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RFID-Enabled Smart Manufacturing: Real-Time Asset Tracking and Operational Workflow Optimization

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Abstract: The article presents the possibility of implementing an RFID system to increase transport efficiency in both classic industrial environments and in infrastructure with a high level of automation. The proposed solution takes into account the possibility of installing RFID readers on poles, suspended ceilings, as well as in the floor of the storage and communication space. Thanks to its universal approach and scalability, it allows to increase the level of process automation, especially in SMEs. The implementation of the proposed system in modern factories will make it possible to track in real time the location of products and materials required for production and will have a positive effect on optimizing the flow of these objects within the production environment. Moreover, the implementation of this system is affordable for most enterprises.

Keywords: Industry 4.0; internal traffic management; Internet of Things; production management; RFID

1 INTRODUCTION

The role of smart factories and intelligent warehouses is becoming increasingly pivotal in the context of a rapidly evolving industrial landscape. Modern enterprises are progressively integrating advanced automation solutions to optimize production processes and enhance operational efficiency. In this regard, the implementation of state-of-the-art systems leveraging technologies such as Radio Frequency Identification (RFID) and the Internet of Things (IoT) is gaining significant traction [1-5]. However, the widespread adoption of these technologies remains constrained primarily by the substantial financial investment required for their deployment within contemporary manufacturing environments. While numerous cutting-edge solutions have demonstrated the potential to significantly enhance production efficiency and streamline inventory management in warehouse settings, financial constraints often pose a substantial barrier to their large-scale implementation, particularly for small and medium-sized enterprises (SMEs) [6]. This challenge underscores the need for cost-effective, scalable solutions that bridge the gap between conventional warehouse management practices and fully autonomous systems, facilitating gradual digital transformation in industrial operations. Solutions that will significantly impact overall operational efficiency with the minimum of impact on existing infrastructure will be in demand in the industry.

The SME sector is a large market that should also be given a chance to participate in the evolution of the industrial landscape. Is it feasible to apply modern Industry 4.0 technologies to warehouses and production facilities without the need to invest enormous amounts of money to entirely overhaul the existing space? The aim of the system outlined in this paper is to ensure a sufficient level of automation in warehousing and manufacturing environments belonging to the SME sector. The proposed system combines affordability and the advantages of automating object tracking and identification processes, providing an ideal solution for SMEs.

Section 2 presents a literature review of existing solutions applicable to modern warehousing environments. Section 3 discusses the proposed solution considering the measurement methodology and a characterization of the research environment. Section 4 is an overview of the results obtained and a discussion of the capabilities of the proposed system.

2 CURRENT APPLICATIONS OF ADVANCED TECHNOLOGIES IN THE FIELD OF SMART FACTORIES AND WAREHOUSES

The adoption of numerous technological solutions in smart warehousing and manufacturing environments is particularly prevalent among technology giants. Small and medium-sized enterprises try to keep up with technological changes and implement them gradually. However, this kind of companies do not have the same financial resources as larger enterprises. The implementation of solutions incorporating various robots and automation-supporting devices requires multimillion-dollar investments posing a significant challenge, especially in the SME sector. The warehouse environment management systems used by tech giants such as Amazon and DHL use autonomous mobile robots (AMRs) to increase operational efficiency. SME companies do not have the financial capacity to fully automate their warehouse environments with this sollutions.

2.1 RFID and IoT in Smart Warehouses

The most advanced technologies have been applied for many years to digitally transform warehousing and manufacturing environments. The cited studies have demonstrated that since 2010, the implementation of technologies such as automated vehicles and Internet of Things devices in warehouses increases space utilization by 15% and reduces order picking time by 10% [1]. The use of RFID technology in these environments increases operational efficiency, which is particularly significant in the FMCG sector [7]. Automated Guided Vehicles (AGVs) are also utilized in intelligent warehousing and production environments, despite the considerable costs associated with procuring such devices. Integrating these robots with RFID capabilities enables a more automated and efficient management of AGVs within warehouses. Proper placement of RFID transponders in such environments facilitates the precise determination of an AGV's position [2]. Additionally, equipping AMRs with supplementary modules that leverage computer vision allows for accurate assessment of inventory levels in a given warehouse environment [6]. The integration of all these devices and robots with IoT capabilities enables real-time responses to various factors, such as new orders or the need to replenish inventory, thereby optimizing processes and increasing product throughput [3].

2.2 Multi-Agent Systems and Robotics in Industry 4.0

In intelligent warehousing and manufacturing environments, it is possible to also use multi-agent cyber-physical management systems, which, combined with RFID technology, enable precise monitoring of warehouse inventory levels, and reduce the likelihood of human error. A simulation demonstrated that the implementation of such systems in a cryogenic warehouse significantly reduces the dwell time of materials in the system. Depending on the stage, the time was reduced from 38.46% to 58.23% [4]. Corporations such as Amazon and DHL are currently employing numerous robots in their logistics centers to improve operational efficiency. The use of robot swarms in these environments makes it possible to perform tasks that individual units would not be able to accomplish - for example, the movement of a 1-ton load by two robots with a lifting capacity of 500 kg each [5]. In these environments, preventing collisions between autonomous robots is also of utmost importance. In this regard, agent-based modelling is proving useful, whereby each robot is able to communicate with the others thereby supporting dynamic decision-making and preventing collisions [8]. The integration of such solutions with RFID capabilities presents a significant challenge, as the RFID network must be properly planned to avoid network overloads and reduce interference. Intelligent swarm optimization algorithms such as Particle Swarm Optimization are instrumental in the planning of RFID networks efficiently [9].

2.3 Digital Twins and Intelligent Manufacturing Analysis

During the complex stage of production, the early detection of possible production errors and their elimination is of paramount importance. To achieve this, the implementation of systems that enable precise monitoring of the position of a given product on conveyor belts is highly beneficial. These systems include the digital twin model, which, in conjunction with an RFID network deployed within a real manufacturing environment, facilitates the accurate location of products, regardless of conveyor speed [10]. The implementation in manufacturing environments of intelligent systems that use deep belief networks to make crucial decisions such as controlling CNC machine tools positively impacts production efficiency and provides the lowest prediction error among those tested [11]. Industry 4.0 technologies including RFID and Sigfox likewise enable more efficient production through reduced waiting times between manufacturing steps. This improvement is made possible by automated and continuous monitoring of product flow [12]. Moreover, the analysis of data acquired from RFID systems in such manufacturing environments facilitates more precise operational decision-making as well as the identification and elimination of rate-limiting steps. This approach significantly improves operational efficiency as well as reduces production errors [13, 14]. Solutions of this sort, based on Industrial Internet of Things (IIoT) devices, significantly facilitate the optimization of production planning and scheduling. The use of wireless sensor networks in manufacturing environments provides a sizable amount of data for analysis and enables dynamic decision-making [15]. Furthermore, the role of RFID-based systems is crucial in modern factories and smart warehouses. In addition to optimizing processes, the analysis of data collected by RFID readers also enables the acquisition of decision rules that can be used for better production planning [16].

2.4 Internal Location and Navigation Systems

One of the mainstream and widely used solutions implemented in modern factories and smart warehouses are certainly Real Time Location Systems (RTLS). The integration of these RTLS with Manufacturing Execution Systems (MES) is crucial for optimizing manufacturing processes [17]. Radio Frequency Identification technique could also be used in the RTLS. Placing RFID transponders in all stationary objects in warehousing or manufacturing environments, along with storing the data about the coordinates of a given transponder and the type of surface, creating a grid of the room concerned is feasible. Furthermore, by placing an RFID reader on the AMR, it is possible to precisely locate the robot in the warehouse environment and prevent collisions [18, 19]. Additionally, the usage of innovative RFID-SLAM technology is suitable for mapping warehouse spaces. Application of this technology in a 35 m^2 research environment has demonstrated an average robot localization error of less than 5cm and an average error in estimating the three-dimensional localization of RFID transponders placed in the research environment of approximately 10 cm [20].

2.5 Smart City and Traffic Management

Nowadays, the use of advanced technologies for traffic management is an essential element of the Smart City 2.0 concept. The application of RFID technology integrated into the road infrastructure or directly within the vehicles provides not only traffic flow monitoring and vehicle identification, but in addition enables dynamic control of traffic flow. This approach significantly improves the efficiency of vehicle movement through smart cities [21]. Extending this kind of solution with 5G technology and cloud computing, urban traffic management is becoming more scalable. Communication between numerous vehicles permits automatic detection of parking space occupancy. This solution facilitates more efficient management of parking infrastructure and reduction of the travel time [22]. Implementing comparable technologies and algorithms in smart warehousing environments would be expected to result in more efficient placement of products on warehouse racks.

3 RFID-ASSISTED INTELLIGENT TRAFFIC MANAGEMENT FOR INTERNAL LOGISTICS IN MODERN FACTORIES

The RFID technology is deployed in nearly all identification systems designed for smart warehouses. This is due to its advantages, particularly operating costs comparable to those incurred when using barcode-based systems. However, in contrast to barcodes, the use of RFID systems is more efficient and less sensitive to weather conditions. The UHF RFID technique makes it possible, using appropriate algorithms that take into account the capture effect, to read up to 1,000 objects once during a single measurement cycle with an identification error of less than 2% [23]. The proposed solution primarily uses RFID-based systems while considering the lowest possible implementation costs to enable SMEs to modernize their manufacturing and warehousing environments. The implementation of this system in modern factories will make it possible to track in real time the location of products and materials required for production and will have a positive effect on optimizing the flow of these objects within the production environment. The developed solution is a connectivity solution that allows SME enterprises to provide a quality of service at a level similar to large international corporations taking a full advantage of available technological solutions. Although this solution will never be better than fully automated environments it certainly is attractive to the SMB sector. Such a solution represents an ideal balance of implementation costs and potential advantages in the context of overall operational efficiency.

3.1 Overview of the Employed Technology

During the conducted measurements of the system for identification and tracking of objects in warehousing and manufacturing environments, an array of RFID readers based on the PN532 controller operating at a frequency of 13.56 MHz has been used. These short-range readers fulfilled their function placed on the prepared mock-up of the measurement environment. However, in case of implementing the solution in smart warehouses, their range will be insufficient. In manufacturing environments, it would be required to use industrial solutions. The appropriate RFID UHF readers for such implementations are those compatible with EPC Class1 Gen2 transponders in accordance with ISO/IEC 18000-6C standard. Real-world tracking capabilities will be made more efficient due to the capabilities of UHF RFID readers, particularly the ability to read numerous transponders during a single read sequence.

In order to measure the efficiency of object identification and tracking, customized cubes were produced, printed using FDM additive manufacturing technology, in which RFID transponders were implemented. The RFID cubes were designed in two different variants: with the transponder implemented inside the cube during the additive manufacturing process, and with the transponder placed on the outer wall in a small dimple. The appearance of the cubes is shown in Fig. 1.

The same type of RFID transponder in the form of NFC NTAG213 stickers has been placed in both variants of RFID boxes. The tests conducted revealed that the type of RFID cubes does not affect the efficiency of identification. In other words, the transponders can be implemented into the product at the production stage and may not be visible as in the case of barcode-based systems. The solution provides efficient and low-failure identification of objects, and ensures that product batches are marked in a secure and difficult-to-defect method. The placement of RFID transponders inside products at the manufacturing stage ensures that any attempt to defect the RFID tag will end up with damage to the entire product. This approach provides greater security in product identification and reduces the risk of misidentification.

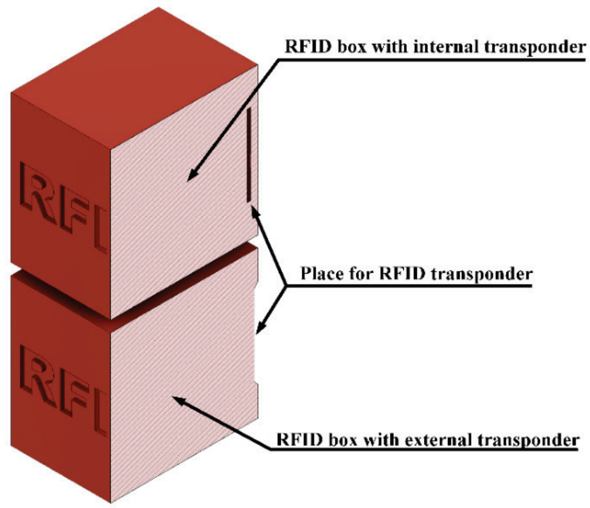

Figure 1 RFID cubes prepared for measurements

3.2 Concept of Asset Tracking and Operational Workflow Optimization System

The primary objective of the concept presented was to provide the SME sector with a solution that would enable real-time object tracking and improve operational efficiency. An additional requirement was the simplicity of implementation and relatively inexpensive implementation and operating expenses, so that smaller enterprises would have the opportunity to implement such a system. Another important aspect is the approachable scalability of the proposed solution. During the design process for a suitable solution, the principal problem that was identified in operational efficiency contexts were the intersections that occur in warehousing and manufacturing environments. These intersections are locations where the utmost caution is required of the operator, and thus the need to reduce travel speed. This is particularly relevant in environments where the space allocated to warehouses or production lines has been expanded compared to the transportation area between these zones. Fig. 2 demonstrates a conceptual layout of part of such an environment. In (a), a diagram representing the various processing zones and storage facilities is provided. In (b), a visualization of a mock-up prepared for measurements to verify the operation of the system is illustrated. This is a diagram of a production environment with integrated warehouses for current production needs. The final environment may consist of numerous such parts, with many more processing zones and their associated warehouses. With an increased number of zones, the number of intersections in the entire manufacturing environment will also be increased. The increase in the number of intersections will directly affect the transit time from point A to point B. The need to cross the numerous intersections will be a multiplier of the time spent traveling through a single intersection. Therefore, the larger the warehouse environment, the more intersections between avenues in the environment, which leads automatically to much higher delays. A delay of for instance 5 seconds at an intersection may look inconspicuous, however, multiplied by 12 intersections, it already gives 60 seconds per trip. Calculating that a transport truck takes such a route 60 times a day, the time savings on the entire cycle is one hour per day.

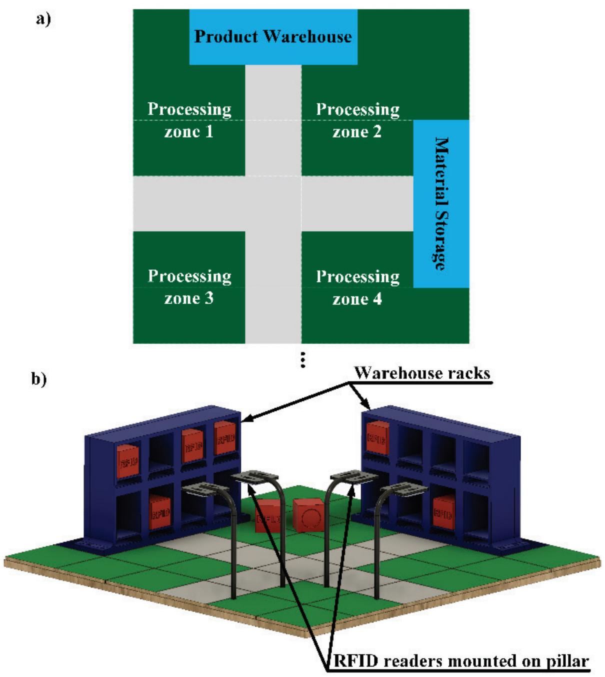

Figure 2 Conceptual representation of a production environment: (a) layout of the manufacturing eniviroment, (b) visualization of the measurement environment

3.3 Prepared Measurement Environment

In the test environment thirty-six identical fields have been located, with an RFID reader based on the PN532 controller implemented under each of them. The array of these readers can be expanded with additional modules placed on poles. The placement of these readers in the described locations would not directly affect the efficiency of the system for tracking objects in the environment. However, the placement of RFID readers in the ground requires a much more invasive renovation and spatial adjustment, which involves more financial investment. Installation of readers on poles, or if possible, directly to the ceiling in a manufacturing environment provides a more cost-effective solution. The mock-up of the research environment is shown in Fig. 3. The entire environment was made of fabrics that do not interfere with the radio waves used by RFID technology. The testing environment also includes two standalone racks each equipped with separate RFID readers for real-time monitoring of inventory levels. In Fig. 3, the research environment is configured to use RFID readers placed in the base. Several of these devices have been exposed for a more transparent demonstration of the prepared mock-up.

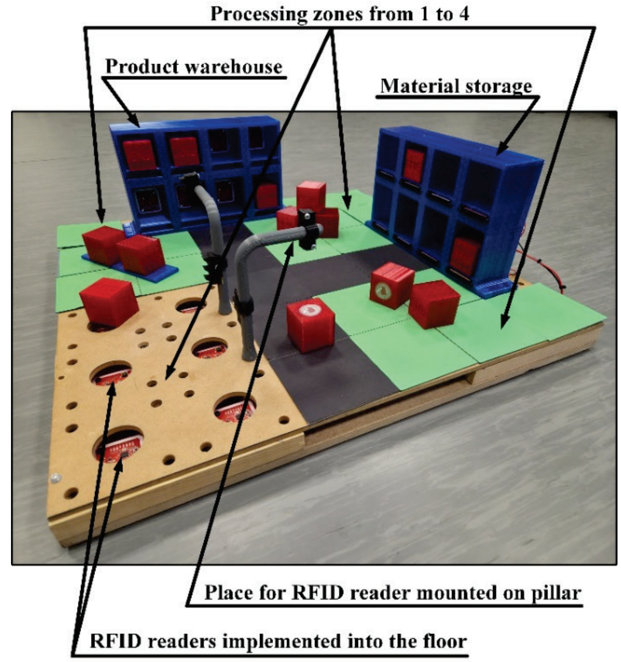

Figure 3 The mock-up of the measurement environment

All of the RFID readers of the research environment were connected to a Raspberry Pi microcomputer using pin multiplexers. The mock-up of the warehouse environment presented is a single system cluster consisting of a control unit and 36 RFID readers with the possibility of expanding with additional readers. Implementation of the solution in smart manufacturing environments requires the use of several clusters. Readers inside one cluster are run sequentially, therefore the higher the number of readers per control unit, the longer the time of one measurement cycle. However, using several clusters, it is possible to run individual zones of a warehouse or production environment independently. Such a solution increases the efficiency of product tracking by enabling several clusters of the system to run the measurement cycle in parallel. Moreover, this type of system is more resilient to setbacks, the breakage of one reader locks up the tracking system in one cluster instead of the entire environment.

3.4 Methodology

In order to make the measurements available, it was necessary to make several assumptions. One such assumption was the time it takes for a vehicle to cross an intersection without the impact of external factors. Based on this assumption, it was possible to calculate the remaining time data in the case of the sequential algorithm. With the knowledge of the time of physical crossing of the intersection and the time of individual traffic cycles in the environment using the sequential algorithm, the average results of crossing and waiting times for such an environment were calculated. In the case of an environment using an RFID-based algorithm, RFID transponders were physically placed on a prepared mock-up of the measurement environment and the algorithm's response to such data was being tested. Similar to the environment based on the sequential algorithm, the crossing time was also equal to the assumed one. The only difference was the time intervals at which each traffic cycle controlled by the corresponding algorithm was launched. This approach makes it convenient to compare the performance of the algorithms themselves uninfluenced by random factors such as different crossing times or driver reaction times.

4 ANALYSIS OF RESULTS AND DISCUSSION

Research conducted on a system for tracking asset flow in warehousing and manufacturing environments has shown that it is possible to accurately track objects. The use of such a system in warehouses and factories improves operational efficiency and significantly speeds up the flow of materials within these environments.

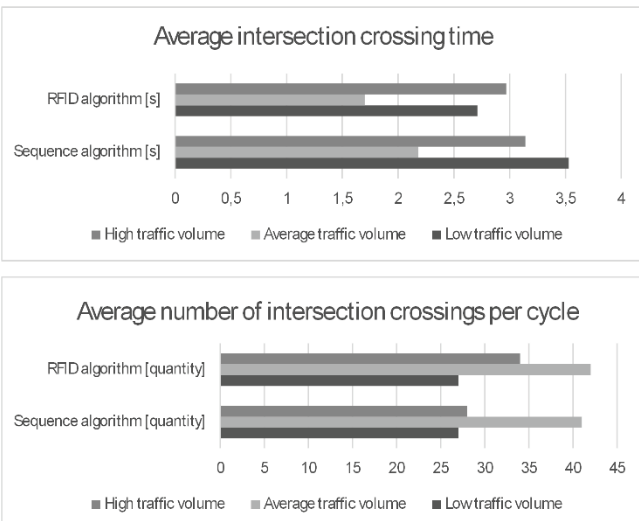

Figure 4 Charts showing the results of conducted measurements

Fig. 4 provides graphs summarizing the realized tests. The first graph shows the average crossing time at the intersection. Two control algorithms have been compared on the chart - one is a traditional sequential algorithm that allows simultaneous crossings by transport trucks from a single aisle. The other is an algorithm that uses RFID techniques to control crossing the intersection based on current demand. The traditional sequential algorithm is based on fixed time intervals assigned to each phase of intersection crossings. This algorithm is particularly inefficient during imbalanced traffic. When the flow of products is primarily through a single avenue, while traffic from another is intermittent, this algorithm will cause time delays. In these situations, the RFID-based algorithm enables dynamic control of material flow, which improves operational efficiency. The deployment of RFID readers throughout the manufacturing environment has made it possible to anticipate demand and dynamically control the flow of traffic through the intersection, thereby reducing average waiting times. With low traffic volumes, the average wait time when using the sequential algorithm was 3.53 s. This is almost a second longer than the average crossing time of 2.71 s when using the RFID-based algorithm. With increased traffic, the difference between the algorithms decreases, however, constantly using the algorithm based on RFID reader data is more efficient. The second graph shows how many average intersection crossings occur during one cycle.

The measurements showed that regardless of traffic volume, the use of the sequential algorithm was never more efficient than the use of the RFID-based algorithm.

5 CONCLUSIONS

RFID technology enables automatic identification and tracking of materials and products in real time, eliminating human errors and improving data accuracy. Thanks to integration with ERP, MES and IoT systems, it allows for intelligent management of production processes and automation of internal logistics. RFID implementation allows for dynamic adjustment of production lines in modern factories, which increases flexibility and enables rapid changes in the production and warehouse environment. Ensuring full automation and digitization of factories and warehouses involves high costs. Moreover, such implementation in an existing environment while maintaining continuity of production processes is a serious challenge. Taking into account the limitations, especially of SMEs, a solution was proposed that is scalable in its concept and can be integrated with the existing infrastructure.

The tests carried out confirm the effectiveness of the system both when installing part of the infrastructure under the floor, as well as on columns or ceiling. Additionally, the system can be expanded based on clusters, which will allow for gradual automation of existing production and warehouse spaces.

The analysis results showed that the RFID-based traffic control algorithm effectively shortens the average waiting time to pass through the intersection compared to the traditional sequential algorithm. At low traffic intensity, this difference was almost a second in favor of the RFID algorithm. With increasing traffic intensity, this advantage decreases, but the RFID algorithm remains more efficient in every situation. In addition, the number of passes per cycle was higher when using the RFID algorithm, which confirms its effectiveness. Therefore, the implementation of RFID technology in traffic control allows for the optimization of the throughput of traffic path intersections and a reduction of waiting time.

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