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Developing An Amr Prototype With Processing Offloading Using 5g Servers For Industry 4.0

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Abstract:
Background: *Industry 4.0, with the integration of technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI), is profoundly transforming production processes. Autonomous mobile robots (AMRs) play a key role in automating logistics operations in factories. However, the growing complexity of these operations requires greater processing capacity, which challenges embedded processors. The proposed solution involves developing a prototype AMR with processing offloading using 5G servers, transferring heavy computational tasks to external servers. This guarantees efficiency and real-time response.*
Materials and Methods: *The aim of this work is to explore offloading via 5G to improve the performance of AMRs in industrial environments, reducing the computational load of robots and optimizing energy efficiency. An architecture was developed that integrates the AMR with the 5G infrastructure, distributing processing between the robot and the servers. The method includes offloading algorithms to balance tasks between local and remote processing, ensuring operation even with temporary loss of connection.*
Results: *The results indicate that offloading via 5G significantly improves the performance of AMRs, optimizing navigation and response to changes in the environment. In addition, the use of external servers reduces energy consumption and maintenance costs, highlighting the viability of this technology in industrial automation.*
Conclusion: *The development of an AMR with processing offloading to 5G servers represents a breakthrough in Industry 4.0. High-speed, low-latency connectivity optimizes control and navigation, improving robot efficiency and performance, reducing energy consumption and increasing component durability.*

Keyword: *AMR, Offloading, Indústria 4.0, Servidores 5G, Processamento do ROS.*

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I. Introduction

Industry 4.0, with technologies such as the Internet of Things (IoT), Artificial Intelligence (AI) and big data, is transforming industrial processes. In this context, autonomous mobile robots (AMRs) have come to the fore in the automation of logistics operations in factories. These robots optimize material flow and operational efficiency, but the growing complexity of operations requires greater processing capacity and real-time response. Traditionally, AMRs use on-board processors for navigation and decision-making, but as tasks become more complex, these processors face limitations [1-3].

Processing offloading, which transfers computational tasks to external servers, offers a solution to these challenges. With 5G technology, which offers low latency and high bandwidth, AMRs can communicate in real time with external servers, allowing complex tasks to be carried out remotely without compromising performance. This reduces the need for embedded processors, cutting costs and energy consumption, since the heaviest tasks can be carried out on the servers [4-6].

In addition, 5G enables scalability, allowing servers to be upgraded as needed, without changes to the robots. The centralization of processing also facilitates maintenance and software updates, as well as enabling the use of advanced AI algorithms, which would be unfeasible on robots. However, offloading brings challenges, such as the need for reliable, low-latency communication and ensuring data security. The implementation of robust encryption measures and protection against attacks is essential. Server infrastructure and network architecture must also be robust to ensure the success of this model [5],[7].

The development of AMRs with offloading via 5G opens up new possibilities for industrial automation, improving the responsiveness and flexibility of production processes, but requires continuous investment in research and development to overcome the technical and security challenges [8-11].

II. Theoretical Framework

Industrial Automation I4.0

Industry 4.0 is revolutionizing production by integrating advanced technologies and dissolving the boundaries between the physical, digital and biological, promoting greater efficiency and flexibility [12]. Industrial automation, one of the pillars of this revolution, reduces human intervention, increases productivity and minimizes errors, ensuring competitiveness in dynamic markets [13]. Systems engineering, which is essential for coordinating different technologies, clearly defines requirements, promoting flexibility and efficiency in processes [14].

Additive manufacturing, or 3D printing, makes it possible to create complex parts with less material waste, encouraging customization and contributing to a more circular economy [15]. Time-sensitive networks are crucial for precise synchronization between devices in automated processes [16], while technologies such as IoT and Big Data make production more sustainable by reducing energy consumption [17].

However, this digital transformation requires a skilled workforce and faces challenges such as adequate infrastructure, large-scale data management and cybersecurity. Despite the obstacles, Industry 4.0 is driving innovation and sustainable growth.

Fixed robotics and mobile robotics

Industrial robotics is fundamental in Industry 4.0, driving automation and the use of artificial intelligence (AI). According to [18],[19], robotics has evolved from simple machines to advanced systems, increasing productivity, reducing costs and improving quality, with robots operating 24 hours a day. In Brazil, [20] highlight the increase in investment in innovation, although challenges such as infrastructure and qualification are still present. For [21] discuss collaborative robots (cobots), which work alongside humans, combining precision and adaptability, but whose implementation requires attention to safety. AI is crucial for autonomous systems, optimizing processes and reducing errors, such as in predictive maintenance and quality inspection [22]. Innovations such as autonomous mobile robots (AMRs) and artificial vision extend industrial capabilities [23], while collaboration between academia and industry is essential to overcome integration and qualification challenges.

IoT - Internet of Things

Industry 4.0 transforms manufacturing with technologies such as the Internet of Things (IoT), artificial intelligence (AI), Big Data and robotics, promoting efficiency, productivity and sustainability. According to [24, 25], IoT and AI optimize the use of resources, reducing waste and emissions. [26] propose a roadmap for improving energy efficiency with AI and big data.

However, the adoption of IoT brings cybersecurity challenges, as warned by [26, 27]. Robust protection measures are essential to mitigate the risks. Companies' readiness for IoT depends on careful preparation, addressed by [28].

For [29] explore IoT in circular business models, facilitating reuse and recycling, although challenges such as data security and complexity remain. Industry 4.0 offers great opportunities, but security and collaboration are key to its success.

CPS - Cyber Physical System

Industry 4.0 transforms production systems by integrating technologies such as cyber physical systems (CPS), the Internet of Things (IoT), artificial intelligence (AI) and robotics. This drives innovations in efficiency and productivity, but also presents challenges. [30] highlight complexity and security as obstacles in implementing CPS, recommending modeling and machine learning techniques to overcome them.

Cyber security is a key concern, especially with the increasing interconnection of devices. According to [31], they propose a risk management methodology, while [32] introduce CPS-GUARD, an intrusion detection system that uses machine learning to identify anomalies in real time.

According to [33], they explore how the integration of IoT and CPS in robotics facilitates collaboration between robots and automated systems, improving production agility. [34] reviews the role of AI in intelligent automation, while [35] discusses mobile robots that perform complex tasks. Although Industry 4.0 offers benefits such as mass customization, cybersecurity and complexity remain crucial challenges.

Edge Computing

Advances in edge computing and autonomous vehicles are transforming mobility and transportation systems. Vehicular edge computing (VEC) combines processing and communication close to vehicles, optimizing efficiency, safety and user experience. For [36] explore joint resource scheduling for navigation of autonomous mobile robots (AMRs), highlighting the importance of intelligent allocation for low latency and high reliability.

For [37] they propose proactive migration of services, dynamically adjusting the location of processing based on mobility and workload. In [37] they investigate task offloading for cooperative perception between vehicles, optimizing the use of distributed resources, crucial for autonomous driving.

According to [38] they analyze connectivity and latency challenges in VEC, exploring emerging applications such as autonomous driving and smart cities. For [39] they highlight content caching with AI, which anticipates data demands to reduce latency. These technologies promise to transform mobility with greater productivity, safety and personalized services, promoting a more connected and efficient future in transport.

Artificial intelligence for robotics

The integration of artificial intelligence (AI) into robotics is transforming education and industry. [40] highlight the use of AI in teaching robotics in schools, enriching the curriculum and promoting critical skills through machine learning. For [41] explore speech recognition in robots such as Pepper, showing how machine learning algorithms enhance human-robot interaction, which is essential for social robots.

For [42] review the use of deep learning, highlighting neural networks for computer vision and motion control, allowing robots to perform complex tasks autonomously. According to [43] they broaden the discussion, addressing the challenges of AI and deep learning, such as the need for large volumes of data and high computational costs. For [44] they explore generative AI, showing how GANs can create more adaptive robotic behaviors. According to [45] they discuss behavior trees, a technique that simplifies the creation of robotic actions. Despite advances, challenges such as computational costs and ethical issues remain, requiring continued research to maximize the potential of AI-driven robotics.

5G network

The integration of 5G in industry is revolutionizing production processes, logistics and automation. For [46] propose a framework to assess the feasibility of 5G in intralogistics, highlighting its low latency and high reliability for the connectivity of devices and automated guided vehicles (AGVs), improving mobile robot control and real- time monitoring. According to [47], they analyze how 5G optimizes the coordination of autonomous mobile robots in manufacturing, enabling continuous communication and advanced analytics for more efficient production processes. [48] explore the impact of 5G on smart factories, enabling the integration of devices and systems, and supporting innovative architectures such as mesh networks and SDN for greater flexibility.

According to [49] they highlight how 5G improves inventory management and goods movement in warehouses, increasing accuracy and efficiency. For [50] prove that 5G meets industrial automation requirements, offering essential support for Industry 4.0, improving productivity, quality and efficiency.

III. Materials And Methods

This methodology aims to develop an Autonomous Mobile Robot (AMR) prototype that integrates processing offloading using 5G servers, with a focus on industrial automation, fixed and mobile robotics, the Internet of Things (IoT), Cyber-Physical Systems (CPS), Edge Computing, and artificial intelligence. The implementation of this prototype aims to meet the requirements of Industry 4.0, taking advantage of 5G capabilities to improve the efficiency, flexibility and intelligence of robotic systems in industrial environments.

Definition of requirements

Functional requirements:

1. **Industrial Automation 4.0:** The prototype must support automated industrial tasks, including material handling, inspection and process monitoring. It must be able to integrate with industrial control systems and sensor networks.
2. **Fixed and Mobile Robotics:** The prototype should include fixed robotics components for performing static tasks and mobile robotics for navigating and performing dynamic tasks. Integration between the two types of robotics must be fluid and efficient.
3. **Internet of Things (IoT):** The system must connect to an IoT network to collect and share data from sensors and industrial devices. It must enable real-time communication with other devices and systems.
4. **Cyber-Physical Systems (CPS):** The prototype should integrate physical sensors and actuators with

computer systems to monitor and control industrial processes. It must ensure efficient interaction between the physical and digital worlds.

5. **Edge Computing:** The AMR should use edge computing to process data locally and reduce latency in communication with 5G servers. It should be able to perform real-time data analysis and send only relevant information to central servers.
6. **Artificial Intelligence for Robotics:** The prototype should incorporate artificial intelligence algorithms for autonomous navigation, pattern recognition and real-time decision-making. It should use machine learning techniques and neural networks to improve its performance.
7. **5G network:** Communication between the AMR and the servers must be carried out over the 5G network to ensure high speed and low latency. The system must use the 5G infrastructure for processing offloading and data synchronization.

Non-functional requirements

1. **Security:** The system must guarantee data and communications security. It must include encryption and authentication protocols to protect against unauthorized access and cyber attacks.
2. **Scalability:** The architecture must be scalable to support the addition of more AMRs and IoT devices without compromising system performance.
3. **Robustness:** The prototype must be robust and reliable, operating efficiently in industrial environments with adverse conditions.
4. **Interoperability:** The system must be compatible with industrial standards and communication protocols to ensure integration with existing systems.

System Architecture

General Architecture

The system architecture will be based on a modular approach, divided into several layers to manage different aspects of the prototype. The general architecture includes:

1. **Robotics layer:** Includes autonomous mobile robots (AMRs), equipped with sensors, actuators and control modules.
2. **Edge Computing Layer:** Includes computing devices that process data locally before sending it to central servers. This layer reduces latency and improves system efficiency.
3. **5G Network Layer:** Provides high-speed, low-latency communication between AMRs, IoT devices and central servers. It includes the network infrastructure needed to support processing offloading.
4. **Artificial Intelligence Layer:** Includes machine learning algorithms and models to enable autonomous navigation, decision-making and pattern recognition by AMRs.
5. **Cyber-Physical System (CPS) Layer:** Integrates physical sensors and actuators with computer systems to monitor and control industrial processes.

Description of Components - Procedures

1. **Autonomous Mobile Robots (AMRs):** Equipped with sensors for navigation and environmental perception, actuators for moving and manipulating objects, and control modules for coordination and decision- making.
2. **Edge Computing Devices:** Local equipment that processes data received from AMRs and IoT devices.

They carry out preliminary analysis and send only relevant information to the central servers.

1. **5G Network Infrastructure:** Includes 5G communication towers and communication modules in AMRs and IoT devices. Provides the necessary connectivity for real-time communication and processing offloading.
2. **Central Servers:** Carry out intensive data processing and perform advanced analysis that cannot be done locally. They manage data synchronization and storage.

Prototype development

Prototype design

1. **Modeling and Simulation:** The initial design of the prototype will be carried out using modeling and simulation tools to create virtual representations of the AMR and associated systems. This will allow the architecture to be tested and optimized before physical construction.
2. **Hardware development:** This includes the construction of the AMRs and edge computing devices. The hardware components will be selected and integrated based on the defined functional and non-functional requirements.
3. **Software Development:** Includes programming the control algorithms for the AMRs, implementing the

artificial intelligence models, and developing the communication systems for integration with the 5G network and edge computing.

Systems integration

1. **Robotics and CPS integration:** Integration between AMRs and cyber-physical systems will be carried out to ensure coordination and efficient communication between devices.
2. **Integration with Edge Computing:** AMRs will be configured to use edge computing to process data locally. Communication between AMRs and edge computing devices will be tested and optimized.
3. **Integration with the 5G Network:** The connection of AMRs and IoT devices to the 5G network infrastructure will be configured and tested to ensure real-time communication and offloading of processing.

Testing and Validation

1. **Functional Tests:** These include checking the basic functionalities of the AMRs and associated systems, such as navigation, object manipulation and communication with IoT devices.
2. **Performance Tests:** Evaluate the efficiency of the system in terms of latency, speed and processing capacity. They include load tests to simulate real operating conditions.
3. **Integration Tests:** Verify the interaction between the different components of the system, including AMRs, edge computing devices, and 5G network infrastructure.
4. **Robustness Tests:** Evaluate the prototype's ability to operate in adverse conditions and guarantee the reliability and security of data and communications.

Implementation and Deployment

Implementation in a Relevant Environment

1. **Environment Configuration:** Preparation of the relevant environment for the prototype installation, including configuration of the 5G Network infrastructure and integration with existing systems.
2. **Installation and Initial Tests:** Installation of the AMRs and edge computing devices in the industrial environment. Carrying out initial tests to verify the system's operation under real conditions.

This methodology describes the process for developing and implementing an AMR prototype with processing offloading using 5G servers for Industry 4.0.

IV. Results And Discussions

Definition of requirements

Hardware requirements

In the hardware requirements gathering phase for the AMR (Autonomous Mobile Robot), various factors were considered to ensure its optimal performance in a relevant environment. The analysis ranged from structure and support, through remote access and external control, to low-level signals, traction system, communication and security.

Firstly, the AMR's structure and support must be robust enough to bear loads and withstand impacts, ensuring longevity and ease of maintenance. Lightweight and durable materials are preferable to optimize energy consumption.

With regard to Remote Access, the system must allow remote monitoring and control, integrating technologies such as 5G networks or Wi-Fi, for rapid response and firmware or software updates.

External Control must be supported by communication interfaces that allow interaction with external systems, such as servers or centralized management systems, enabling manual control in emergency situations.

For Low Level Signals, it is essential to integrate sensors and actuators that provide and receive precise signals, such as proximity sensors, cameras and motor controllers, in order to guarantee safe and precise movement.

The Traction System must consider efficient motors, providing precise speed and torque control, necessary for autonomous navigation on different surfaces.

Communication between the AMR and other systems needs to be highly reliable, with low latency and a high transmission rate, ensuring real-time synchronization of sensor data.

Finally, Safety must cover obstacle and fault detection systems, guaranteeing the integrity of the environment and operators.

Table 1 shows the hardware requirements for an AMR based on the topics mentioned above. This table provides a clear and organized view of the hardware requirements for an AMR, highlighting the main aspects and their objectives.

Table 1: Hardware requirements for AMR.

Id	Topic	Description	Objective
1	Structure and Support	Robust structure to withstand loads and impacts, using lightweight and durable materials.	To ensure longevity and ease of maintenance.
2	Remote Access	Communication technology (5G, Wi-Fi) for remote monitoring and control.	To enable upgrades and efficient remote control.
3	External Control	Communication interfaces for interaction with external systems.	To facilitate manual control and integration with management systems.
4	Low Level Signals	Sensors and actuators to provide and receive precise signals, such as proximity sensors and cameras.	To ensure safe and accurate movement of the AMR.
5	Traction System	Efficient motors for precise speed and torque control.	To optimize autonomous navigation on various surfaces.
6	Communication	Reliable communication with low latency and high transmission rate.	To ensure real-time synchronization of sensor data.
7	Security	Obstacle and fault detection systems to protect the environment and operators.	To ensure the integrity and safety of the environment and the AMR.

Source: Authors, (2024).

AMR Software Requirements

To develop an AMR, it is essential to meet several software requirements to ensure its performance. The Ubuntu LTS operating system (20.04 or 22.04) is recommended for its compatibility with ROS2, which must be configured with communication, motion control, and sensor packages. The nav2 package is crucial for navigation and mapping, allowing route planning and robot localization, with SLAM in novel environments. Sensors such as LiDAR, cameras, and IMUs require specific drivers for real-time data collection. Simulation tools such as Gazebo and RViz allow testing of robot behavior before deployment. System safety includes exclusion zones and obstacle detection, essential for collision avoidance and reliability.

Table 2: Software requirements for the AMR.

Id	Requirements	Description
1	Operating System	ROS2 requires compatible operating systems, with Ubuntu LTS (20.04 or 22.04) being the most recommended.
2	ROS2 Installation	Required for communication between nodes, control packages and specific libraries.
3	SLAM	Use of the nav2 package for autonomous navigation and creation of real-time maps with SLAM.
4	Sensor Integration	Drivers for sensors such as LiDAR, cameras and IMU must be configured for real-time data.
5	Simulation	Tools such as Gazebo and RViz to test the behavior of the AMR in simulations.
6	DDS Middleware	Use of DDS to ensure flexible and scalable communication between nodes.
7	Security and Control	Implementation of exclusion zones, obstacle detection and remote control of the AMR.

Source: Authors, (2024).

5G Network Requirements

To develop an AMR (Autonomous Mobile Robot), several software requirements are essential to ensure its performance. The recommended operating system is Ubuntu LTS (20.04 or 22.04), compatible with ROS2. The ROS2 installation should include the configuration of communication between nodes, messaging libraries, and packages for motion control and sensors. The nav2 package is crucial for navigation and mapping, allowing route planning and localization of the robot, whether in predefined maps or new environments with SLAM. The integration of sensors such as LiDAR, cameras, and IMUs requires specific drivers for real-time data collection and processing. Simulation tools such as Gazebo or RViz help to test the behavior of the AMR before physical deployment. The DDS middleware in ROS2 facilitates communication between nodes. Safety features such as exclusion zones and obstacle detection are essential to avoid collisions and ensure system reliability. These requirements ensure that the AMR operates autonomously and safely.

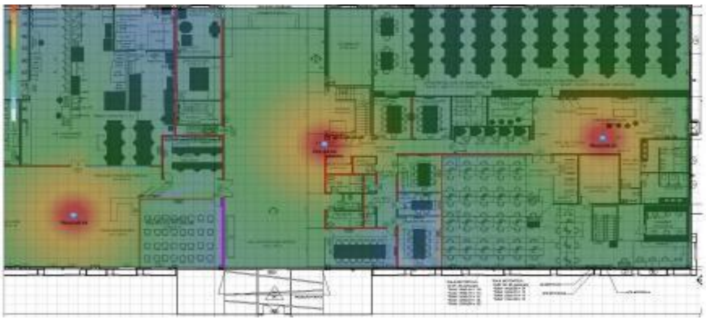


Figure 1: Antenna arrangement in the INDT building.
Source: Authors, (2024).

The building's floor plan served as the basis for the simulation, with three Picocell antennas strategically positioned in the main corridors and critical areas, such as the laboratory and pantry. The simulation ensured robust 5G coverage, avoiding shadow areas and minimizing interference. This survey identified the equipment and materials needed to install the 5G network at INDT, in addition to defining best practices for positioning antennas and cabling infrastructure. The use of the radio simulation tool optimized the arrangement of the devices, ensuring effective coverage. In conclusion, the requirements survey was essential to prepare the infrastructure and ensure the success of future tests, providing a reference model for other environments.

System Architecture

Operational Architecture of Devices in the AMR in the conventional model

In this activity, a detailed architecture for the equipment system and its communications in the AMR was developed, based on the bill of materials (B.O.M.). After adding all the components to the list, the types of communication were categorized, facilitating the creation of the block diagram. This diagram provides a clear view of the interconnections between devices, such as the IMU via USB, SLAM scanners using RS-422 and digital communication for control and safety, and the joystick and BMS with analog communication. The creation of a detailed block diagram, with color-coded interconnections for the different types of communication, allowed for a clearer and more organized view of the operational architecture. The use of images of the components reinforced the practicality and understanding of the connections between them, as shown in Figure 2.

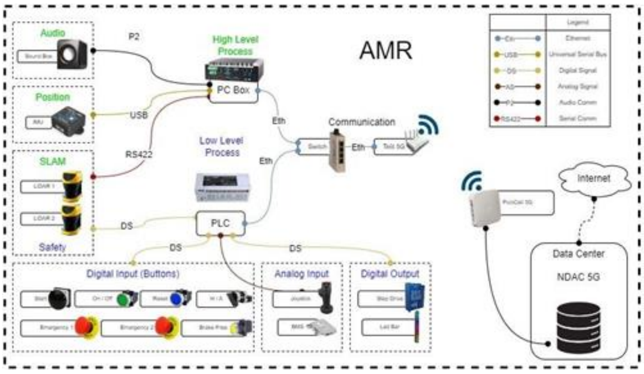


Figure 2: Conventional AMR communication block diagram.
Source: Authors, (2024).

Through this activity, it was possible to visualize in a practical and integrated way all the communications and interfaces between the AMR components, ensuring greater efficiency in implementation and control. The block diagram provides a comprehensive understanding of the interactions, facilitating future adjustments and ensuring the proper functioning of the robot in complex operational scenarios.

Proposed Offloading Architecture with Edge Computing

In this proposal, an offloading architecture based on edge computing was developed, moving the intensive processing of the AMR to an edge server. The main objective is to optimize the robot's performance and reduce local hardware requirements, taking advantage of the efficiency of the 5G network to ensure fast and reliable transmission.

Local Computing - The Programmable Logic Controller (PLC) is responsible for low-level actions, such as movement and sensor reading. Sensors such as LiDAR and IMU transmit data via 5G to the edge server, enabling fast and efficient communication.

Edge Computing - The edge server performs complex tasks such as odometry, mapping, and navigation, relieving the AMR of intensive processing. The PLC receives commands from the server via the 5G network and executes them locally. This approach reduces the computational complexity and the cost of the local hardware of the AMR. Communication via 5G ensures reliable transmission between the PLC and the server, optimizing the robot's performance. The edge computing offloading architecture maximizes the performance of AMRs by simplifying local processing and leveraging the advanced capabilities of the remote server for an efficient solution, as shown in Figure 3.

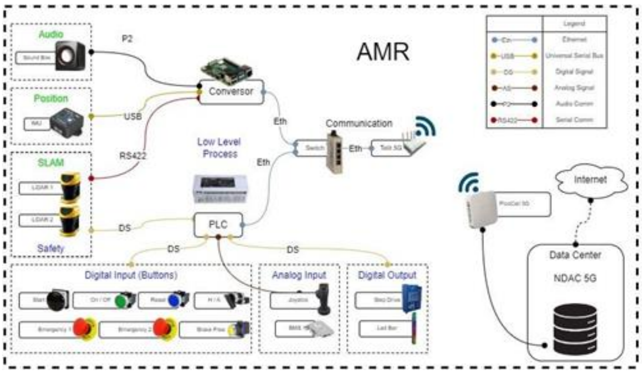


Figure 3: AMR offloading communication block diagram.
Source: Authors, (2024).

5G Network Architecture

The activity focused on designing an operational architecture for the installation of a 5G network in the INDT laboratory, with the aim of evaluating the impact of the position of the equipment on the operation of existing devices. This study in partnership with Nokia was essential to ensure that the integration of the new equipment occurred efficiently, without interference or operational problems, as shown in Figure 4.

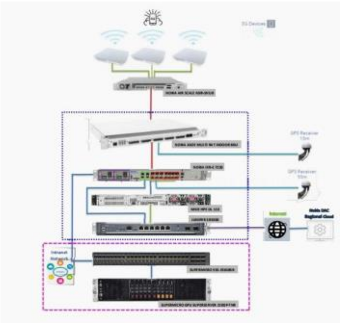


Figure 4: 5G Network Architecture Diagram.
Source: Authors, (2024).

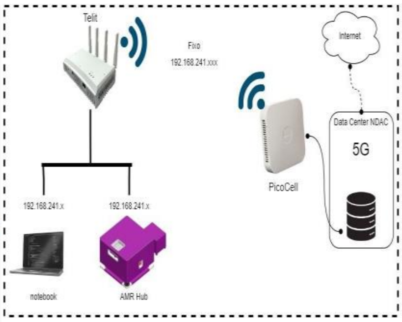


Figure 5: 5G communication architecture.
Source: Authors, (2024).

The use of a 19" 22U rack was defined, which will house the main equipment required for the 5G network. Among these equipment, three PICOCELL antennas stand out, which will be strategically installed at pre-defined points within the building. In addition, the system will include an ASIR-SHUB, -48V DC power supplies, and an ASOE MULTIRAT INDOOR BBU in the primary cabinet. The installation of a GPS antenna, positioned in an outdoor area with an open view, was an essential step to guarantee the time and location accuracy, necessary for synchronizing the 5G network. The communication interface will be carried out through an LC-PC/LC-PC fiber optic connection, ensuring high efficiency in data transmission between systems.

Regarding network security, the JUNIPER SRX300 firewall will be implemented, offering robust threat protection capabilities. Other essential equipment, such as the Supermicro SSE-X3648SR switches and the Supermicro GPU server SuperServer 220GP-TNR will also be part of the architecture. These components will contribute to the robustness and performance of the network, allowing operations to occur with low latency and high availability. The operational architecture developed was designed to ensure that the installation of the 5G network at INDT occurs efficiently and safely. The integration of equipment, including antennas, servers, synchronization systems, AMR and Terminal (Computer for monitoring and control), was carefully planned to minimize interference and ensure the expected accuracy and performance. This approach provides a solid foundation for future expansions and optimizations, in addition to ensuring a safe and controlled environment for 5G network testing, as shown in Figure 5.

Prototype Development

The development of an Autonomous Mobile Robot (AMR) prototype involves several stages, starting with a study and research of compatible technologies to determine the best components and systems to be integrated. This includes the selection of sensors, navigation, communication and processing systems, always taking into account the mobility and autonomy requirements of the AMR. After this phase, the analysis of the project requirements follows, which establishes the functionalities and limitations of the AMR, in addition to defining the technical specifications. This process is essential to ensure that the prototype meets operational needs, is efficient and safe. The next stage involves the study of similar technologies on the market, where existing robots and solutions are evaluated to identify good practices and innovations that can be incorporated into the new prototype. This begins the development of the AMR concept, which focuses on the creation of a preliminary proposal that integrates all the technologies researched and meets the project requirements. Once the concept has been defined, the next step is to model the AMR 3D concept, which results in the creation of a three-dimensional model of the robot, detailing its structure, components, and mechanical interactions. This modeling serves as a basis for technical validation and necessary adjustments, as shown in Figure 6. After reviewing and adjusting the 3D concept, the final phase involves manufacturing the prototype. The robot is built based on the model and specifications, including 3D printing, electronic assembly, and software integration, resulting in a functional prototype for testing, as shown in Figure 7.

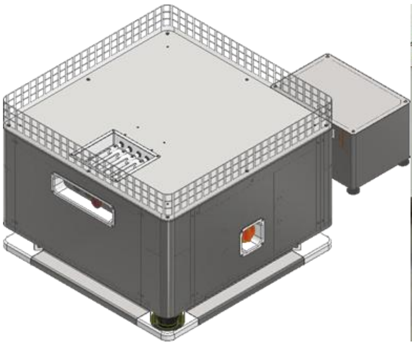


Figure 6: 3D modeling of the AMR.
Figure 7: AMR prototype. Source: Authors, (2024).
Source: Authors, (2024).

Implementation

This study focuses on the implementation and validation of an AMR (Autonomous Mobile Robot) prototype using the ROS2 (Robot Operating System 2) architecture. To ensure robust and accurate performance, a series of components and functionalities were explored and implemented, such as speed control, navigation and safety systems, and sensor reading. The steps range from creating a workspace in ROS2, simulation in Gazebo, to script refactoring, PID control of the wheels, and hardware integration such as RS485/Ethernet converters. This results and discussion section addresses the main challenges and advances obtained in each of these fronts.

Speed Control - AMR Hub and cmd_vel Function

The AMR speed control was implemented using the `cmd_vel` function, responsible for sending linear and angular speed commands to the robot control system. To improve the accuracy of this control, adjustments were made based on feedback from sensors, such as encoders, and by implementing a PID (Proportional-Integral-Derivative) controller for the robot's wheels. The PID control was adjusted to ensure that the AMR maintained the appropriate trajectory and speed, reducing the error between the desired and actual speed. The challenge was to find the optimal parameters for the PID in a dynamic environment, which required continuous adjustments during testing, as shown in Figure 8.

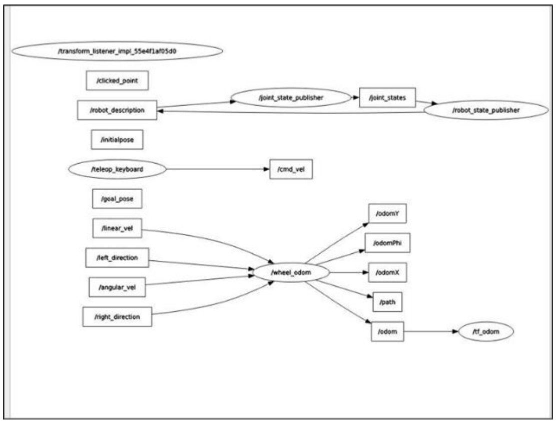


Figure 8: Graph of wheel data being published in odometry.
Source: Authors, (2024).

ROS2 Workspace and System Operational Architecture

The development of the entire project was centralized in a ROS2 workspace. This workspace organized the packages necessary for the simulation, control, and navigation of the AMR. At this stage, a script was developed to map the folder and file structure of each ROS package, allowing a quick visualization of how the package was structured. Visualizing the packages allows for a standardization of the package structure, ensuring that all follow the same format and reducing errors, since the visualization allows the identification of essential elements and compliance with naming conventions, as shown in Figure 9. The operational architecture of the ROS2 system was designed to be modular and extensible, allowing for the easy addition of new components and functionalities. Refactoring the scripts was essential to ensure the organization of the packages and the reuse of code in multiple scenarios. The division into packages also facilitated the integration with the Gazebo simulator and the Nav2 navigation system. At the highest levels of abstraction in ROS 2, the implementation of a state machine often focuses on coordinating complex, high-level logical behaviors in a distributed robotic system, as shown in Figure 10.

```
hub_main_pkg/
        setup.py
        package.xml
        setup.cfg
        launch/
                launch-slam-toolbox.launch.py
                launch-modbus.launch.py
                bring_lasers.launch.py
        resource/
                main_pkg
                hooks/
                        post-update.sample
                        push-to-checkout.sample
                        fsmonitor-watchman.sample
                        applypatch-msg.sample
                        commit-msg.sample
                        pre-push.sample
                        pre-rebase.sample
                        update.sample
                        prepare-commit-msg.sample
                        pre-merge-commit.sample
                        pre-receive.sample
                        pre-applypatch.sample
                        pre-commit.sample
                branches/
                logs/
                        HEAD
                        refs/
                                heads/
```

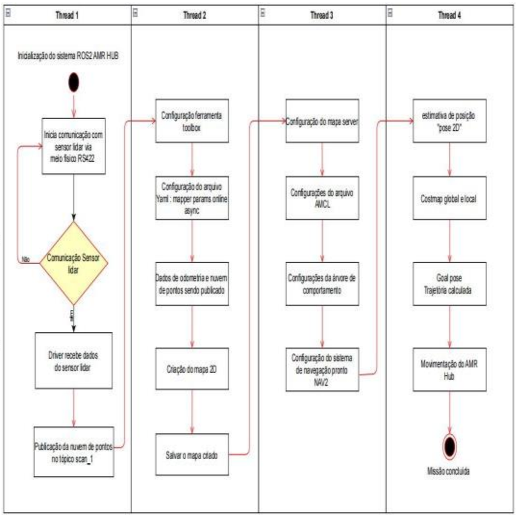


Figure 9: Generated image containing the file tree of a ROS package. Source: Authors, (2024).
Figure 10: Example of the description of a ROS package available in your repository.
Source: Authors, (2024).

Gazebo Simulation

Creating a simulation in Gazebo was crucial to test the AMR in a controlled environment before its physical implementation. The robot model and simulated environment were configured to be as close to the real world as possible, allowing a realistic evaluation of the AMR's performance. The simulation included generating maps and executing navigation missions, which accelerated the development process by reducing the need for constant physical testing. With the model loaded into Gazebo and Rviz, a third-party scenario was used to simulate a real environment, a warehouse scenario being chosen to perform tests as close as possible to the environments in which the real AMR will navigate, as shown in Figure 11.

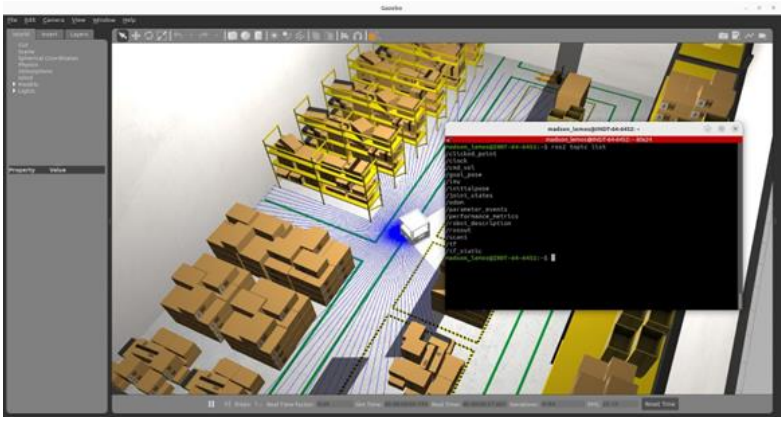
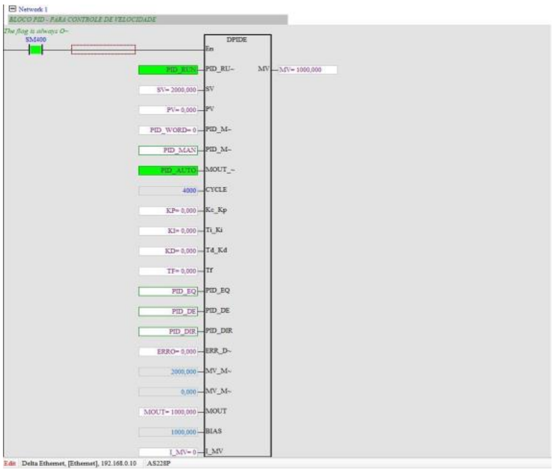


Figure 11: AMR model loaded into Gazebo with Warehouse scenario.
Source: Authors, (2024).

PID Wheel Control

To ensure precise locomotion, PID control was implemented in the wheels of the AMR Hub prototype. This control adjusts the power of the motors in real time, correcting speed deviations and ensuring that the robot follows the planned trajectory. Using encoders on the wheels and simulations in Gazebo, the control parameters were optimized to minimize speed error and maintain stability. The electrical connection included a Delta AS228P-A

PLC, HSS860 Drive, 24VDC power supply and stepper motor. Ladder programming in the PLC performs automatic PID control based on data sent by ROS via cmd_vel topic, adjusting acceleration and deceleration without the need for manual adjustments. The PID block constantly calculates during wheel movement, as shown in Figure 12.

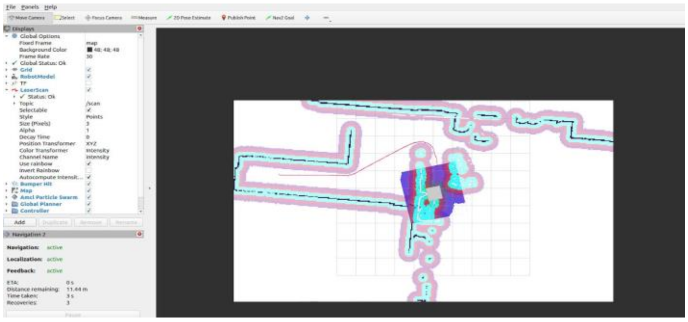


MV= 1000,000
SV= 2000,000
PV= 0,000
PID_WORD= 0
4000
KP= 0,000
KI= 0,000
KD= 0,000
TF= 0,000
ERRO= 0,000
2000,000
0,000
MOUT= 1000,000
1000,000
I_MV= 0
Delta Ethernet, [Ethernet], 192.168.0.10 AS228P

Figure 12: PID block for speed control.
Source: Authors, (2024).

Navigation System and Nav2

Nav2 was chosen to implement the AMR's autonomous navigation system. The refinement focused on creating accurate maps, adjusting the path planner, and controlling speed, aiming to avoid collisions and improve efficiency. Nav2 allowed testing and validating navigation in several scenarios, both virtual and physical. Validation included executing complete missions, with the robot navigating in mapped environments, using sensors to monitor its position and avoid obstacles. To start the navigation system, it is necessary to run the wheel odom and cloud point publisher packages, responsible for odometry and reading LiDAR points, respectively. After that, initialize the navigation launch and define the AMR point with the 2D estimate pose, as shown in Figure 13.



Fixed Frame: map
Background Color: 48; 48; 48
Frame Rate: 30
Global Status: Ok
Status: Ok
Topic: /scan
Style: Points
Size (Pixels): 3
Alpha: 1
Decay Time: 0
Position Transformer: XYZ
Color Transformer: Intensity
Channel Name: intensity
Navigation: active
Localization: active
Feedback: active
ETA: 0 s
Distance remaining: 11.44 m
Time taken: 3 s
Recoveries: 3

Figure 13: Navigation system. Source: Authors, (2024).

Hardware Integration and Communication Tests

Hardware integration was another crucial point, with emphasis on the use of an RS485/Ethernet converter, responsible for communication between the sensors and the robot control system. Testing of this system included creating maps and validating the odometry, with the aim of ensuring that the robot navigated efficiently. In addition, the encoder reading system was developed to ensure the accuracy of the AMR's displacement data, allowing for adequate control of its position. During testing with a real AMR, it was necessary to adjust sensitivity parameters in the cost maps, to avoid unnecessary recalculation of the paths. It was also necessary to adjust the AMR's odometry, as the display was becoming desynchronized with the

AMR's real position, causing problems with the location feedback. After the adjustments, it was possible to validate that when navigating in a real environment, the navigation system is able to stay updated and reflect the AMR's movements, as shown in Figure 14.

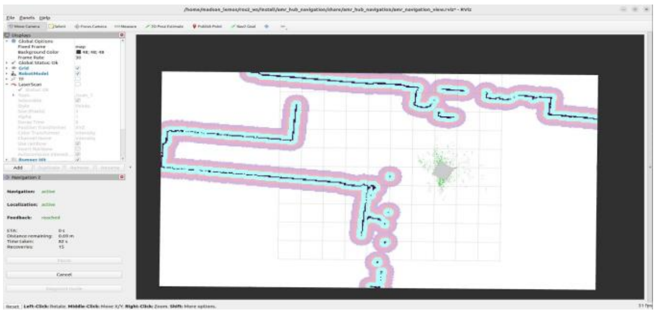
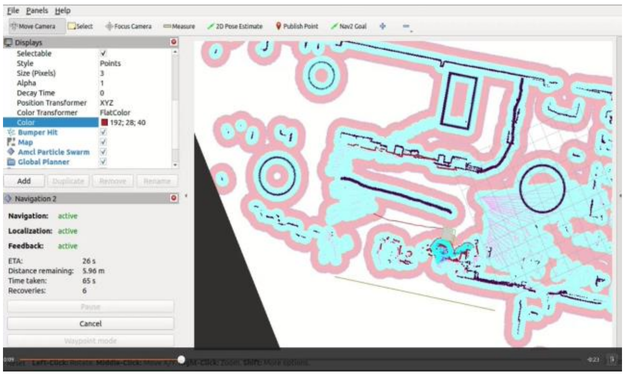


Figure 14: AMR at the target point marked on the map.
Source: Authors, (2024).

Testing and Validation

The internal functional tests performed at INDT were essential to validate the AMR navigation system. Each module was tested separately and then integrated to ensure that the robot could complete its missions autonomously. Speed, mapping, and navigation tests were performed in different environments, both simulated and real. During the tests, fine-tuning of the control and navigation parameters was performed to ensure the efficiency of the system. These adjustments allowed the AMR to navigate efficiently and safely, avoiding unwanted areas and maintaining an accurate location even with the presence of virtual barriers on the map and also dynamic barriers that were detected by the AMR's LiDAR, as shown in Figure 15.



Selectable ☑
Style Points
Size (Pixels) 3
Alpha 1
Decay Time 0
Position Transformer XYZ
Color Transformer FlatColor
Color 192; 28; 40
Bumper Hit ☑
Map ☑
Amcl Particle Swarm ☑
Global Planner ☑

Navigation: active
Localization: active
Feedback: active

ETA: 26 s
Distance remaining: 5.96 m
Time taken: 65 s
Recoveries: 6

Figure 15: AMR navigating alongside a virtual barrier with its updated cost layers.
Source: Authors, (2024).

The development and implementation of the AMR prototype using ROS2 brought a series of challenges, especially related to speed control, navigation and hardware integration. However, the results obtained demonstrate that the system was able to operate autonomously, using sensors and PID controllers to ensure accuracy and efficiency. The simulation in Gazebo and the refinement of Nav2 were fundamental for the validation of the robot's functionalities, allowing a smooth transition to physical testing.

Discussions

The development of an AMR (Autonomous Mobile Robot) prototype with processing offloading using 5G servers represents a significant advance in industrial automation, bringing new levels of efficiency, flexibility and connectivity. This approach integrates industrial automation, robotics, Internet of Things (IoT), cyber-physical systems (CPS), edge computing and 5G networks.

Industry 4.0 digitalizes production processes to optimize production and reduce costs, using automation to control and monitor machines and processes. Robotics, both fixed and mobile, are essential to perform tasks with precision and speed. Stationary robots, such as those used in welding and painting, are effective at repetitive tasks but limited in flexibility. In contrast, mobile robots, such as AMRs, offer greater adaptability, autonomously navigating complex environments and performing varied tasks, such as transportation and inspection.

AMRs use sensors such as LiDAR and cameras to detect changes in the environment, and IoT enables real- time data integration with other devices and systems, automatically adjusting operations. Cyber-physical systems (CPS) combine sensors, actuators, and software to create smart factories, monitoring and controlling physical processes digitally. Offloading processing to 5G servers improves efficiency by performing intensive processing remotely, while edge computing enables fast decisions locally. Artificial intelligence (AI) is crucial to advanced robotics, enabling AMRs to learn and adapt. Combining AI with remote processing via 5G enables more autonomous and adaptive AMRs, with enhanced navigation and decision-making capabilities. 5G, with its high bandwidth and low latency, enables processing offloading, allowing AMRs to operate efficiently and in a connected manner in densely connected industrial environments. This technology also facilitates the integration of robots with other IoT systems, creating a cohesive automation ecosystem.

In summary, the integration of industrial automation, mobile robotics, IoT, CPS, edge computing and 5G in the development of AMRs represents a crucial innovation in Industry 4.0. This combination improves the efficiency of production processes and enables the creation of autonomous and adaptable factories, optimizing the integration between the physical and digital worlds.

V. Conclusion

The development of the prototype of an Autonomous Mobile Robot (AMR) with processing offloading using 5G servers is a significant advance for Industry 4.0. The integration of AMRs in the industrial environment allows for advanced automation and optimization of production processes. Offloading processing to 5G servers improves efficiency, as complex tasks are managed externally, relieving the burden on the robot hardware. 5G servers offer high-speed, low-latency connectivity, essential for the real-time operation of AMRs. This allows for optimized execution of the Robot Operating System (ROS), facilitating control and navigation without compromising robot performance. This approach not only improves the performance of AMRs, but also reduces energy consumption and increases the durability of components. The prototype represents an advance in Industry 4.0 by combining emerging technologies, allowing AMRs to operate with greater intelligence and adaptability. This innovation meets the growing demands of modern industries and contributes to the digital transformation of production processes.

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References

[1] Lampropoulos, Georgios; Siakas, Kerstin; Anastasiadis, Theofylaktos. Internet Of Things In The Context Of Industry 4.0: An Overview. International Journal Of Entrepreneurial Knowledge, V. 7, N. 1, 2019.

[2] Peres, Ricardo Silva Et Al. Industrial Artificial Intelligence In Industry 4.0-Systematic Review, Challenges And Outlook. Ieee Access, V. 8, P. 220121-220139, 2020.

[3] González-Sarmiento, E.; Roa-Perez, J.; Ortiz-Ospino, L. Big Data And Artificial Intelligence In The Development Of Industry 4.0; A Bibliometric Analysis. In: Iop Conference Series: Materials Science And Engineering. Iop Publishing, 2021. P. 012008.

[4] Aljubayrin, Saad Et Al. Dynamic Offloading Strategy For Computational Energy Efficiency Of Wireless Power Transfer Based Mec Networks In Industry 5.0. Journal Of King Saud University-Computer And Information Sciences, V. 35, N. 10, P. 101841, 2023.

[5] Shu, Wanneng Et Al. An Improved And Efficient Computational Offloading Method Based On Admm Strategy In Cloud-Edge Collaborative Computing Environment For Resilient Industry 5.0. Ieee Transactions On Consumer Electronics, 2023.

[6] Goswami, Shikha; Goswami, Rohit; Verma, Govind. Artificial Intelligence-Based Internet Of Things For Industry 5.0. 2024.

[7] Mali, Bhabesh Et Al. Edge Computing For Latency-Critical Task Offloading In Industry 5.0. Ieee Sensors Letters, 2024.

[8] Sharma, Megha; Tomar, Abhinav; Hazra, Abhishek. Edge Computing For Industry 5.0: Fundamental, Applications And Research Challenges. Ieee Internet Of Things Journal, 2024.

[9] Hazra, Abhishek; Kalita, Alakesh; Gurusamy, Mohan. Distributed Service Provisioning With Collaboration Of Edge And Cloud In Industry Ieee Internet Of Things Journal, 2024.

[10] Yang, Miao Et Al. An Online Learning Approach To Computation Offloading In Dynamic Fog Networks. Ieee Internet Of Things Journal, V. 8, N. 3, P. 1572-1584, 2020.

[11] Park, Catherine Et Al. Smart Offloading Boot System For Remote Patient Monitoring: Toward Adherence Reinforcement And Proper Physical Activity Prescription For Diabetic Foot Ulcer Patients. Journal Of Diabetes Science And Technology, V. 17, N. 1, P. 42-51, 2023.

[12] Velázquez, Alexei Pérez. A Quarta Revolução Industrial: Um Modelo De Câmbios E De Integração Multidisciplinar. In: Open Science Research Vi. Editora Científica Digital, 2022. P. 1746-1758.

[13] Freitas, Elton Da Silva. Aplicação De Tecnologias De Automação Industrial Para Melhoria De Processos De Produção: Um Estudo De Caso. 2020.

[14] Comenale, Wagner; Wiltgen, Filipe. Automação Industrial Para A Manufatura Avançada Com Apoio Da Engenharia De

Sistemas & Requisitos. In: 11 Congresso Brasileiro De Engenharia De Fabricação, Curitiba. 2021. P. 24-26.

[15] Godina, Radu Et Al. Impact Assessment Of Additive Manufacturing On Sustainable Business Models In Industry 4.0 Context. Sustainability, V. 12, N. 17, P. 7066, 2020.

[16] Kang, Yoohwa Et Al. Time-Sensitive Networking Technologies For Industrial Automation In Wireless Communication Systems. Energies, V. 14, N. 15, P. 4497, 2021.

[17] Jamwal, Anbesh Et Al. Industry 4.0 Technologies For Manufacturing Sustainability: A Systematic Review And Future Research Directions. Applied Sciences, V. 11, N. 12, P. 5725, 2021.

[18] Ferreira, Cloves Wanderlande Torres; Leite, Jandecy Cabral. Applied Autonomous Maintenance In The Improvement Of Production Quality: A Case Study. Itegam-Jetia, V. 2, N. 7, 2016.

[19] Frascá, Greicy Echiley; Bruno, Diego Renan. Automação: Introdução A Robótica Industrial. Revista Interface Tecnológica, V. 18, N. 2, P. 639-651, 2021.

[20] Dos Reis, Ney Robinson Salvi; De Souza, Lucia Helena Ramos. Robótica No Brasil: Relatos De Pesquisa E Desenvolvimento.

[21] Santoni, Fabiano; Lucato, André Vicente Ricco. Robótica Colaborativa: A Utilização De Robôs Nos Processos Produtivos. Recima21- Revista Científica Multidisciplinar-Issn 2675-6218, V. 1, N. 1, P. E210914-E210914, 2021.

[22] Amaral, Hudson Nunes; Gasparotto, Angelita Moutin Segoria. Inteligência Artificial: O Uso Da Robótica Indústria 4.0. Revista Interface Tecnológica, V. 18, N. 1, P. 474-486, 2021.

[23] Dzedzickis, Andrius Et Al. Advanced Applications Of Industrial Robotics: New Trends And Possibilities. Applied Sciences, V. 12, N. 1, P. 135, 2021.

[24] Gonçalves, Marcelo Carneiro Et Al. Application Of Operational Research In Process Optimization In The Cement Industry. Itegam-Jetia, V. 6, N. 24, P. 36-40, 2020.

[25] Jamwal, Anbesh Et Al. Industry 4.0 Technologies For Manufacturing Sustainability: A Systematic Review And Future Research Directions. Applied Sciences, V. 11, N. 12, P. 5725, 2021.

[26] Pinon, Marcia M. Barreto Et Al. Applications And Advantages Of The Internet Of Things (Iot) At Industry (189-194). Itegam-Jetia, V. 4, N. 15, P. 189-194, 2018.

[27] Alsalem, Thanaa Saad; Almaiah, Mohammed Amin; Lutfi, Abdalwali. Cybersecurity Risk Analysis In The Iot: A Systematic Review. Electronics, V. 12, N. 18, P. 3958, 2023.

[28] Benotmane, Meryem; Elhari, Kaoutar; Kabbaj, Adil. A Review & Analysis Of Current Iot Maturity & Readiness Models And Novel Proposal. Scientific African, V. 21, P. E01748, 2023.

[29] Ding, Suiting; Tukker, Arnold; Ward, Hauke. Opportunities And Risks Of Internet Of Things (Iot) Technologies For Circular Business Models: A Literature Review. Journal Of Environmental Management, V. 336, P. 117662, 2023.

[30] Dafflon, Baudouin; Moalla, Nejib; Ouzrout, Yacine. The Challenges, Approaches, And Used Techniques Of Cps For Manufacturing In Industry 4.0: A Literature Review. The International Journal Of Advanced Manufacturing Technology, V. 113, P. 2395-2412, 2021.

[31] Wang, Zezhou; Liu, Xiang. Cyber Security Of Railway Cyber-Physical System (Cps)–A Risk Management Methodology. Communications In Transportation Research, V. 2, P. 100078, 2022.

[32] Catillo, Marta; Pecchia, Antonio; Villano, Umberto. Cps-Guard: Intrusion Detection For Cyber-Physical Systems And Iot Devices Using Outlier-Aware Deep Autoencoders. Computers & Security, V. 129, P. 103210, 2023.

[33] Jain, Parita Et Al. Convergence Of Iot And Cps In Robotics. In: Emergence Of Cyber Physical System And Iot In Smart Automation And Robotics: Computer Engineering In Automation. Cham: Springer International Publishing, 2021. P. 15-30.

[34] Haldorai, Anandakumar. A Review On Artificial Intelligence In Internet Of Things And Cyber Physical Systems. Journal Of Computing And Natural Science, V. 3, N. 1, P. 012-023, 2023.

[35] Ghodsian, Nooshin Et Al. Mobile Manipulators In Industry 4.0: A Review Of Developments For Industrial Applications. Sensors, V. 23, N. 19, P. 8026, 2023.

[36] Eisen, Mark Et Al. Joint Resource Scheduling For Amr Navigation Over Wireless Edge Networks. Ieee Open Journal Of Vehicular Technology, V. 4, P. 36-47, 2022.

[37] Zaki, Amr M. Et Al. Heuristic-Based Proactive Service Migration Induced By Dynamic Computation Load In Edge Computing. In: Globecom 2022-2022 Ieee Global Communications Conference. Ieee, 2022. P. 5668-5673.

[38] Liu, Lei Et Al. Mobility-Aware Multi-Hop Task Offloading For Autonomous Driving In Vehicular Edge Computing And Networks. Ieee Transactions On Intelligent Transportation Systems, V. 24, N. 2, P. 2169-2182, 2022.

[39] Javed, Muhammad Awais; Zeadally, Sherali. Ai-Empowered Content Caching In Vehicular Edge Computing: Opportunities And Challenges. Ieee Network, V. 35, N. 3, P. 109-115, 2021.

[40] Chipantiza, Ninfa Elizabeth Pacha; Palma, Henry Marcelo Barba; Morocho, Lizbeth Estefania Sevilla. Systematic Analysis Of Artificial Intelligence Integration In Robotics Learning In Secondary Education. Universidad Ciencia Y Tecnología, V. 28, N. 123, P. 111-121, 2024.

[41] Pande, Akshara; , Deepti. Assessment Of Pepper Robot's Speech Recognition System Through The Lens Of Machine Learning. Biomimetics,V. 9, N. 7, P. 391, 2024.

[42] Károly, Artúr István Et Al. Deep Learning In Robotics: Survey On Model Structures And Training Strategies. Ieee Transactions On Systems, Man, And Cybernetics: Systems, V. 51, N. 1, P. 266-279, 2020.

[43] Soori, Mohsen; Arezoo, Behrooz; Dastres, Roza. Artificial Intelligence, Machine Learning And Deep Learning In Advanced Robotics, A Review. Cognitive Robotics, V. 3, P. 54-70, 2023.

[44] Aristeidou, Christoforos; Dimitropoulos, Nikos; Michalos, George. Generative Ai And Neural Networks Towards Advanced Robot Cognition. Cirp Annals, 2024.

[45] Iovino, Matteo Et Al. A Survey Of Behavior Trees In Robotics And Ai. Robotics And Autonomous Systems, V. 154, P. 104096, 2022.

[46] Lackner, Thorge; Jooste, Johannes L.; Palm, Daniel. Decision-Support Framework To Evaluate The Practicality Of 5g For Intralogistics Use Cases In Standalone Non-Public Networks. Procedia Cirp, V. 120, P. 51-56, 2023.

[47] López, Melisa Et Al. Towards The 5g-Enabled Factories Of The Future. In: 2023 Ieee 21st International Conference On Industrial Informatics (Indin). Ieee, 2023. P. 1-8.

[48] George, Roshan; Cherbaka, Natalie S.; Ellis, Kimberly. 5g Opportunities In Warehousing. 2023.

[49] Rodriguez, Ignacio Et Al. An Experimental Framework For 5g Wireless System Integration Into Industry 4.0 Applications. Energies, V. 14, N. 15, P. 4444, 2021.

[50] Ansari, Junaid Et Al. Performance Of 5g Trials For Industrial Automation. Electronics, V. 11, N. 3, P. 412, 2022.