eng

MDPI

Article

Integration of Digital Twin, IoT and LoRa in SCARA Robots for Decentralized Automation with Wireless Sensor Networks

William Aparecido Celestino Lopes [1,2], Adilson Cunha Rusteiko [2], Cleiton Rodrigues Mendes [3], Nicolas Vinicius Cruz Honório [2] and Marcelo Tsuguio Okano [1,*]

[1] Graduate Program in Production Engineering, Paulista University UNIP, Campus Indianapolis, São Paulo 04026-002, Brazil; william.lopes12@aluno.unip.br
[2] The Brazilian National Service for Industrial Training, SENAI VOLKSWAGEN, São Bernardo do Campo 09823-000, Brazil; adilson.rusteiko@sp.senai.br (A.C.R.); nicolas.honorio@sp.senai.br (N.V.C.H.)
[3] Salvador Arena Foundation Educational Center, São Bernardo do Campo 09850-550, Brazil; pro21002107@cefsa.edu.br
* Correspondence: marcelo.okano1@docente.unip.br; Tel.: +55-11-99109-6575

Abstract: The integration of Digital Twin (DT), Internet of Things (IoT), and Long Range Wireless (LoRa) technology in industrial automation increases efficiency, flexibility, and real-time monitoring. This study proposes a decentralized automation architecture for SCARA robots, leveraging wireless sensor networks to improve scalability, reduce the number of infrastructure components, and optimizing data-driven decision-making. Experimental validation demonstrated a 74.9% reduction in cycle time, decreasing from 55.42 s to 13.91 s across all test scenarios. The system achieved a 98.6% packet delivery success rate, ensuring reliable communication, while latency remained between 1 and 2 s, maintaining synchronization between the real robot and its digital twin. The main contributions include the following: (i) a decentralized control framework for SCARA robots, (ii) an evaluation of LoRa-based wireless communication, and (iii) experimental validation of feasibility. The results confirm the effectiveness of the system in stable real-time data transmission and precise robotic movements, offering a cost-effective alternative to conventional structures. Despite the advantages, challenges such as data security, interoperability, and real-time synchronization require further research. This study provides insights into the practical implementation of DT, IoT, and LoRa in industrial robotics, paving the way for advancements in smart manufacturing and Industry 4.0.

Keywords: Digital Twin (DT); Internet of Things (IoT); LoRa (long range); wireless sensor networks (WSNs); SCARA robot; Industry 4.0; smart manufacturing; cyber-physical systems (CPS)

check for updates

Academic Editors: Antonio Gil Bravo and Hao Yu

Received: 24 February 2025
Revised: 22 April 2025
Accepted: 23 April 2025
Published: 26 April 2025

Citation: Lopes, W.A.C.; Rusteiko, A.C.; Mendes, C.R.; Honório, N.V.C.; Okano, M.T. Integration of Digital Twin, IoT and LoRa in SCARA Robots for Decentralized Automation with Wireless Sensor Networks. *Eng* **2025**, *6*, 90. https://doi.org/10.3390/eng6050090

1. Introduction

The increasing demand for automation in industrial environments has driven the development and adoption of innovative technologies aimed at improving efficiency, flexibility, and real-time monitoring of processes. Among these technologies, Digital Twin (DT), the Internet of Things (IoT), and wireless sensor networks (WSNs) have gained prominence due to their ability to create smart, autonomous, and decentralized systems [1]. The integration of these technologies has enabled industries to optimize their operations by providing real-time insights, predictive maintenance, and enhanced decision-making capabilities [2].

SCARA (Selective Compliance Articulated Robot Arm) robots are widely used in automated industrial environments due to their speed, precision, and adaptability in assembly, pick-and-place, and material handling applications [3]. While many traditional automation architectures depend on wired communication and centralized control systems, their scalability and flexibility may be constrained in environments requiring high adaptability and distributed intelligence. This limitation is particularly evident in applications that demand real-time reconfigurability and seamless integration of heterogeneous devices [4]. In this context, the incorporation of IoT and WSN technologies into SCARA robots offers a decentralized approach that enhances operational autonomy while reducing infrastructure dependency [5].

One of the main obstacles in using decentralized automation is establishing a reliable and efficient communication network that can operate over long distances with minimal energy consumption. Long Range (LoRa) technology has emerged as a viable solution, providing low-power, long-range wireless connectivity for industrial applications [6]. LoRa enables seamless data transmission between sensors and control systems, facilitating the integration of DT and IoT in SCARA robots without the need for extensive wired infrastructure [7]. This integration is particularly beneficial for environments with limited network access, remote manufacturing facilities, and mobile automation applications [8].

Despite the advantages of DT, IoT, and LoRa in industrial automation, several challenges remain, including data security, real-time synchronization, and interoperability between heterogeneous devices [9]. Despite the advances promoted by the integration of DT, IoT and LoRa in industrial automation, relevant technical challenges persist, particularly in relation to information security, real-time synchronization and interoperability between heterogeneous devices [9]. The adoption of networks such as LoRaWAN increases the surface area of exposure to cyberattacks, especially due to the presence of IoT devices connected to sensors with limited computing capacity, which makes it difficult to implement robust cryptographic algorithms [10,11]. Although the LoRaWAN protocol uses AES-128 encryption in the network and application layers, its effectiveness depends directly on the secure management of keys such as AppKey, NwkSKey and AppSKey. The vulnerability of any element of the infrastructure—sensors, gateways, network and application servers or the DT platform itself—can compromise operational data or allow unauthorized access [11]. The function of DT as an aggregator and processor of data from critical assets makes it a sensitive point within the system architecture. In this scenario, it is essential to ensure the authenticity, integrity and confidentiality of data, from its origin in the sensor to its virtual representation and the return of commands, which requires integrated security solutions compatible with distributed environments [10]. Although there are studies applying DT in large-scale industrial contexts, there is a lack of research addressing its application in decentralized systems with restrictions on computational resources [12]. Overcoming these challenges requires the creation of methodologies and architectures that ensure robust, secure, and scalable automation solutions [13].

This study presents a novel approach by integrating DT, IoT, and LoRa for wireless communication in SCARA robots, addressing challenges in real-time decentralized automation, reducing latency, and improving data transmission efficiency. The Digital Twin was developed through a structured process involving three main stages, the first being 3D modeling and simulation: the SCARA robot was modeled in Autodesk Inventor 2025, with integrated kinematic and dynamic properties for accurate replication. The second stage was real-time data synchronization: sensor data were collected via a LoRa-based wireless network and processed using an IoT-enabled edge computing system. The third stage was the deployment of the Digital Twin: the real system was implemented in a virtual environment in Blender 3.4 software, ensuring continuous synchronization with the physical robot and enabling predictive analytics for performance optimization. The research aims to assess the feasibility, benefits, and potential limitations of this approach, focusing on real-time data transmission, system synchronization, and operational efficiency. Through experimental validation, the study provides insights into the practical implementation of these technologies and their impact on industrial automation.

This paper is organized as follows: Section 2 provides a literature review on Digital Twin applications in industrial robotics, wireless sensor networks and IoT in decentralized automation, and LoRa as a connectivity solution for SCARA robots. Section 3 details the materials and methods used in the study, including the design and implementation of the proposed system. Section 4 presents the results and analysis of experimental validation, and Section 5 discusses the key findings, challenges, and future research directions. Finally, Section 6 concludes the paper by summarizing the contributions and potential industrial implications of the study.

2. Background

2.1. Digital Twin in Industrial Robotics: Advances, Challenges, and Emerging Technologies

The concept of Digital Twin (DT) is associated with the creation of a digital replica of a physical system, which allows the simulation, operation and monitoring of processes in real time for their optimization [14]. This technology has established itself as an efficient tool in industrial robotics, especially for the automation and control of complex systems [15]. DT enables the integration of the virtual model with the physical structure of the robot, enabling real-time adjustments based on data collected by sensors [16]. This integration contributes to improving operational accuracy and efficiency, in addition to allowing fault diagnosis and reducing operational costs [17].

In recent years, the application of DT has predominantly been observed in large automotive and manufacturing industries, where precision and automation are essential [18]. Digital Twin (DT) technology enables continuous monitoring and predictive analysis in industrial systems. However, in centralized control architectures, the scalability and complexity of the network infrastructure can limit the efficiency of DT, especially in environments with multiple distributed devices. In these contexts, the centralization of data traffic can generate congestion points, increasing system response time and compromising the near-real-time communication required by sensitive industrial applications [19]. The integration of DT with wireless sensor networks (WSNs) and LoRa technology enables decentralized automation architectures that distribute the communication and control load, reducing bottlenecks and increasing operational flexibility in environments with infrastructure constraints and the need for dynamic adaptation [20]. Current studies demonstrate that DT can be used to simulate the behavior of industrial robots, enabling the identification of faults and optimizations without interrupting production [21]. The use of modeling and simulation to optimize industrial processes has been widely explored in the automotive industry, as demonstrated by recent research into validation protocols for new designs [22]. The implementation of digital twins (DT) follows this same approach by integrating virtual models into production processes, allowing the identification of risks and reducing validation times. In decentralized environments, this application becomes even more relevant, as it enables continuous monitoring of operations without the need for robust centralized infrastructure. The ability to predict failures and optimize operational cycles reinforces the viability of DT to increase industrial efficiency and competitiveness [23].

This simulation process is closely related to the integration of emerging technologies, such as IoT and wireless sensor networks, which allow the creation of a more agile and flexible control system [24]. The use of emerging technologies included in industry 4.0, such as Simulations, Vertical and Horizontal Integration, Augmented Reality, Virtual Reality, and IoT can also be associated with DT in a synergistic way in the automation process specifically in real-time data collection [25]. The integration of emerging technologies, such as Augmented Reality (AR) and Computer Vision, strengthens the adoption of DT in industrial processes, offering intuitive interfaces for analysis and control of operations [14]. An example of this synergy is observed in the identification of aromatic herbs using mobile devices, demonstrating how digital solutions can improve the accuracy of classification and decision-making [15]. In the context of industrial automation, the incorporation of AR can provide improved visualization of DT models, facilitating remote supervision of SCARA robots. This technological convergence contributes to the decentralization of automation, expanding its applicability in manufacturing sectors with limited infrastructure [26].

SCARA robot models can be improved with machine learning methods to optimize their behavior and prevent failures. Autonomous systems such as DT can incorporate learning techniques to improve the performance of robots in real time, optimizing their actions through autonomous learning methods [27].

However, despite advances, there are still gaps in the use of DT, especially in decentralized automation environments. Most of the literature addresses its implementation in industrial environments with robust IT infrastructures and centralized control [28]. The application of DT in smaller-scale environments, such as small factories or research laboratories, which do not have a high capacity network, has been little explored [29].

From a methodological point of view, most studies use simulations and systems modeling, with the help of platforms such as Autodesk and Blender, to create 3D models of robots. These models are used to simulate and analyze the behavior and movement of robots [30]. However, real-time integration with data from sensors still faces challenges in information security, such as communication latency and synchronization between virtual models and physical systems [31]. The adoption of cloud computing platforms for data processing and analysis is also an area of growing interest, but there are still issues related to connectivity and the cost of the infrastructure required to support this type of implementation [32].

Among the main contributions of DT to industrial robotics, the improvement in monitoring the health of robots and the optimization of operations stands out. DT allows the robot's operating condition to be monitored continuously, which results in increased accuracy and minimized operational failures. The implementation of DT in SCARA-type robots has contributed to reducing downtime and improving resource management, which directly impacts the efficiency of the production process [33].

The use of DT can transform the management and control of operational processes, allowing real-time adjustments to the operations of SCARA robots. In environments with limited network infrastructure, such as in remote locations or mobile applications, DT can facilitate system adaptation to operating conditions, improving the flexibility of the automation system [34]. The ability to operate in decentralized scenarios, where centralized control is unfeasible, makes DT an important solution in industrial environments with logistical or connectivity challenges [35].

Despite its potential, the large-scale adoption of DT in SCARA robots still faces technical and economic barriers [36]. The integration of DT with real-time systems requires efficient solutions to deal with data latency and ensure synchronization between the virtual model and the physical structure, as observed in studies using cloud platforms for data processing [37]. The costs associated with implementing the infrastructure necessary to support this integration, such as servers and sensors, still represent an obstacle for small and medium-sized companies [38]. Examples of difficulties include the need for advanced computing resources to process large volumes of data generated by sensors and the implementation of cybersecurity solutions to protect information during communication between the robot and the digital model. These factors still limit the application of DT in industrial scenarios with budget restrictions [39].

2.2. Wireless Sensor Networks and IoT in Decentralized Industrial Automation

The integration of Wireless Sensor Networks (WSNs) and Internet of Things (IoT) has transformed the field of industrial automation, especially in the context of decentralized systems. WSNs are composed of sensors that collect and transmit data in real time, using low-energy consumption communication protocols [40].

Associated with IoT, these networks become more efficient, enabling the interconnection of heterogeneous devices and large-scale data management. This technological evolution offers greater flexibility to industrial systems, allowing the automation of processes in remote locations and the optimization of production in dynamic environments [41]. The study of IoT hardware platforms through frugal innovation directly contributes to the development of low-cost and efficient solutions, essential for the integration of Digital Twin and IoT in SCARA robots, enabling decentralized automation in smaller-scale industrial environments [42].

The application of WSNs and IoT has been widely explored in industrial systems for predictive monitoring and real-time control. The use of sensors connected via IoT in industrial robotics allows the continuous collection of performance data and the identification of anomalies before failures occur [43]. Practical studies show that the integration of these technologies already contributes to predictive maintenance in assembly lines, reducing repair costs and increasing the efficiency of production processes. The integration of IoT and mobile sensors allows you to optimize industrial processes in real time, essential for the automation of SCARA robots. An applied example is the proposed architecture for identifying aromatic herbs, where mobile devices and AR enable data collection and analysis, improving operational efficiency [44]. However, these implementations have largely focused on scenarios with robust infrastructure, while applications in decentralized environments, with limited infrastructure, are still challenging [45].

Despite advances, critical gaps remain in the integration of WSNs and IoT in decentralized industrial automation. One of the main barriers is the limitation of communication over long distances, especially in large industrial environments where wired or high-speed connectivity is not available [46]. Another point to be observed is that the energy consumption of sensors and the security of data transmission continue to present recurring challenges. Also noteworthy is the lack of universally accepted standards for interoperability between IoT devices, making it difficult to integrate different manufacturers and platforms [47].

To address these challenges, methodologies focused on long-range, low-power communication protocols, such as LoRa (Long Range), have gained prominence. This protocol offers the ability to transmit data over distances greater than 10 km in open environments, with significantly reduced power consumption [48]. Practical implementations demonstrate that the use of LoRa in wireless sensor networks allows reliable communication even in remote locations, making it an ideal solution for decentralized automation in large industries. The implementation of IoT-based architectures with LoRa gateways facilitates connectivity between sensors and centralized or distributed control systems, promoting greater scalability [49].

The results of these approaches highlight clear advantages, such as reduced dependence on traditional network infrastructure and greater flexibility in monitoring and controlling industrial processes. Decentralized systems using IoT and WSNs have greater ability to adapt to variable operational conditions, such as changes in production demand or failures in specific sensors. For example, in a manufacturing plant, LoRa-based sensors can communicate machine conditions in real time, enabling automatic decision-making by controllers [50].

However, security issues remain a point of attention. The implementation of encryption and authentication techniques to protect communication between sensors and controllers is essential to guarantee data integrity. Attacks on wireless sensor networks can compromise the operation of industrial systems, highlighting the need for robust security measures. Protocols such as LoRaWAN (Long Range Wide-Area Network) support end-to-end encryption, minimizing the risks associated with data interception during transmission [51].

The integration of WSNs and IoT in decentralized industrial automation represents a significant advance, allowing greater flexibility, efficiency and adaptability of industrial systems. Protocols such as LoRa have proven to be essential for overcoming connectivity and energy consumption limitations in decentralized environments. However, the success of this integration depends on continued efforts to address existing gaps, such as data security and interoperability between devices [52].

2.3. LoRa as a Connectivity Solution in SCARA Robots for Industrial Environments

LoRa (Long Range) technology has established itself as an efficient option for solving connectivity problems in industrial environments, especially where traditional network infrastructure is limited [53]. LoRa enables wireless communication over long distances with low power consumption, making it suitable for wireless sensor networks (WSNs) and Internet of Things (IoT)-based applications [54]. The use of LoRa in SCARA robots facilitates communication between robots and control systems, enabling decentralized automation and continuous operation in remote industrial environments or with limited internet coverage [55].

The integration of LoRa with SCARA robots has demonstrated substantial advantages, especially in large-scale industrial environments or remote areas. The range of up to 10 km in open environments and energy efficiency are important features that enable data communication without the need for a wired network infrastructure [56]. The application of LoRa in SCARA robots allows autonomous operation of these systems in locations where traditional connectivity would be unfeasible, in addition to providing a solution for real-time data transmission, improving automation efficiency, even in isolated industrial locations [57].

However, the adoption of LoRa in SCARA robots faces challenges related to data security and reliability. Data encryption and strong authentication are essential to protect the integrity of transmitted information. Communication in LoRa networks is susceptible to interference and transmission failures, especially in complex industrial environments, which requires the development of advanced security mechanisms. Securing communication in wireless networks is a critical factor for large-scale adoption, as data integrity is vital in sensitive industrial systems [58].

In addition to security aspects, the integration of LoRa with other technologies such as wireless sensor networks (WSNs) still presents technical difficulties. Although there are established standards for LoRa, compatibility between these standards and other communication protocols can limit the system's efficiency. The need to ensure interoperability between heterogeneous devices is an important challenge for the implementation of decentralized industrial automation solutions, requiring that new communication models be developed to meet these needs [59].

In terms of methodologies, the application of LoRa in SCARA robots has been investigated mainly through experimental studies and tests in controlled environments. These studies focus on measuring communication range, latency and reliability, as well as energy consumption under different conditions. Preliminary results indicate that, although LoRa is efficient in terms of range and consumption, real-time data transmission and synchronization with control systems still present challenges in high data-demand scenarios [60].

The main benefits of using LoRa in industrial systems include reducing operational costs and reducing dependence on traditional networks. In SCARA robots, wireless connectivity provides greater flexibility and operational autonomy, without the need for wired infrastructure. The implementation of this technology can contribute to the automation of production processes in remote or difficult-to-access locations, in addition to facilitating predictive maintenance through real-time monitoring [61].

The creation of hybrid communication architectures, which integrate LoRa with other technologies, can expand the practical applications of this technology in complex industrial environments. Furthermore, the development of more robust and secure protocols will be critical to ensure the long-term viability of decentralized automation [62].

Craig (2018) described the inverse kinematics of SCARA robots as a fundamental approach to ensure accurate joint positioning and trajectory execution [63]. Pearson de Oliveira (2001) presents PID control as a widely adopted method for joint stabilization, mitigating dynamic variations and improving response times [64]. Spong (1989) discusses the role of incremental encoders in position feedback, increasing repeatability in robotic tasks such as pick-and-place operations [65]. Tsai (1999) addresses the integration of wireless communication networks with two digital technologies, allowing real-time monitoring and interruption adjustment without interrupting system operation [66]. These concepts provide a theoretical basis for the experimental setup and validation methodology applied in this study.

3. Materials and Methods

The Background section reviews Digital Twin, IoT, and LoRa technologies and their application in industrial automation. While previous studies have explored these technologies independently, there is limited research on their combined implementation in SCARA robots for decentralized automation. This study addresses this gap by developing a fully integrated system that leverages real-time data synchronization between the physical and virtual models, achieving improved responsiveness and adaptability in industrial environments.

The three-dimensional modeling of the SCARA robot was carried out in the Inventor 2025.0.1 software package (AutoDesk, San Francisco, CA, USA) and then inserted into the Blender virtual environment, allowing the simulation of the project's kinematics and validation of dimensions and geometries before manufacturing.

The controller was also developed digitally to test the control interface in the virtual environment. The development of the drive control aimed to connect and verify the compatibility of the model with the physical components and optimize the printing and assembly process, as illustrated in Figure 1.

The physical structure of the SCARA robot was manufactured through 3D printing using filament with PLA material, due to its good balance of rigidity and ease of manufacturing. The assembly was carried out using bearings, cables and servomotors to guarantee the mobility and stability of the axes. This process allows the creation of a functional prototype, replicating the characteristics of an industrial system on a reduced scale.

Figure 2 shows the controller in its real state. It was 3D-printed using filament with PLA material, incorporating electronic components such as on/off buttons and controlling the robot's movements. LEDs were implemented to indicate the operational status of the process in real time. To enable mobility, the controller was equipped with a rechargeable battery, allowing operation without the need for constant connection to an external power source.

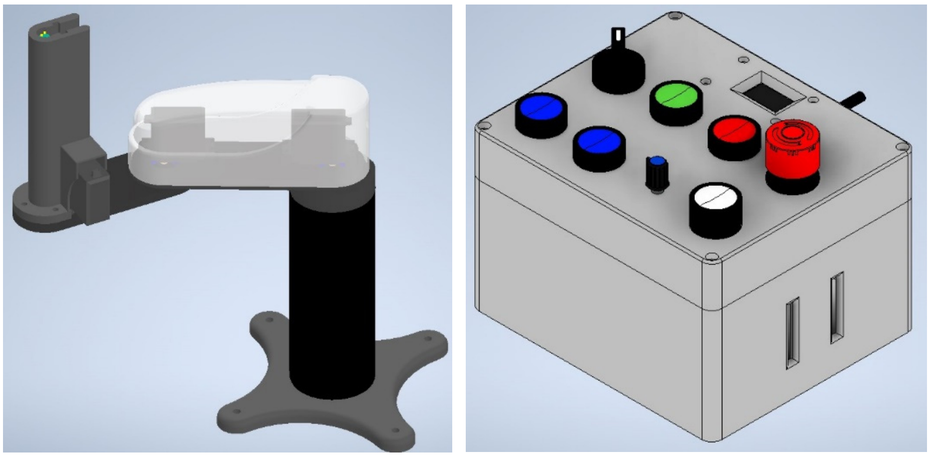

Figure 1. SCARA model robot and controller in the virtual environment. Source: Authors.

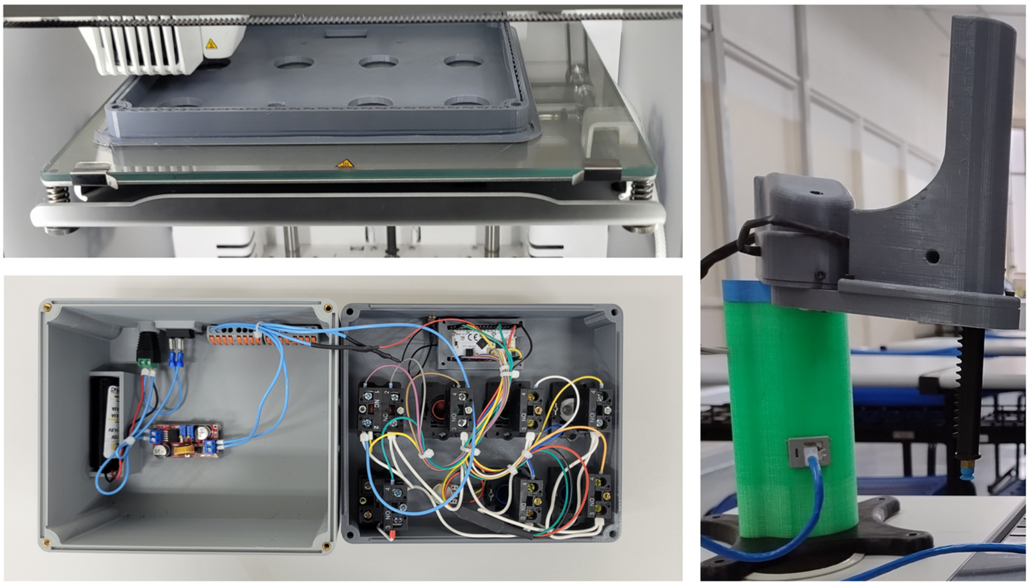

Figure 2. Images of 3D-printed SCARA model robot and controller. Source: Authors.

Wireless communication was established using two ESP32 LoRa V3 modules (TSMC, Hsinchu, Taiwan) with OLED display, configured as transmitter (controller) and receiver (SCARA robot). The system uses an integrated antenna for efficient data transmission over long distances, ensuring connectivity between devices. This approach eliminates the need for cabling and enables robot integration in decentralized industrial environments [67].

The LoRaWAN protocol was adopted to ensure reliable communication between devices using Semtech's LoRa radio frequency technology. Data transmission was implemented via coded packets, ensuring integrity and security in communication. The system continuously scans the controller states, buffering the information before sending it to the receiver, ensuring a quick and efficient response from the SCARA robot, as illustrated in Figure 3.

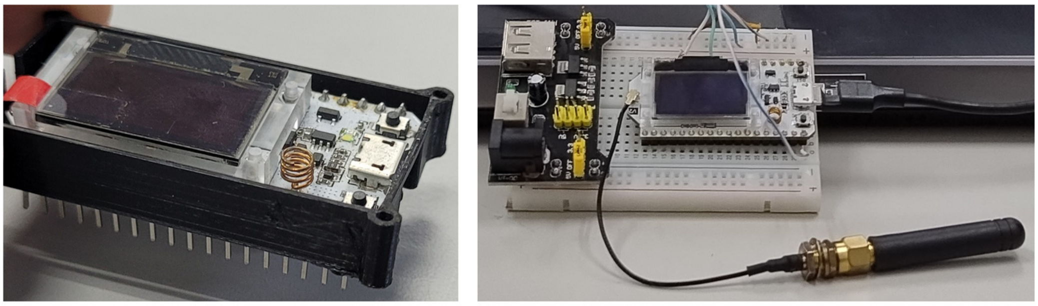

Figure 3. LoRaWAN communication protocol. Source: Authors.

4. Results

The DT implementation was initially developed and tested in a virtual environment using Blender software, followed by validation on a real SCARA robotic system. Performance metrics such as response time, synchronization accuracy, and error rates were measured to ensure consistency between digital twins and the real world. The tests carried out confirmed the successful transmission of commands between the button panel and the SCARA robot using LoRaWAN technology. Wireless communication has demonstrated stability, ensuring efficient exchange of information without noticeable latency. During the evaluations, no significant external interference was observed, demonstrating the robustness of the protocol adopted for the industrial environment. The antenna integrated into the devices allowed a reliable transmission range, ensuring the system's viability in scenarios with physical obstacles, as illustrated in Figure 4.

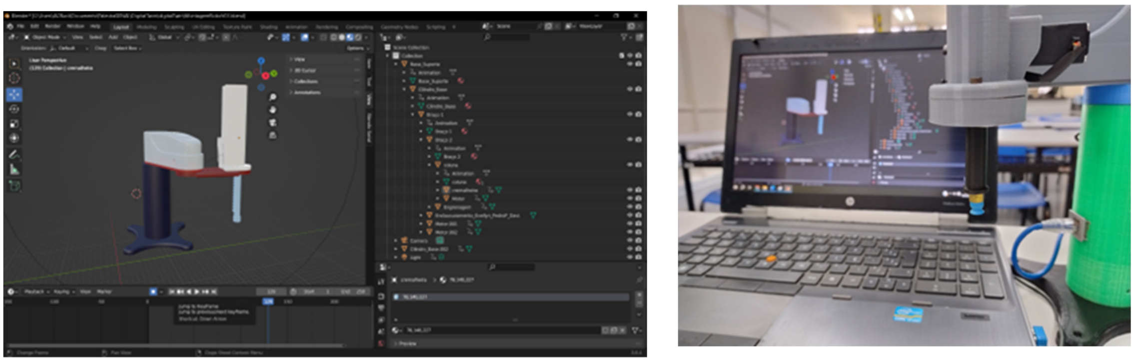

Figure 4. DT of the project in operation. Source: Authors.

In Figure 5, the system's response to command input has been accurately validated. The controller sent activation signals efficiently, and the SCARA robot responded immediately, without noticeable delays. Displaying operational states on the ESP32′s OLED display confirmed that the data were processed correctly, allowing real-time monitoring of communication and system operation. This behavior is fundamental for industrial applications where synchronization and reliability are essential for process automation.

The physical and logical architecture of the system was designed to ensure efficient communication between the physical and digital environments, with a focus on decentralized control and operational robustness. Figure 5 illustrates the practical implementation, demonstrating the functional results obtained. The system consists of two ESP32 LoRa V3 modules with 915 MHz antennas, which play a key role in wireless communication and real-time data processing. One of the modules, coupled to an OLED display, provides a local monitoring interface to display the system's operational status. The 3D-printed controller contains physical buttons that, when pressed, efficiently send activation signals to the ESP32 LoRa V3 module. These signals are then transmitted wirelessly to the receiver module, which controls the movements of the SCARA robot, also 3D-printed. The robot, equipped with SG90 servomotors, performs precise movements in all three axes, without evidence of noticeable delays between command and execution. Wireless communication between modules, precise actuator response and OLED display ensure system reliability and synchronization, essential for industrial applications. The control box is powered by a Li-Ion 18650 battery module, which allows autonomous operation and system portability. Blender software, running on a PC, serves as the environment for building and simulating the robot's digital twin, promoting integration between the physical and digital models.

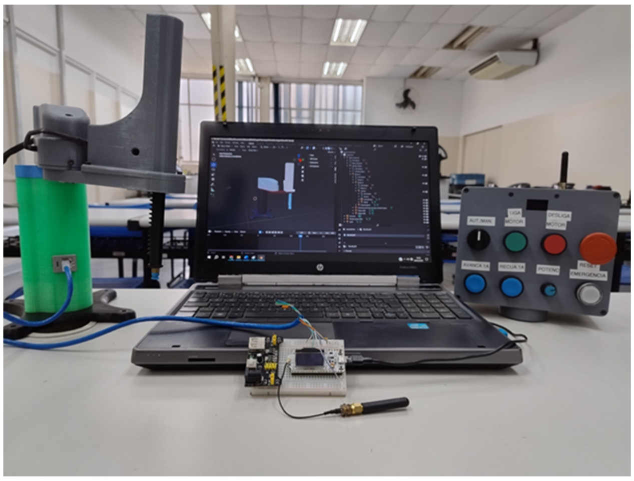

Figure 5. Interface and operation details. Source: Authors.

The control logic is structured to efficiently and responsively transform physical actions into digital signals. Internally, the controller is wired to the first ESP32 LoRa V3 module, which receives operator input via physical buttons and converts them into digital signals. These signals are then transmitted via 915 MHz wireless communication to the second ESP32 LoRa V3 module, positioned next to the SCARA robot. The receiver module interprets the digital signals and drives the SG90 servomotors, causing the physical robot to move. At the same time, the same instructions are sent to the virtual environment in Blender, ensuring synchronization between the physical robot and its digital twin. This decentralized and wireless architecture enables efficient communication and continuous monitoring without the need for a wired connection, making the system suitable for industrial applications that require high reliability and flexibility.

The use of the LoRa module as communication middleware in this study is not restricted to a traditional wireless communication application, such as those offered by technologies such as Wi-Fi, Bluetooth and 4G/5G, but seeks to explore its technical characteristics, such as greater range and low energy consumption, which are fundamental in decentralized industrial scenarios. LoRa is particularly suitable for environments where wired infrastructure is limited or unfeasible, providing an efficient communication solution between the SCARA robot and the digital simulation environment, maintaining synchronization between the physical system and the digital twin, justifying its applicability in this customized context. The logical diagram of the system can be seen in Figure 6.

The assembly of the SCARA robot followed the established plan, with all mechanical components correctly integrated. During the movement tests, the servomotors responded to commands without failure, ensuring precision of movement in all axes. The PLA-printed structure demonstrated sufficient resistance to withstand the simulated operations, presenting structural stability and adequate mechanical functioning. These results reinforce the feasibility of the prototype for future applications in real industrial scenarios.

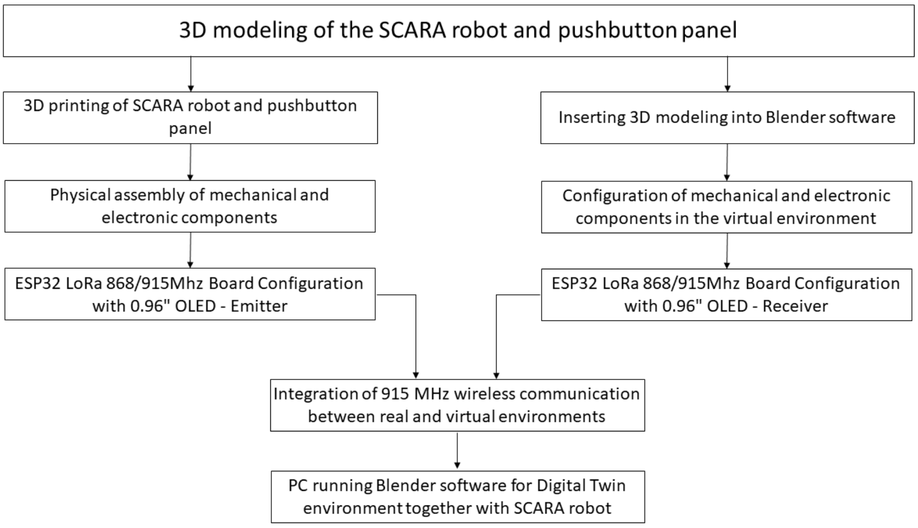

Figure 6. Logical diagram of the system. Source: Authors.

The implementation of the rechargeable battery in the controller guaranteed autonomous operation of the system, eliminating the need for connection to external power sources. During testing, the energy autonomy was sufficient to support prolonged periods of operation without noticeable degradation in performance. The modular design of the system allowed for easy integration of the solution into different industrial environments, without the need for additional cable infrastructure. This flexibility expands the application possibilities of the SCARA robot in decentralized production lines, where mobility and cable independence are significant advantages.

The simulation was carried out with 50 repetitions for each scenario, using different speed and acceleration settings to evaluate the impact of these parameters on the cycle time of the SCARA robot. In scenario 1, with an average speed of 16.25 mm/s and acceleration of 2.03 mm/s^2, the total time was 55.42 s. In scenario 2, by doubling the speed to 32.5 mm/s and increasing the acceleration to 8.13 mm/s^2, the time was reduced to 27.96 s. In scenario 3, with an average speed of 65 mm/s and acceleration of 32.5 mm/s^2, the total time reached 13.91 s, demonstrating the evolution of the project based on trajectory optimization.

Analysis of individual times shows that speed and acceleration directly impact the duration of transitions between robot movement points. In scenario 1, for example, the movement between P0 and P3 was completed in 31.03 s, while in scenario 3, this same trajectory was completed in 7.87 s. The consistency of the times obtained throughout the repetitions validates the model's accuracy, demonstrating that the optimization of kinematic parameters can be applied to increase the system's efficiency. Below, Table 1 presents detailed information about the displacements in the axes and the average values obtained for each scenario.

The values of latency, packet delivery success rate, and cycle time reduction were obtained from the analysis of experimental data recorded during system tests. The latency ranged between 1 and 2 s, measured as the time difference between the real SCARA robot's movement and its representation in the digital twin. The success rate of 98.6% was determined by comparing the total number of packets sent with the number of packets correctly received in the controlled industrial environment. The 74.9% reduction in cycle time between scenarios 1 and 3 was calculated by analyzing the difference between the initial and final times recorded in Table 1, where the time dropped from 55.42 s to 13.91 s, demonstrating system optimization. Cycle time represents the total time taken to complete one full movement sequence of the SCARA robot, including transitions between all predefined positions.

Table 1. Results obtained in relation to movements along axes and times.

Points	X Axis	Distance (mm)	Y Axis	Distance (mm)	Z Axis	Distance (mm)	Scenario 1—Time (s)	Scenario 2—Time (s)	Scenario 3—Time (s)
Home Position—P0	X	0	Y	0	Z	0	0.00	0.00	0.00
P1	X	−130	Y	−130	Z	−130	8.12	4.03	1.97
P2	X	−130	Y	−130	Z	0	8.23	4.07	2.02
P3	X	0	Y	−250	Z	0	14.68	7.98	3.88
P4	X	130	Y	−130	Z	0	7.96	4.06	2.05
P5	X	130	Y	−130	Z	−130	8.18	3.88	1.93
P6	X	130	Y	−130	Z	0	8.25	3.94	2.06
Home Position—P7	X	0	Y	0	Z	0	0.00	0.00	0.00
Cycle time							55.42	27.96	13.91

5. Discussion

The significant reduction in cycle time between scenarios demonstrates the impact of speed and acceleration on the efficiency of the robotic cell. Scenario 3, operating at 65 mm/s and 32.5 mm/s^2, presented the lowest total time, showing that the controller parameterization can be adjusted to maximize productivity. The accuracy of the movement during its start and respective stops at this point of the study requires further study, since these variables were not addressed at this time [1]. However, there is a limit to these gains, as high speeds can increase mechanical wear and energy consumption, factors that must be balanced when optimizing the system [2].

Compared with previous studies, it was found that similar speed and acceleration settings result in equivalent performance in different industrial applications [3]. The implementation of these strategies requires strict control of operating conditions, as dynamic oscillations can negatively impact the robot's stability. Another point to be considered is the interaction between hardware and software, as response and processing times can influence the real cycle time [5].

The experimental system comprises the following:

- Robot: 2-axis SCARA (J1, J2), 150 mm reach, nominal load capacity of 0.4 kg. Driven by DC servomotors with gearbox and nominal torque of 10 kgf-cm, equipped with 1000 PPR incremental encoders for position feedback [63].
- Microcontroller: Dedicated microcontroller (e.g., ESP32 or similar) performing the inverse kinematics, PID control for the joints and communication [64].
- Communication Module: LoRa module (e.g., SX1276/78) connected to the microcontroller, configured as a Class A LoRaWAN device, operating in the 915 MHz ISM band (or 868 MHz, depending on the region), with Spreading Factor (SF) 7 and transmission power of 14 dBm.
- Gateway and Network: Commercial LoRaWAN gateway connected to the internet, using a network server (e.g., The Things Network or ChirpStack) and an application server to decode payloads and interact with the Digital Twin [65].
- Digital Twin: Blender-based platform with Python 3.13 script that receives data via MQTT/API from the application server [66].

Test procedure:

Primary validation was performed via a standard pick-and-place task:

1. Path: Pick up a light object (<0.1 kg) at position A (Polar Coordinates: Radius = 120 mm, Angle J1 = 0°) and deposit it at position B (Radius = 120 mm, Angle J1 = 90°), returning to position A. Vertical movement (Z axis) was not considered in this 2-axis model.
2. Measurements: Cycle Time: Measured by the on-board microcontroller, from the start to the end of a complete cycle (A → B → A). Average of 1000 consecutive cycles.

- Response Time (Remote Command): Measured on the Digital Twin/application server as the delta between sending a 'start cycle' command via the LoRaWAN downlink and receiving confirmation of the start of movement via the uplink. Average of 50 commands.
- Accuracy (Repeatability): Measured using a clock comparator positioned at point B. The robot performed 100 cycles, and the maximum deviation in the final position at B was recorded.
- Accuracy (Estimated Absolute): Checked by comparing the commanded end position (point B) with the achieved position measured by an external vision system (calibrated) for 10 cycles.

3. Conditions: Tests carried out in a laboratory environment with controlled temperature (22 ± 2 °C) and a fixed robot base to minimize external vibrations.

Although the results indicate improvements, it is necessary to consider limitations inherent to the model. The simulation does not incorporate effects such as variations in the robot's payload or possible interference in the production environment, which could alter the system's dynamic response. Future work should include experimental tests with loads to validate the results in real operating conditions. Another point to be observed as a limiting factor is the insertion of several SCARA robots in the same network; in this situation, network congestion and increased data traffic could lead to packet loss and transmission delays [6].

The data presented reinforces the feasibility of integrating IoT sensors and LoRa networks to optimize decentralized automation [7]. The capability for remote monitoring and dynamic adjustments can further improve operational efficiency by minimizing downtime and enabling predictive adjustments to process conditions [8]. This approach is in line with Industry 4.0 trends, where connectivity and intelligent automation play a central role in modernizing production [9].

6. Conclusions

The experiments carried out demonstrate that the optimization of kinematic parameters directly impacts the reduction of cycle time in SCARA robots, being a determining factor for production efficiency. The results obtained validate the effectiveness of the proposed method in optimizing the operation of the SCARA robot. The cycle time was reduced by 74.9%, from 55.42 s to 13.91 s, demonstrating the impact of trajectory optimization. The latency between the real and virtual systems ranged from 1 to 2 s, indicating adequate synchronization for real-time applications. The packet delivery success rate of 98.6% confirms the reliability of the communication system in a controlled industrial environment. These findings highlight the feasibility of integrating DT and wireless communication to increase automation efficiency.

In addition to the quantitative improvements, the study reinforces the importance of integration between hardware and software for decentralized automation. The adoption of LoRa networks and IoT sensors can allow more efficient control of robotic trajectories, enabling real-time adjustments and reducing unplanned stops. These solutions are aligned with the principles of Industry 4.0, where connectivity and remote monitoring play an essential role in optimizing production.

Given the relevance of the results, it is recommended that experiments be carried out in a real industrial environment to validate the simulations and explore the feasibility of large-scale implementation. Future studies can investigate the application of artificial intelligence algorithms for predictive trajectory optimization, further improving the system's efficiency. The integration of these techniques can consolidate a new paradigm of flexible automation, reducing operational costs and expanding the autonomy of robotic systems.

The results indicate the need for a multidisciplinary approach in industrial automation, where aspects of mechanical engineering, electronics and computer science must be combined to obtain innovative solutions. Cycle time optimization through kinematic adjustments and intelligent sensor integration can redefine the performance of SCARA robots, making them even more suitable for advanced industrial uses.

Author Contributions: W.A.C.L.: Conceptualization, Methodology, Validation, Investigation, Data curation, Writing–original draft, Writing—review and editing, Visualization, Funding acquisition. A.C.R.: Conceptualization, Methodology, Software, Validation, Investigation, Resources, Writing—original draft, Writing—review and editing, Visualization. C.R.M.: Conceptualization, Methodology, Software, Resources, Writing—original draft, Visualization. N.V.C.H.: Formal analysis, Investigation, Writing—original draft, Writing—review and editing, Visualization. M.T.O.: Validation, Formal analysis, Data curation, Supervision, Project administration. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest. William Aparecido Celestino Lopes, Adilson Cunha Rusteiko, Nicolas Vinicius Cruz Honório are employees of SENAI VOLKSWAGEN. The paper reflects the views of the scientists, and not the company.

Abbreviations

The following abbreviations are used in this manuscript:

DT	Digital Twin
IoT	Internet of Things
LoRa	Long Range
PLA	Polylactic Acid
SCARA	Selective Compliance Assembly Robot Arm
WSNs	Wireless Sensor Networks

References

1. Sadri, H.; Yitmen, I.; Tagliabue, L.C.; Westphal, F.; Tezel, A.; Taheri, A.; Sibenik, G. Integration of Blockchain and Digital Twins in the Smart Built Environment Adopting Disruptive Technologies—A Systematic Review. *Sustainability* **2023**, *15*, 3713. [CrossRef]
2. Bousdekis, A.; Lepenioti, K.; Apostolou, D.; Mentzas, G. A Review of Data-Driven Decision-Making Methods for Industry 4.0 Maintenance Applications. *Electronics* **2021**, *10*, 828. [CrossRef]
3. Dinakaran, V.P.; Balasubramaniyan, M.P.; Muthusamy, S.; Panchal, H. Performa of SCARA based intelligent 3 axis robotic soft gripper for enhanced material handling. *Adv. Eng. Softw.* **2023**, *176*, 103366. [CrossRef]
4. Xia, D.; Jiang, C.; Wan, J.; Jin, J.; Leung, V.C.M.; Martínez-García, M. Heterogeneous Network Access and Fusion in Smart Factory: A Survey. *ACM Comput. Surv.* **2022**, *55*, 1–31. [CrossRef]
5. Vásárhelyi, J.; Salih, O.M.; Rostum, H.M.; Benotsname, R. An Overview of Energies Problems in Robotic Systems. *Energies* **2023**, *16*, 60. [CrossRef]
6. Li, C.; Cao, Z. LoRa Networking Techniques for Large-scale and Long-term IoT: A Down-to-top Survey. *ACM Comput. Surv.* **2022**, *55*, 1–36. [CrossRef]
7. Leonardi, L.; Lo Bello, L.; Patti, G. LoRa support for long-range real-time inter-cluster communications over Bluetooth Low Energy industrial networks. *Comput. Commun.* **2022**, *192*, 57–65. [CrossRef]
8. Mariappan, R. Design and Implementation of Long Range Wide Area Networks for Future Industrial IoT Applications. *Int. J. Sens. Wirel. Commun. Control* **2024**, *14*, 215–225. [CrossRef]

9. Mansour, D.-E.A.; Numair, M.; Zalhaf, A.S.; Ramadan, R.; Darwish, M.M.F.; Huang, Q.; Hussien, M.G.; Abdel-Rahim, O. Applications of IoT and digital twin in electrical power systems: A comprehensive survey. *IET Gener. Transm. Distrib.* **2023**, *17*, 4457–4479. [CrossRef]
10. Jouhari, M.; Saeed, N.; Alouini, M.-S.; Amhoud, E.M. A survey on scalable LoRaWAN for massive IoT: Recent advances, potentials, and challenges. *IEEE Commun. Surv. Tutor.* **2023**, *25*, 1841–1876. [CrossRef]
11. Goulart, A.; Chennamaneni, A.; Torre, D.; Hur, B.; Al-Aboosi, F.Y. On Wide-Area IoT Networks, Lightweight Security and Their Applications—A Practical Review. *Electronics* **2022**, *11*, 1762. [CrossRef]
12. Zhang, Z.; Qu, T.; Zhao, K.; Zhang, K.; Zhang, Y.; Guo, W.; Liu, L.; Chen, Z. Enhancing trusted synchronization in open production logistics: A platform framework integrating blockchain and digital twin under social manufacturing. *Adv. Eng. Inform.* **2024**, *61*, 102404. [CrossRef]
13. Sleiti, A.K.; Kapat, J.S.; Vesely, L. Digital twin in energy industry: Proposed robust digital twin for power plant and other complex capital-intensive large engineering systems. *Energy Rep.* **2022**, *8*, 3704–3726. [CrossRef]
14. Liu, M.; Fang, S.; Dong, H.; Xu, C. Review of digital twin about concepts, technologies, and industrial applications. *J. Manuf. Syst.* **2021**, *58*, 346–361. [CrossRef]
15. Xu, W.; Cui, J.; Li, L.; Yao, B.; Tian, S.; Zhou, Z. Digital twin-based industrial cloud robotics: Framework, control approach and implementation. *J. Manuf. Syst.* **2021**, *58*, 196–209. [CrossRef]
16. Laaki, H.; Miche, Y.; Tammi, K. Prototyping a Digital Twin for Real Time Remote Control Over Mobile Networks: Application of Remote Surgery. *IEEE Access* **2019**, *7*, 20325–20336. [CrossRef]
17. Pérez, L.; Rodríguez-Jiménez, S.; Rodríguez, N.; Usamentiaga, R.; García, D.F. Digital Twin and Virtual Reality Based Methodology for Multi-Robot Manufacturing Cell Commissioning. *Appl. Sci.* **2020**, *10*, 3633. [CrossRef]
18. Botín-Sanabria, D.M.; Mihaita, A.-S.; Peimbert-García, R.E.; Ramírez-Moreno, M.A.; Ramírez-Mendoza, R.A.; Lozoya-Santos, J.d.J. Digital Twin Technology Challenges and Applications: A Comprehensive Review. *Remote Sens.* **2022**, *14*, 1335. [CrossRef]
19. Hakiri, A.; Gokhale, A.; Yahia, S.B.; Mellouli, N. A comprehensive survey on digital twin for future networks and emerging Internet of Things industry. *Comput. Netw.* **2024**, *244*, 110350. [CrossRef]
20. Singh, M.; Fuenmayor, E.; Hinchy, E.P.; Qiao, Y.; Murray, N.; Devine, D. Digital Twin: Origin to Future. *Appl. Syst. Innov.* **2021**, *4*, 36. [CrossRef]
21. Stan, L.; Nicolescu, A.F.; Pupăză, C.; Jiga, G. Digital Twin and web services for robotic deburring in intelligent manufacturing. *J. Intell. Manuf.* **2023**, *34*, 2765–2781. [CrossRef] [PubMed]
22. Müller, B.; Stork, A.; Neumann, T. Virtual and Augmented Reality for Quality Assurance and Design Validation in the Automotive Development Process. *Virtual Real.* **2020**, *24*, 527–539.
23. Lopes, W.A.C.; Rusteiko, A.C.; Mendes, C.R.; Honório, N.V.C.; Okano, M.T. Optimization of New Project Validation Protocols in the Automotive Industry: A Simulated Environment for Efficiency and Effectiveness. *J. Comput. Cogn. Eng.* 2025, *Online First*. [CrossRef]
24. Bi, Z.; Xu, L.D.; Wang, C. Internet of Things for Enterprise Systems of Modern Manufacturing. *IEEE Trans. Ind. Inform.* **2014**, *10*, 1537–1546. [CrossRef]
25. Lopes, W.A.; Fernandes, J.C.; Antunes, S.N.; Fernandes, M.E.; Nääs, I.D.; Vendrametto, O.; Okano, M.T. Augmented Reality Applied to Identify Aromatic Herbs Using Mobile Devices. *AgriEngineering* **2024**, *6*, 2824–2844. [CrossRef]
26. Lopes, W.A.C.; Okano, M.T.; Fernandes, J.C.L.; Antunes, S.N.; Vendrametto, O. ARomaticLens: Augmented Reality Applied to the Identification and Classification of Aromatic Herbs Through Computer Vision and Mobile Devices. In *Human-Centred Technology Management for a Sustainable Future*; Zimmermann, R., Rodrigues, J.C., Simoes, A., Dalmarco, G., Eds.; Springer: Cham, Switzerland, 2025; pp. 79–87. [CrossRef]
27. Da Silva Filho, J.I.; Fernandes, C.L.; Silveira, R.S.; Gomes, P.M.; Matos, S.L.; Santo, L.D.; Nunes, V.C.; Côrtes, H.M.; Lopes, W.A.C.; Mario, M.C.; et al. Process of Learning from Demonstration with Paraconsistent Artificial Neural Cells for Application in Linear Cartesian Robots. *Robotics* **2023**, *12*, 69. [CrossRef]
28. Mihai, S.; Yaqoob, M.; Hung, D.V.; Davis, W.; Towakel, P.; Raza, M.; Karamanoglu, M.; Barn, B.; Shetve, D.; Prasad, R.V.; et al. Digital Twins: A Survey on Enabling Technologies, Challenges, Trends and Future Prospects. *IEEE Commun. Surv. Tutor.* **2022**, *24*, 2255–2291. [CrossRef]
29. Mylonas, G.; Kalogeras, A.; Kalogeras, G.; Anagnostopoulos, C.; Alexakos, C.; Muñoz, L. Digital Twins from Smart Manufacturing to Smart Cities: A Survey. *IEEE Access* **2021**, *9*, 143222–143249. [CrossRef]
30. Lopes, W.A.C.; Rusteiko, A.C.; Mendes, C.R.; Honório, N.V.C.; Okano, M.T. Digital Twins (DT) Applied to the Customization of 3D Printed SCARA Robots Using Intelligent Manufacturing. In *Advances in Production Management Systems. Production Management Systems for Volatile, Uncertain, Complex, and Ambiguous Environments; Proceedings of the APMS 2024. IFIP Advances in Information and Communication Technology, Chemnitz/Zwickau, Germany, 8–12 September 2024*; Thürer, M., Riedel, R., von Cieminski, G., Romero, D., Eds.; Springer: Cham, Switzerland, 2024; Volume 731. [CrossRef]

31. Qian, C.; Liu, X.; Ripley, C.; Qian, M.; Liang, F.; Yu, W. Digital Twin—Cyber Replica of Physical Things: Architecture, Applications and Future Research Directions. *Future Internet* **2022**, *14*, 64. [CrossRef]
32. Bello, S.A.; Oyedele, L.O.; Akinade, O.O.; Bilal, M.; Davila Delgado, J.M.; Akanbi, L.A.; Ajayi, A.O.; Owolabi, H.A. Cloud computing in construction industry: Use cases, benefits and challenges. *Autom. Constr.* **2021**, *122*, 103441. [CrossRef]
33. Zafar, M.H.; Langås, E.F.; Sanfilippo, F. Exploring the synergies between collaborative robotics, digital twins, augmentation, and industry 5.0 for smart manufacturing: A state-of-the-art review. *Robot. Comput.-Integr. Manuf.* **2024**, *89*, 102769. [CrossRef]
34. Mashhadany, Y.A.; Abbas, A.K.; Algburi, S.; Taha, B.A. Design and Analysis of a Hybrid Intelligent SCARA Robot Controller Based on a Virtual Reality Model. *J. Robot. Control* **2024**, *5*, 1722–1735. [CrossRef]
35. Vilas-Boas, J.L.; Rodrigues, J.J.P.C.; Alberti, A.M. Convergence of Distributed Ledger Technologies with Digital Twins, IoT, and AI for fresh food logistics: Challenges and opportunities. *J. Ind. Inf. Integr.* **2023**, *31*, 100393. [CrossRef]
36. Leng, J.; Wang, D.; Shen, W.; Li, X.; Liu, Q.; Chen, X. Digital twins-based smart manufacturing system design in Industry 4.0: A review. *J. Manuf. Syst.* **2021**, *60*, 119–137. [CrossRef]
37. Jin, T.; Han, X. Robotic arms in precision agriculture: A comprehensive review of the technologies, applications, challenges, and future prospects. *Comput. Electron. Agric.* **2024**, *221*, 108938. [CrossRef]
38. Barton, M.; Budjac, R.; Tanuska, P.; Sladek, I.; Nemeth, M. Advancing Small and Medium-Sized Enterprise Manufacturing: Framework for IoT-Based Data Collection in Industry 4.0 Concept. *Electronics* **2024**, *13*, 2485. [CrossRef]
39. Jagatheesaperumal, S.K.; Rahouti, M.; Ahmad, K.; Al-Fuqaha, A.; Guizani, M. The Duo of Artificial Intelligence and Big Data for Industry 4.0: Applications, Techniques, Challenges, and Future Research Directions. *IEEE Internet Things J.* **2022**, *9*, 12861–12885. [CrossRef]
40. Fatima, Z.; Tanveer, M.H.; Waseemullah Zardari, S.; Naz, L.F.; Khadim, H.; Ahmed, N.; Tahir, M. Production Plant and Warehouse Automation with IoT and Industry 5.0. *Appl. Sci.* **2022**, *12*, 2053. [CrossRef]
41. Al Shahrani, A.M.; Alomar, M.A.; Alqahtani, K.N.; Basingab, M.S.; Sharma, B.; Rizwan, A. Machine Learning-Enabled Smart Industrial Automation Systems Using Internet of Things. *Sensors* **2023**, *23*, 324. [CrossRef]
42. Lopes, W.A.C.; Okano, M.T.; Lengua, S.B.; Vendrametto, O.; Fernandes, J.C.L.; Fernandes, M.E. Evaluating Iot Hardware Platforms Through Frugal Innovation. *S. Am. Dev. Soc. J.* **2024**, *10*, 29. [CrossRef]
43. Javaid, M.; Haleem, A.; Singh, R.P.; Rab, S.; Suman, R. Significance of sensors for industry 4.0: Roles, capabilities, and applications. *Sens. Int.* **2021**, *2*, 100110. [CrossRef]
44. Fernandes, J.C.L.; Okano, M.T.; Lopes, W.A.C.; Antunes, S.N.; Vendrametto, O. An Architecture to Identify Aromatic Herbs using Augmented Reality (AR) and Mobile Application. *WSEAS Trans. Environ. Dev.* **2023**, *19*, 1459–1467. [CrossRef]
45. Dzedzickis, A.; Subačiūtė-Žemaitienė, J.; Šutinys, E.; Samukaitė-Bubnienė, U.; Bučinskas, V. Advanced Applications of Industrial Robotics: New Trends and Possibilities. *Appl. Sci.* **2022**, *12*, 135. [CrossRef]
46. Alabadi, M.; Habbal, A.; Wei, X. Industrial Internet of Things: Requirements, Architecture, Challenges, and Future Research Directions. *IEEE Access* **2022**, *10*, 66374–66400. [CrossRef]
47. Omolara, A.E.; Alabdulatif, A.; Abiodun, O.I.; Alawida, M.; Alabdulatif, A.; Alshoura, W.H.; Arshad, H. The internet of things security: A survey encompassing unexplored areas and new insights. *Comput. Secur.* **2022**, *112*, 102494. [CrossRef]
48. Bouras, C.; Gkamas, A.; Salgado, S.A.K. Energy efficient mechanism for LoRa networks. *Internet Things* **2021**, *13*, 100360. [CrossRef]
49. Aldhaheri, L.; Alshehhi, N.; Manzil, I.I.J.; Khalil, R.A.; Javaid, S.; Saeed, N.; Alouini, M.-S. LoRa Communication for Agriculture 4.0: Opportunities, Challenges, and Future Directions. *IEEE Internet Things J.* **2025**, *12*, 1380–1407. [CrossRef]
50. Gkotsiopoulos, P.; Zorbas, D.; Douligeris, C. Performance Determinants in LoRa Networks: A Literature Review. *IEEE Commun. Surv. Tutor.* **2021**, *23*, 1721–1758. [CrossRef]
51. Abosata, N.; Al-Rubaye, S.; Inalhan, G.; Emmanouilidis, C. Internet of Things for System Integrity: A Comprehensive Survey on Security, Attacks and Countermeasures for Industrial Applications. *Sensors* **2021**, *21*, 3654. [CrossRef]
52. Stanco, G.; Navarro, A.; Frattini, F.; Ventre, G.; Botta, A. A comprehensive survey on the security of low power wide area networks for the Internet of Things. *ICT Express* **2024**, *10*, 519–552. [CrossRef]
53. Augustin, A.; Yi, J.; Clausen, T.; Townsley, W.M. A Study of LoRa: Long Range Low Power Networks for the Internet of Things. *Sensors* **2016**, *16*, 1466. [CrossRef] [PubMed]
54. Idris, S.; Karunathilake, T.; Förster, A. Survey and Comparative Study of LoRa-Enabled Simulators for Internet of Things and Wireless Sensor Networks. *Sensors* **2022**, *22*, 5546. [CrossRef] [PubMed]
55. Ahmed, U.; Lin, J.C.-W.; Srivastava, G. Exploring the Potential of Cyber Manufacturing System in the Digital Age. *ACM Trans. Internet Technol.* **2023**, *23*, 1–38. [CrossRef]
56. Cheikh, I.; Aouami, R.; Sabir, E.; Sadik, M.; Roy, S. Multi-Layered Energy Efficiency in LoRa-WAN Networks: A Tutorial. *IEEE Access* **2022**, *10*, 9198–9231. [CrossRef]
57. Yao, F.; Ding, Y.; Hong, S.; Yang, S.-H. A Survey on Evolved LoRa-Based Communication Technologies for Emerging Internet of Things Applications. *Int. J. Netw. Dyn. Intell.* **2022**, *1*, 4–19. [CrossRef]

58. Ayoub Kamal, M.; Alam, M.M.; Sajak, A.A.B.; Mohd Su'ud, M. Requirements, Deployments, and Challenges of LoRa Technology: A Survey. *Comput. Intell. Neurosci.* **2023**, *2023*, 5183062. [CrossRef]
59. Daousis, S.; Peladarinos, N.; Cheimaras, V.; Papageorgas, P.; Piromalis, D.D.; Munteanu, R.A. Overview of Protocols and Standards for Wireless Sensor Networks in Critical Infrastructures. *Future Internet* **2024**, *16*, 33. [CrossRef]
60. Shamshiri, R.R.; Navas, E.; Dworak, V.; Schütte, T.; Weltzien, C.; Cheein, F.A.A. Internet of robotic things with a local LoRa network for teleoperation of an agricultural mobile robot using a digital shadow. *Discov. Appl. Sci.* **2024**, *6*, 414. [CrossRef]
61. Lu, Y.; Pei, W.; Peng, K. State of the art of automatic disassembly of WEEE and perspective towards intelligent recycling in the era of Industry 4.0. *Int. J. Adv. Manuf. Technol.* **2023**, *128*, 2825–2843. [CrossRef]
62. Reddy, G.P.; Kumar, Y.V.P.; Chakravarthi, M.K. Communication Technologies for Interoperable Smart Microgrids in Urban Energy Community: A Broad Review of the State of the Art, Challenges, and Research Perspectives. *Sensors* **2022**, *22*, 5881. [CrossRef]
63. Craig, J.J. *Introduction to Robotics: Mechanics and Control*, 4th ed.; Pearson: London, UK, 2018.
64. Pearson de Oliveira, M.A.A. *Modeling and Control of Robot Manipulators: Lorenzo Sciavicco and Bruno Siciliano*; Mc Graw-Hill: New York, NY, USA, 2001; ISBN 0-07-114726-8.
65. Spong, M.W.; Vidyasagar, M. (Eds.) *Robot Dynamics and Control by Spong*, 1st ed.; Wiley: Hoboken, NJ, USA, 1989.
66. Tsai, L.-W. *Robot Analysis: The Mechanics of Serial and Parallel Manipulators*, 1st ed.; Wiley-Interscience: Hoboken, NJ, USA, 1999.
67. Ali, A.; Mohamed, R.; Ismail, M.; Nordin, R. Antenna Design Considerations for LPWAN IoT Devices: A Review. *IEEE Access.* **2021**, *9*, 139263–139284.