible to develop a comprehensive toolkit structure necessary for web interface implementation, as well as a structural scheme that reflects the types of information flows in this system (Fig. 2).

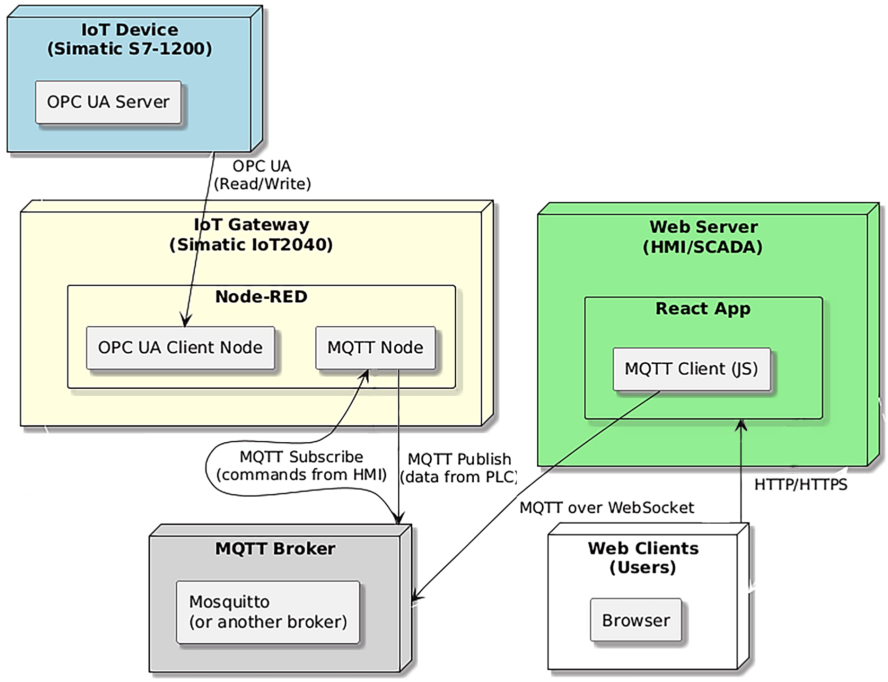

Figure 2. UML deployment diagram of the proposed system

Source: authors' development

Thus, UML deployment diagram in Figure 2 illustrates the physical architecture of the developed system, the distribution of computational functions across the nodes, and the interconnections between the software and hardware components of the system. At the lowest level of the hierarchy are sensors and actuators, namely: laser sensors, servo drives, conveyor motor, and others. They are connected to the Siemens S7-1200 PLC, which receives data from sensors and sends control commands to actuators. Data from the OPC UA server on the S7-1200 controller will be transmitted through a local network to IoT gateway with a Node-RED server installed. This software complex will perform initial processing (such as data logging or basic reading) and data aggregation, as well as provide visualisation of the system's main parameters in a user-friendly interface. For communication between the Node-RED server and React, the MQTT protocol can be used through the MQTT broker. Using a public MQTT broker simplified system deployment and eliminated the need to configure a proprietary infrastructure. This architecture reflects the basis of the conducted study, flexibility, scalability, and reliability of data transmission between system components, allowing easy integration of additional elements by connecting to appropriate MQTT topics.

The client-side of the web-based human-machine interface for the physical model of the SCARA robot was developed using the JavaScript library React.The project architecture is built using modern approaches to creating interactive web applications, specifically the Single Page Application (SPA) concept with React.js. The selected technological solutions provided high performance, scalability, and development convenience for the modelling system user interface. The technology stack included React.js as the foundational library for building a component-based architecture, Material-UI for unified design and ready-to-use interface components, MQTT.js for ensuring communication with message brokers, and mechanisms for local application state storage.

Results

Figure 3 shows a UML sequence diagram that shows the order of interaction between the components shown in Figure 2. After launching the React application, an attempt is made to establish a connection with the MQTT broker. If the connection fails, a reconnection loop is initiated with a delay timer between attempts. In case of a successful connection, the client subscribes to a topic containing the PLC status data. Simultaneously, on the IoT Gateway node, Node-RED reads data from the OPC UA server on the PLC and sends it to the broker via MQTT. The React application receives these messages, updates its internal state, and displays the current information in the web interface. When a user interacts with the interface (e.g., by pressing a button), it triggers the formation of an MQTT command, which is published by the client to the appropriate topic. The MQTT broker forwards the command to the IoT Gateway, where Node-RED recognises it and performs a write operation to the PLC via OPC UA. This ensures full bidirectional communication: reading data for visualisation and sending commands to control the process in real time.

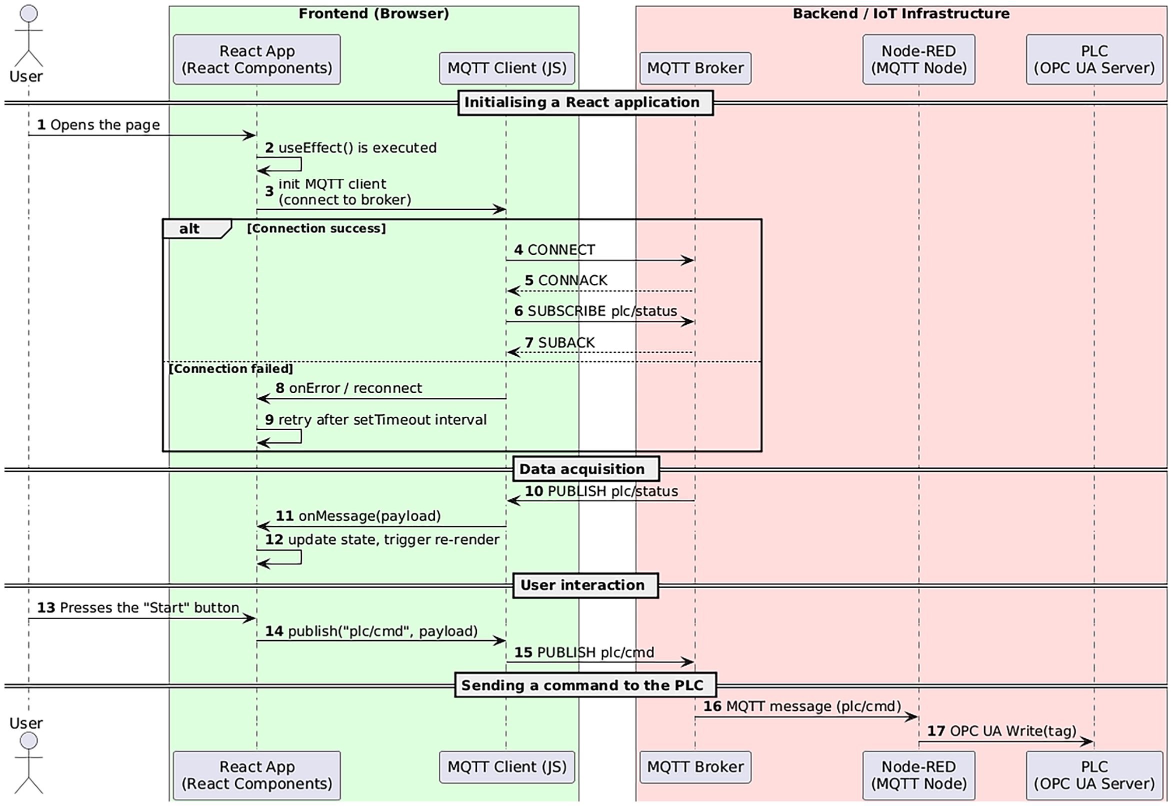

Figure 3. UML Sequence diagram of nominal scenario of communication between PLC and web- oriented HMI in the developed solution

Source: authors' development

The activity diagram in Figure 4 details the logic of implementing data read and write scenarios within the system, complementing the interaction sequence with internal flow control. After the React application is initialised, a loop of connection attempts to the MQTT broker is launched. In the event of failure, a delay timer is applied before the next retry. A successful connection results in a subscription to the topic from which data from the PLC will be received. Simultaneously, Node-RED on the IoT gateway reads this data from the PLC's OPC UA server and publishes it via MQTT, after which the React client receives the messages, updates the interface state, and displays the values to the user. Another activity branch describes the reverse action – transmitting commands from the user to the PLC. When the user interacts with the UI (for example, changes a parameter or presses a button), React forms a command and publishes it to the MQTT broker. Upon receiving the message, Node-RED interprets it and performs the appropriate write operation to a variable on the PLC via OPC UA. Thanks to the parallel structure of the diagram, it is evident that both flows (reading and control) operate independently but interact through the shared MQTT and OPC UA infrastructure, ensuring reliable bidirectional integration of the human-machine interface with the real process. The primary stage of software development for the stand is the implementation of an integration platform between the web interface and the stand, using the Node-RED tool. Software development for the given implementation can be divided into several stages: configuring connection to the OPC UA server; developing a data collection and monitoring mechanism; developing a control and recording mechanism (Baig *et al.*, 2021). The process begins with system initialisations – launching a node that periodically generates lists of topics for reading data from the OPC UA server. These topics correspond to tag identifiers in the system, the data of which need to be monitored and managed. Topic list generation is performed in the "Generate Topics" node on the block diagram (Fig. 5). Next, the OPC UA client, configured for data reading, cyclically polls the server, reading current values for each topic. These values are compared with previously saved ones, and in case of changes, new data is written to the Node-RED global context. The global context is used to store the current system state, which allows easily obtaining the necessary data at any moment. To work with MQTT in Node-RED, specialised nodes "mqtt in" (MQTT Control Input block on Fig. 5) and "mqtt out" (scada/data block on Fig. 5) are used. They allow subscribing to specific MQTT topics and publishing messages to other topics, respectively (Malhi *et al.*, 2023; Safitri *& Priambodo* 2023; Jadhav, 2024).

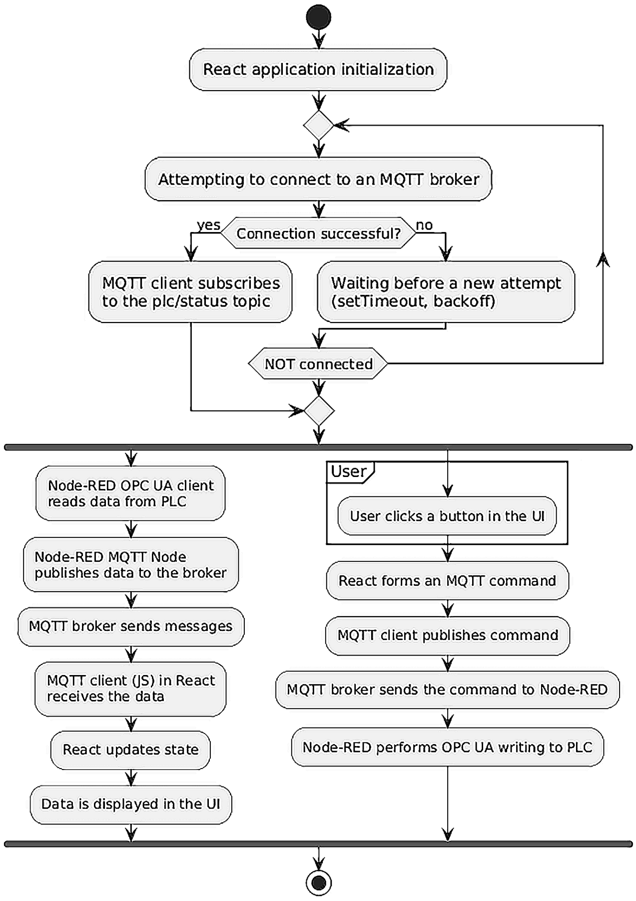

Figure 4. UML Activity diagram for modelling of the developed IoT solution for web-oriented HMI
Source: authors' development

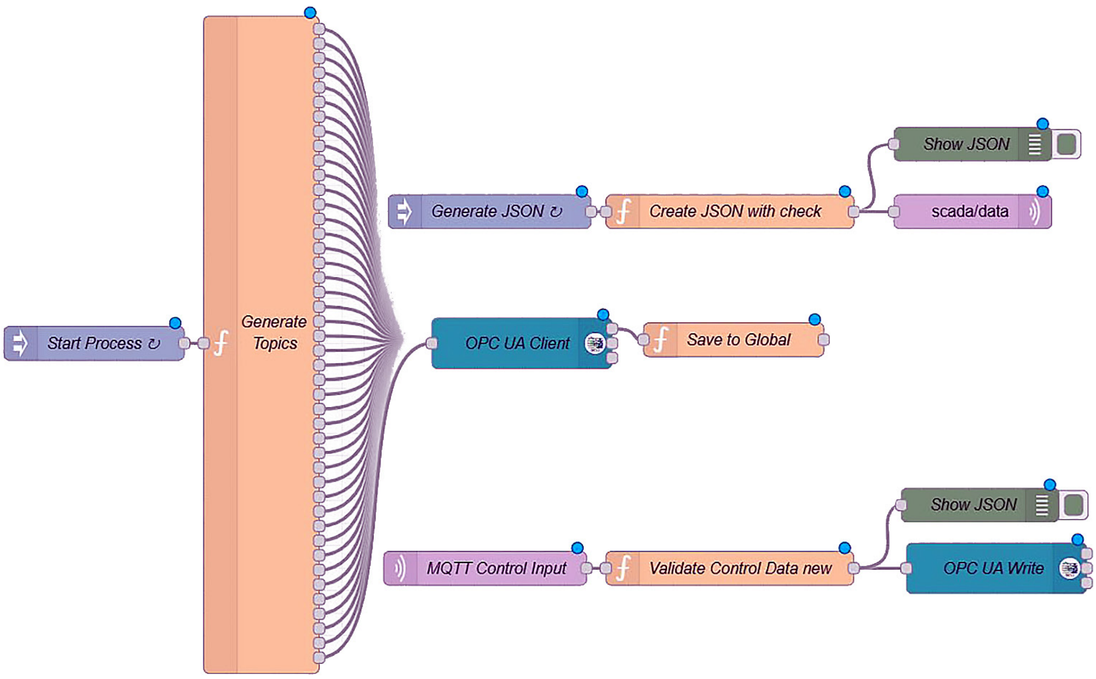

Figure 5. Basic nodes and data flow in Node-RED for implementation of data exchange between PLC and MQTT-broker
Source: authors' development

The HMI panel (HMIPanel) is a key interface component that provides interactive system control. Developed using reactive programming approaches, the panel offers users a comprehensive set of controls for managing the primary parameters of the modelling complex. The component architecture is constructed using advanced React patterns, specifically component memoisation via React.memo to optimise performance. Each subcomponent (ControlUnit, TemperatureControl) has its own logic for handling user interactions and transmitting control commands. The Visualisation component implements graphical representation of the system's state. Utilising SVG graphics allows for creating a dynamic and interactive visualisation with the ability to instantly update colours and element states based on received data. The approach to building the graphical interface was based on principles of adaptability and informativeness.

The Notification System (NotificationStack) provides user feedback through a mechanism of pop-up messages. Implemented using custom-configured Material-UI components, the system delivers instant information about connection status, command execution results, and system events. An important aspect of the architecture is the mechanism for local application state storage. Utilising localStorage allows the application to retain its current state between page reloads, enhancing the user experience and ensuring continuity in system interaction. The application adheres to the principles of reactive programming, enabling efficient interface updates as new data is received from the MQTT broker. The graphical design is implemented using Material Design, providing a modern, intuitive, and minimalist interface.

Structurally, the site consists of the following key elements:

- control panel. The central part of the interface that provides the user with complete control over the stand's operation (Fig. 6).
- Visualisation block. A section of the page where the movement of the robot, conveyor, and the status of the deployed sensors are dynamically displayed (Fig. 7).

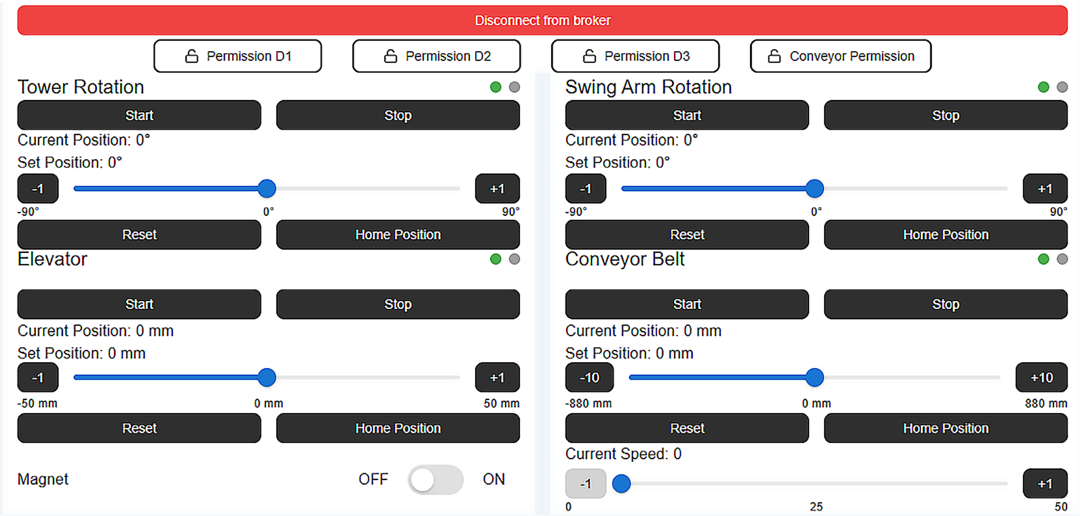

Figure 6. Control panel web interface

Source: authors' development

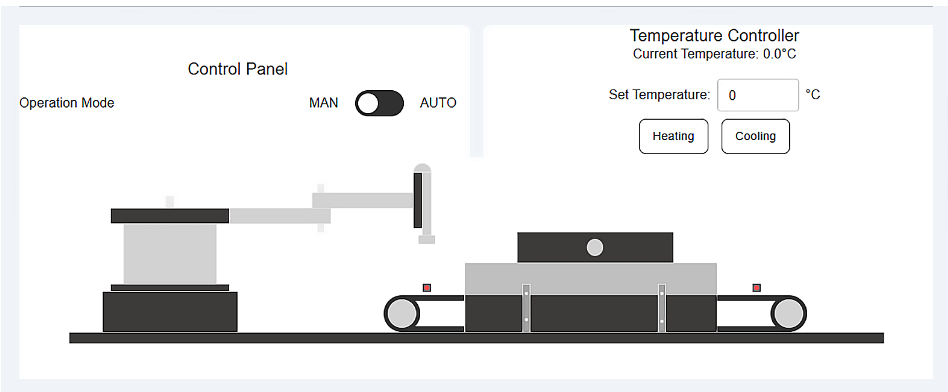

Figure 7. Visualisation block of the stand

Source: authors' development

The developed web interface serves as a visualisation and control system for load-handling operations involving a SCARA robot. The platform is a comprehensive tool for monitoring and managing the technological complex built on the educational stand, ensuring functionality and ease of use. The primary functional purpose of the site is to provide the user with a convenient and intuitive toolkit for managing all aspects of a SCARA robot's operations. The operator gains the ability to both observe the current state and process of operations execution, as well as directly intervene in the technological process, adjusting the robot's operating parameters and those of other machines. Thus, the website represents a comprehensive solution that combines the functionality of monitoring, control, and visualisation of key aspects of the SCARA robot's operation.

Discussion

The developed software and methodological complex demonstrated effective integration of modern industrial automation technologies with educational and research purposes. Its architecture was based on five logically interconnected nodes, enabling a visual, interactive, and flexible approach to studying and managing automated systems. The developments presented in this work for the SCARA robot-based stand demonstrated effective integration of modern industrial automation and Internet of Things (IoT) technologies. The use of the Simatic S7-1200 programmable logic controller (PLC) as an OPC UA server ensured a standardised approach to data exchange between system components. A similar approach was applied in the study by A.H. Embong *et al.* (2024), where the Siemens S7-1200 was used for real-time monitoring and control of asynchronous motors via Node-RED, highlighting the effectiveness of such integration in both laboratory and industrial settings.

The use of an IoT gateway based on the Simatic IoT2040 with Node-RED installed for processing data from the OPC UA server and transmitting it via an MQTT broker is an important step toward ensuring system flexibility and scalability. The study conducted by M. Rozan *et al.* (2024) demonstrated a similar approach, where Node-RED and OPC UA were used for monitoring an automated warehouse, highlighting the effectiveness of this solution in industrial applications. Additionally, the use of an IoT gateway implemented segmentation of the industrial Internet of Things network, which, as indicated in the study by R. Yatagha *et al.* (2023), is a highly recommended protection policy in accordance with international standards.

The use of MQTT as a data exchange protocol between system nodes aligns with current trends in industrial automation. In the work by J. Odier *et al.* (2024), the process of integrating OPC UA and MQTT using Node-RED was described, emphasising the advantages of such an approach in ensuring a continuous data flow and improved real-time monitoring. It was demonstrated in the study by K. Ferencz & J. Domokos (2020) how this platform can be used to integrate various industrial devices and systems, providing flexibility and ease of configuration. Particular attention should be paid to the implementation of the visualisation and remote control subsystem, which was developed as a web application based on React. This approach supports the concept of using web technologies to create human-machine interfaces in industrial applications. It aligns with current trends in both industry and education, allowing for the development of flexible, user-friendly HMI systems with remote access support. This enables students and researchers to control the test bench in real time from any device with internet access.

The use of the system in educational settings, especially under conditions of remote learning, is highly relevant. The studies by A.F. Santacruz *et al.* (2021) and S.V. Kandala *et al.* (2025) emphasised the importance of implementing remote laboratories for education, enabling students to gain practical skills without being physically present in the lab. The development and deployment of remote laboratories based on SCARA robots contributed to improving the quality of education in the fields of robotics and automation (Faridan *et al.*, 2023). The article by T. Kaarlela *et al.* (2022) described the creation of a platform for remotely controlling robots, allowing students to interact with real robotic systems over the internet, which is particularly important in situations with limited access to laboratory equipment.

In addition, the architecture that utilises MQTT as an intermediary for data exchange ensures system scalability and allows the connection of an unlimited number of clients, making the system convenient for collaborative work or remote laboratories. This is especially relevant in the context of distance learning, where providing a practical component in education presents a challenge. Considering other studies in this field, the work by D.R. de Sousa *et al.* (2024) is noteworthy, proposing a methodology for creating semantic digital twins using Node-RED and OPC UA. The authors described a sequence of steps covering data collection, semantic annotation, and asset modelling, generating a graph of nodes and connections stored in a graph database. This study emphasised the importance of semantic data integration and the creation of digital twins for modernising legacy systems, which aligns with the approach used in the developed system in the current study.

Additionally, the article by P. Kuriščák *et al.* (2022) presented a modular platform for remote control of robotic manipulators through a digital twin. The authors conducted a survey involving 37 participants who used various controllers to operate robots remotely and demonstrated the usability of the platform. This study highlighted the importance of creating intuitive interfaces for remote robot control, which was also taken into account during the development of React-based web application in the current study.

Overall, the system not only ensures effective interaction between hardware and software but also lays the groundwork for further functionality expansion. Potential directions include integration with cloud platforms, real-time data analytics, and the use of artificial intelligence for predictive analysis. The developed system meets current industrial automation requirements and contributes to the improvement of the educational process, providing students with access to advanced technologies and tools for remote learning and research.

Conclusions

The architecture of the developed system was based on modern IIoT principles and demonstrated a fundamentally new approach to building communication control systems. The proposed solution implemented a three-tier model comprising the hardware layer, the data transmission layer, and the analytics layer, ensuring maximum flexibility, scalability, and efficiency in component interaction. At the hardware configuration level within TIA Portal, a significant controller upgrade was performed updating the processor version to enable support for the OPC UA protocol. The integration platform Node-RED has been implemented as a powerful communication layer, providing reliable data exchange between the OPC UA server and the MQTT broker. The developed algorithm minimised system load by publishing only changed values, thereby enhancing data transmission efficiency.

The client web interface was developed using modern React.js technologies. Its architecture is modular, reactive, and user-friendly, achieved through a well-designed component structure and the application of Material-UI libraries. The developed solution represents a comprehensive monitoring and control system for a SCARA robot, offering a full range of functional capabilities – from establishing connections to real-time visualisation and management of the technological process. A key advantage of the developed web interface is its ability to provide full-scale real-time monitoring of the technological process, offer intuitive control tools, and promptly respond to system state changes. The use of modern technological solutions, such as OPC UA, Node-RED, MQTT, and React.js, has enabled the creation of a high-performance, secure, and easily integrable software product.

The next step in this work could involve offloading part of the computational workload to cloud services (such as AWS IoT, Azure IoT Hub, or Google Cloud IoT). This would enhance the scalability of the system, enable big data analytics, and improve the reliability of data storage. Another promising direction is the implementation of machine learning (ML) algorithms for failure prediction, control parameter optimisation, or user behavior analysis, which unlocks a new dimension in managing robotic systems. In particular, it would allow the system's responses to be adapted to specific industrial or educational scenarios. Based on the current platform, it is possible to build a modular infrastructure for remote laboratories. This is especially relevant in hybrid or distance learning settings, where students can simultaneously connect to the system, observe its behavior, and interact with it via a web browser.

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Conflict of Interest

None.

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Створення веб-орієнтованого людино-машинного інтерфейсу для фізичної моделі робота SCARA на основі технологій промислового Інтернету речей

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Анотація. Навантажувально-розвантажувальні операції є однією із ключових ланок багатьох виробни-чих процесів у сучасній промисловості. Для підвищення ефективності процесів навантаження та розвантаження важливим є підвищення точності, продуктивності та швидкості керування. Цього можна досягти шляхом інтеграції виробничих процесів у web через впрова-дження концепції «Industry 4.0». Метою цієї роботи була розробка веб-інтерфейсу для системи, що імітує навантажувально-розвантажувальні операції на базі робота SCARA, що забезпечує ефективний моніторинг та керування технологічним процесом. Для визначення ар-хітектури запропонованої системи було проаналізовано сучасні підходи до розробки автоматизованих систем керування з використанням концепції «Industry 4.0». Для вибору інструментів для створення компонентів системи було проаналізовано та визначено технології розробки програмного забезпечення, що підходять для цього завдання. Було розроблено комплексну систему керування та моніторингу робота SCARA з використанням веб-інтерфейсу на основі концепції «Industry 4.0». Розроблений web-інтерфейс демонструє ефективний підхід до побудови інтерактивних систем керування, підвищення продуктивності та зручності для операторів. Практичне значення результатів полягає у створенні єдиного рішення для моніторингу та керування роботизованими комплексами, яке можна адаптувати та впровадити на різних виробничих та освітніх платформах. Крім того, розроблене рішення може бути використане в навчальному процесі для лабораторних робіт з нормативних дисциплін

Ключові слова: автоматизація; індустрія 4.0; інтернет речей; MQTT; OPC UA; ПЛК; веб-SCADA