Sensor-Based Target Positioning Technologies in Industrial Automation

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Abstract. This thesis examines the critical role of sensor-based target positioning technologies in industrial automation within the context of Industry 4.0, highlighting their importance for operational efficiency and adaptability. Emphasizing the significance of sensors in automation, the study explores the principles, capabilities, and constraints of RFID, LiDAR, and WSN technologies, each pivotal for accurate target localization. It presents a comparative analysis of these technologies, focusing on their applications across various industrial scenarios, such as production lines, warehousing, and logistics, and evaluates their effectiveness through a series of experiments. The experimental analysis reveals RFID's precision improvement within 10 centimeters and LiDAR's enhanced accuracy with light information integration. It also shows that WSN's precision is contingent on noise levels, with the distance-corrected iterative localization algorithm significantly reducing localization error. The study concludes that while advancements have been made, future research should address the limitations observed in harsh industrial environments, with an emphasis on machine learning and AI integration for data processing to navigate environmental challenges.

Keywords: Sensor localization; industrial automation; target positioning.

1. Introduction

1.1. Background and motivation

Sensors play a pivotal role in the realm of industrial automation. With the advent of the Industry 4.0 era, automated systems have become increasingly reliant on sensors of high precision and efficiency to carry out complex monitoring tasks. In a broad spectrum of applications, ranging from ensuring precise positioning of workpieces on conveyor belts to enabling logistics robots within warehouses to accurately locate themselves, the sensor-based localization is essential. Sensors offer precise and dependable positioning data within these scenarios, thereby guaranteeing that automated systems function effectively even in intricate settings. Technologies such as infrared, radar, and ultrasonic sensors provide critical location data for targets, data that is indispensable for the navigation and positioning assistance of automated machinery.

1.2. Research Objectives

The goal of this study is to survey and contrast the various sensor-based target localization technologies within the industrial automation sector. We will delve into the fundamental principles, strengths, and limitations of diverse sensor technologies, as well as their applications in industrial automation. By analyzing the performance and application outcomes of various sensor positioning technologies, we aim to provide a valuable reference for the selection and implementation of sensor localization techniques in the field of industrial automation.

1.3. Outline of the Thesis Structure

The document is structured into six main sections. The second section discusses the significance of sensors in industrial automation and associated research on target localization. The third section presents and compares sensor positioning technologies that may be utilized in industrial automation. The fourth section examines case studies of these technologies in real-world industrial automation applications, including automation of production lines and warehousing and logistics. The fifth

section evaluates the performance and effectiveness of different sensor positioning technologies through experimental data. Finally, the sixth section summarizes the principal findings of the paper and discusses future research directions and potential challenges in the application of sensors in industrial automation.

2. Research Background

2.1. Significance of Localizing Targets Using Sensors in Automated Industrial Settings

In the realm of automated Industry 4.0, sensors serve as a pivotal element due to their proficiency in acquiring environmental data for situation analysis and aiding the decision-making processes of automated systems, thereby markedly improving the system's adaptiveness to environmental fluctuations [1]. The functionality of pinpointing targets via sensors stands as a critical aspect in automation realms. Enhanced precision in locating targets bolsters the industrial production's precision and operational efficiency by meticulously pinpointing and monitoring the placement of objects, machinery, and personnel. For instance, precision in target positioning on automated assembly lines assures that robotic mechanisms can accurately manipulate workpieces, augmenting productivity. Moreover, in the domain of logistics and inventory control, the instantaneous information on target positioning enables businesses to optimize resource allocation, curtail idle times and transit durations, hence elevating the efficiency of the logistics and warehousing frameworks. Techniques for locating sensor targets empower automated systems to detect environmental alterations in real-time and to recalibrate their actions and strategic decisions accordingly [1]. This level of responsiveness and versatility is integral in managing the complexities and dynamic nature of industrial contexts, particularly where swift adaptation and responsiveness are mandated.

2.2. Evolution in Target Localization Studies

Research in the field of sensor target positioning encompasses a plethora of foundational techniques and technologies. These methods not only furnish rudimentary positioning capabilities but also refine target localization precision and efficiency via a myriad of enhancement algorithms and data processing strategies. This segment will outline several fundamental positioning strategies and their respective technological applications, with a brief overview of their implementation and performance in industrial automation contexts.

Techniques for Measuring Distances: Technologies encompassing radar, ultrasonics, and laser systems facilitate distance estimations between targets and sensors, furnishing automated apparatus with precise locational data essential for flawless functionality amidst intricate settings.

Triangulation and Multilateration Techniques: These are quintessential sensor positioning strategies that deduce the position of a target by gauging its distance or signal latency relative to at least three sensors situated at predefined coordinates. Their utilization is prevalent in automated industry operations, such as confirming exact workpiece placement on conveyor belts or fostering effective merchandise tracking and oversight in storage and distribution operations.

Advent of Wireless Positioning Technologies: In the sphere of industrial sensor target positioning, prevalent wireless technologies include Distance-Sensor-Based Wireless Sensor Networks and Radio Frequency Identification systems [2]. RFID is particularly effective in recognizing tagged items, while WSNs are instrumental in pinpointing and perceiving items within challenging environments. When synergized, they offer superior target positioning capabilities [2]. RFID's consistency in signal detection complements WSN's limitations, while WSN's advancements enable broader RFID operational ranges and heightened precision [2].

Localization via Signal Intensity and Temporal Discrepancies: Utilizing the intensity of signals and differences in signal transit times allows for position determinations within existing wireless infrastructural setups, without necessitating supplementary hardware [3].

2.3. Advances in Sensor Data Integration and Algorithmic Processing

Localization technologies typically involve an amalgamation of several sensors to heighten measurement accuracy. Integrating data from multiple sensors is pivotal, facilitating data enhancement, precision in positioning, improved identification, and robustness against noise interference [4]. Data fusion of sensors entails an approach that merges diverse sensor data and uniformly processes it to diminish noise impact and bolster the accuracy and completeness of sensor data. Notable algorithms in sensor fusion generally include Bayesian networks, Kalman filters, and inverse variance weighting approaches, Dempster–Shafer theoretical analysis and so on. Kalman filters amalgamate predicted and actual data optimally, given a physical model, for a refined synthesis of sensor signals and noise filtration. Algorithms like Bayesian networks and weighted averages rely on statistical methods and information theory for data integration. Besides, there are also machine learning-based adaptive sensor algorithms [5]. Sensor fusion encompasses a broad spectrum of algorithms, each with inherent constraints, necessitating careful selection based on the specific environmental conditions [6].

3. Sensor Positioning Technologies in Industrial Automation

3.1. RFID

Radio-Frequency Identification (RFID) functions by emitting signals at a specific frequency from sensors, with the reader device capturing the emitted signals. The positioning is then determined by assessing the signal strength. Signal searching strategies vary depending on the number of readers, from localizing nearby areas based on communication position, angle positioning of the signal emitter based on two points, to more precise location estimations based on triangulation from three points [7].

3.2. WSN

Wireless Sensor Network (WSN) technology utilizes wireless communication and embedded sensor technology to deploy sensors in specific environments. These sensors gather surrounding data, process it, and send it to a central point [8]. For target localization, distance-sensing devices such as radar and infrared sensors are used to construct a network that facilitates precise distance measurements.

3.3. LiDAR

Light Detection and Ranging (LiDAR) technology maps the distance between objects and the sensor by emitting laser pulses and detecting the reflections. By measuring distances at numerous points, LiDAR can construct three-dimensional maps to accurately represent and locate the spatial structure of objects [9]. In industrial automation, LiDAR is applied to assess environmental conditions, offering exact positional information that aids in precise decision-making and judgment by the systems.

4. Applications in Industrial Automation

4.1. Automation on Production Lines

In automated production lines where real-time human monitoring and control are minimal, the machine's own target detection capabilities are essential for smooth operation and for providing early warning and correction of errors. Machines must confirm the correct positioning of workpieces and make timely adjustments upon detecting any discrepancies.

4.2. Warehousing and Logistics Automation

Real-time target positioning technology in warehousing and logistics enables more efficient resource scheduling, reducing wait times and transit periods. Sensor technology allows for the continuous monitoring of the location and condition of goods, thus enhancing the overall efficiency of storage and logistics systems.

4.3. Intelligent Drone Patrols

Automated patrol systems in factories require robots to be cognizant of their surroundings and their own location. To effectively navigate complex industrial environments and enhance adaptability, mobile robots are equipped with target localization capabilities. This knowledge helps them understand their position within the industrial setting and complete tasks successfully.

4.4. Equipment Monitoring

Continuous operation of the production line and minimizing downtime are crucial in industrial automation settings. Target localization technologies can monitor and pinpoint the status and location of equipment, allowing for rapid response to issues. For instance, real-time monitoring of critical equipment positions enables quick problem identification and reduces the time for fault diagnosis and repair.

4.5. Safety Monitoring

Safety surveillance is a vital aspect of industrial automation. Sensor positioning technology can monitor the factory's safety status in real-time, such as detecting unauthorized personnel entry into hazardous zones, ensuring a safe working environment.

5. Experiments

5.1. RFID

Yang and Wu's research indicated that their refined system configuration yielded superior results in accurately and precisely locating passive RFID tags compared to standard localization algorithms [10]. Their testing setup was constructed indoors, where passive RFID tags were strategically positioned at specific, predetermined spots arranged in a grid-like formation, providing a comprehensive distribution pattern [10]. The RFID reader was modified for mobility by equipping each corner with a compact wheel, facilitating its movement [10]. It was presumed that the reader would follow a straightforward, linear path during the operation [10].

In Figure 1, all verified location accuracies are within 10 centimeters [10]. Two movement trajectories, along the X and Y axes, were tested separately. The precision was measured by the Mean Absolute Error of the positioning accuracy [10].

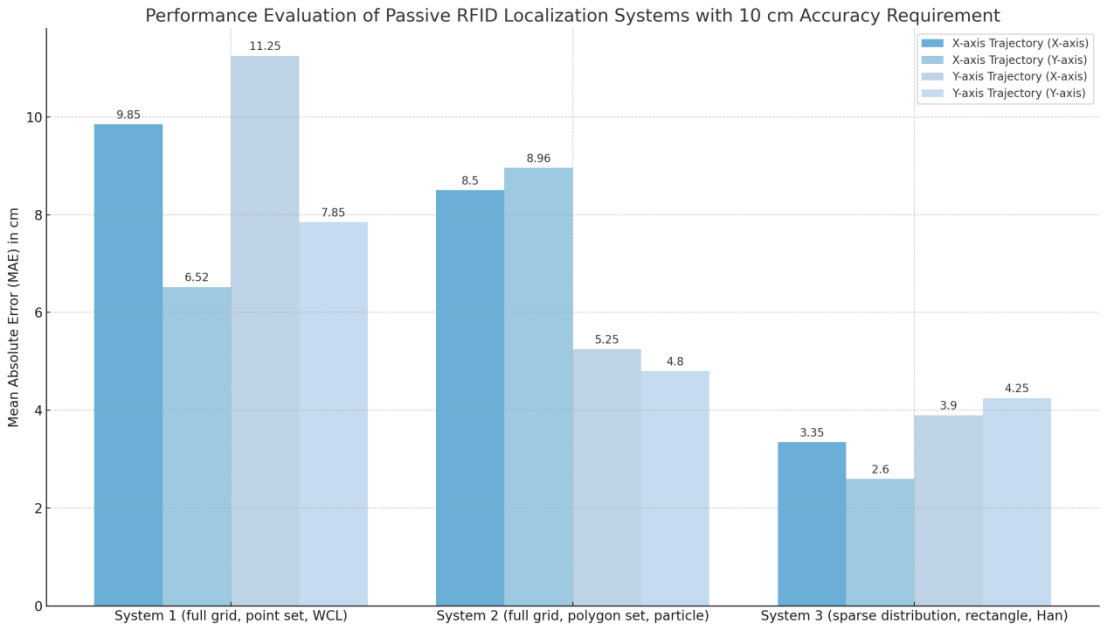


Fig 1. Position Measurements of Different RFID-based Methods.

However, the accuracy of RFID can be affected by the RFID hardware equipment. For example, the high precision of PRLS requires a high-density distribution of tags within a relatively short distance, but this high-density distribution reduces the Signal-to-Ratio Error (SRE), increasing RFID interference issues [10]. As the number of button tags increased (5, 10, 15, 20), the operational success rate dropped from 0.6 to 0.3 [10]. This indicates that as the number of tags increases, the tag recognition success rate of the RFID system decreases, and the orientation and positioning of the tags also have certain impacts on the measurement precision [10].

In summary, the optimization of data filters and positioning algorithms can improve the ability to determine locations accurately, keeping the precision of RFID within five centimeters. However, in practical use, they are subject to the physical limitations of the tags.

5.2. LiDAR

Chen, Liu, and others designed and tested a LiDAR-assisted multi-sensor indoor positioning system that integrates LiDAR sensors, odometers, and light sensors, using a pattern matching algorithm of LiDAR point clouds - Iterative Closest Point (ICP) [11]. In the experiments, heading and positional changes derived from ICP, along with measurements computed by light sensors, were ultimately fused through an Extended Kalman Filter (EKF) [11].

The system was deployed on a low-end home cleaning robot equipped with an IBEO LUX laser scanner [11]. The system was used to collect raw data along indoor corridors. During the tests, the robot traveled down the corridor at a speed of 25 centimeters per second [11]. Light intensity information was collected every second and post-processed in Matlab [11].

Data results as shown in Figure 2, when light information is introduced as a signal, the accuracy of indoor positioning can be significantly improved by the fingerprint matching method [11]. With the compensation of light information, the accuracy of the ICP algorithm was significantly enhanced, whether the light source was turned on or off. In this case, the error of target positioning was reduced to about one meter, a quarter of that without environmental variable inputs.

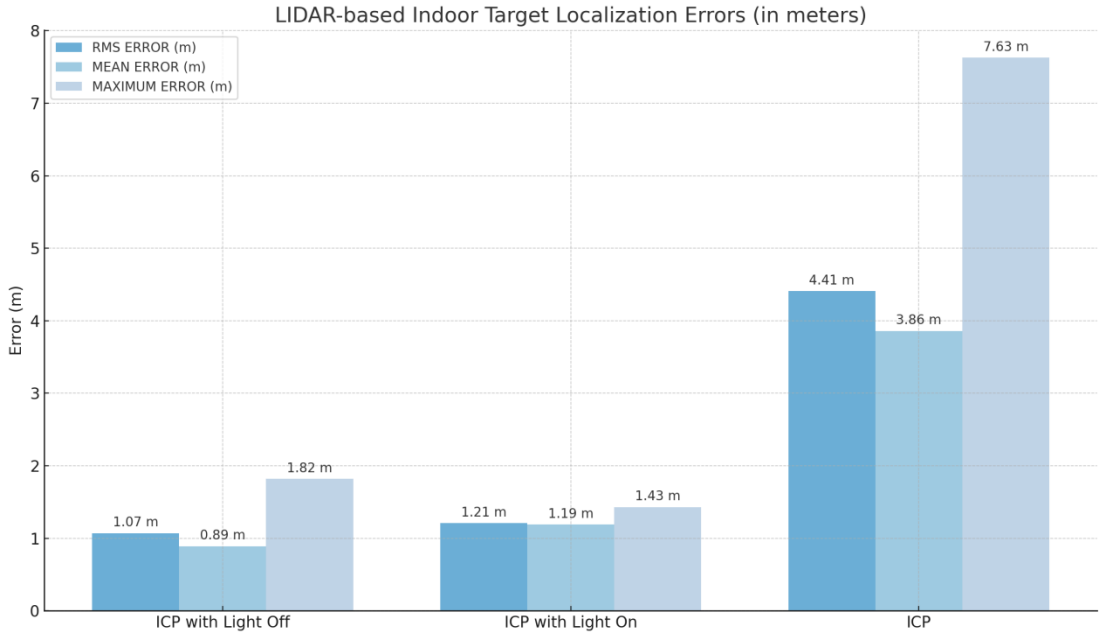


Fig 2. LiDAR Target Positioning.

It is evident that algorithms in LiDAR greatly improve the measurement precision and need to be adjusted accordingly in different lighting environments. After compensation, LiDAR can work continuously in the corresponding environment with a lower error rate.

5.3. WSN

Chen et al. introduced an innovative iterative positioning technique that refines node location by continuously updating the bias coefficient of distance, which is built upon a logarithmic distance distribution model derived from the Received Signal Strength Indicator (RSSI) measurements [12]. The testing zone was arranged as a square of 40 meters on each side, with anchor nodes placed at every corner, the midpoint of each edge, and the square's center [12]. Within this space, 50 nodes designated as targets were randomly distributed, and their positions were determined in sequence [12]. During the testing phase, they introduced a noise impact factor, denoted as FN, and assessed the localization error using three distinct approaches: the distance-corrected iterative localization algorithm, the centroid localization method, and the weighted centroid localization approach [12].

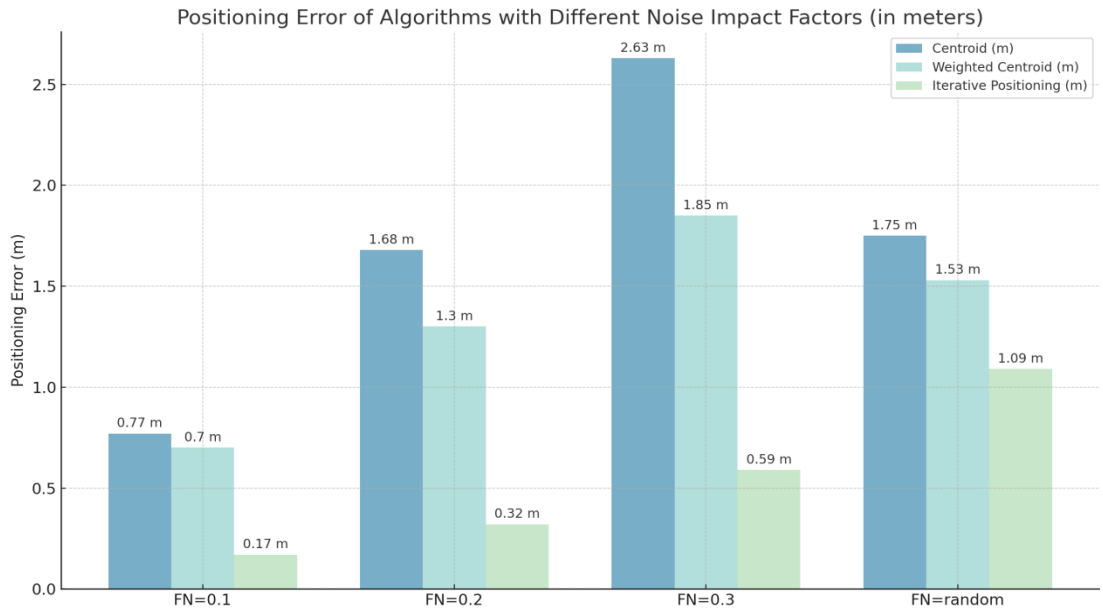


Fig 3. WSN Target Positioning.

Experimental results as shown in Figure 3. The results indicate that the distance-corrected iterative node localization algorithm can significantly lower the localization error of nodes in wireless sensor networks, achieving more precise node positions. However, similarly, the target positioning based on WSN is relatively sensitive to noise; the error with a noise impact of 0.1 is less than a third of that with 0.3. Therefore, it is necessary to deploy corresponding filters for different environments or perform positioning in a quieter environment.

6. Conclusion

6.1. Summary of Research Findings

This paper provides a detailed examination of sensor-based target positioning technologies in industrial automation, focusing primarily on the applications of RFID, LiDAR, and WSN systems. Studies indicate that significant improvements in positioning accuracy and system efficiency can be achieved through the optimization of positioning algorithms and data fusion techniques. However, each system has its limitations and is best suited to particular environments.

RFID systems are constrained by factors such as tag placement, orientation, and density, necessitating a balance between accuracy and efficiency. Since they require the deployment of corresponding readers, they are best used for fixed-position targeting scenarios.

LiDAR systems are greatly affected by ambient light, yet with algorithmic optimization and the integration of environmental light variables, there is a notable increase in positioning accuracy. They are best employed in environments with minimal light variation and where measurements can be easily taken.

WSN systems perform exceptionally in noise-free environments but can experience significant declines in measurement accuracy with increasing noise levels. They require the use of filters on sensors or operation in relatively quiet settings.

6.2. Future Outlook

Future research should focus on further enhancing the robustness of sensor systems, particularly in the variable conditions of industrial environments. Combining various systems may serve as an approach to optimize target positioning. Moreover, the application of machine learning and artificial intelligence could potentially lead to breakthroughs in data processing and environmental perception.

6.3. Potential Challenges in Sensor

Applications for Industrial Automation Despite the maturation of sensor technologies, environmental factors such as interference and noise, along with technological constraints like signal attenuation and hardware limitations, remain significant challenges to overcome.

6.4. Final Thoughts

Fundamentally, technology for pinpointing the location of targets is crucial for the advancement of industrial automation. With ongoing advancements, it stands to reason that such systems will gain enhanced precision and sophistication, playing a pivotal role in the progression towards fully automated and smart manufacturing within the industrial sector.

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