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A 3D Localization System for Complex Indoor RFID Tag Environments

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Abstract
Radio Frequency Identification (RFID) is an information exchange technology that leverages radio wave communication. The RFID system facilitates automatic identification and tracking of individuals and products by comprising two components- reader and tag. It also presents a viable solution for indoor localisation. In this study, we propose a novel, low-cost, range-free localization scheme tailored for three-dimensional (3D) positioning within high-complexity indoor RFID environments. The scheme employs a network of RFID tags with known locations as reference points to estimate the 3D coordinates of a target object enclosed within a hexahedral space and tagged with an RFID. Additionally, we assess the localization error to ensure robust performance. Simulation results demonstrate that our algorithm achieves notable accuracy, showcasing its effectiveness in addressing the challenges of 3D localization. This study contributes a scalable and cost-efficient approach to RFID-based localization, paving the way for advancements in smart indoor environments.

Keywords: RFID, localization, indoor communications.

I. Introduction

Radio Frequency Identification (RFID) has emerged as a promising object identification and positioning in various applications, including mobile robotics and smart environments. Existing methods, such as the Portable RFID Localization Approach for Mobile Robots [1], the RFID 3D-LANDMARC Algorithm optimized with quantum particle swarm techniques [2], and E3DinSAR-based synthetic aperture approaches [3], demonstrate advancements in positioning accuracy and scalability. Optimization strategies, such as neural network-based reference tag

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location algorithms [4] and frequency-stepped continuous-wave techniques [5], have further improved performance.

However, many existing solutions face challenges in 3D localization accuracy, deployment complexity, and cost-efficiency, particularly in high-density indoor environments. To address these limitations, this study proposes a robust and scalable RFID-based 3D localization method for high-complexity environments. Using a network of reference tags and strategically placed readers, our approach achieves high positioning accuracy within hexahedral spaces. Simulation results validate its effectiveness, with the potential for enhanced performance through optimized reader configurations. The remainder of this article is organized as follows. Section 2 presents a Literature Review. In Section 3, we describe our approach and introduce our algorithm. The simulation method and results are discussed in Section 4 Finally, Section 5 concludes the paper.

II. . Literature Review

RFID-based localization has been extensively studied, with significant progress made in both two-dimensional (2D) and three-dimensional (3D) positioning methods. This section reviews the key contributions and limitations of recent advancements in the field.

Xie et al. [1] proposed a portable RFID localization approach tailored for mobile robots. While effective for dynamic environments, the method primarily focuses on 2D localization and lacks scalability to 3D applications. Similarly, Wu et al. [2] introduced the 3D-LANDMARC algorithm enhanced by quantum particle swarm optimization, which improved localization accuracy but demonstrated high computational complexity, limiting its practical deployment in real-time scenarios.

Liang et al. [3] developed E3DinSAR, a 3D localization method leveraging synthetic aperture techniques, achieving notable accuracy for RFID-tagged objects. However, this approach requires complex hardware configurations and is less suitable for low-cost deployments. Wang et al. [4] addressed tag reference optimization using backpropagation neural networks, which enhanced the precision of 2D localization but exhibited reduced performance in 3D environments with high tag density. Scherhäufl et al. [5] explored passive UHF RFID tags with a frequency-stepped continuous-wave method, which improved localization in controlled conditions but struggled with multipath effects and interference in complex indoor spaces.

While these studies have made strides in advancing RFID-based localization, challenges such as scalability to 3D positioning, cost-efficiency, and robustness in high-density environments remain. This study builds upon these findings, addressing the gaps with a novel, low-cost 3D localization algorithm designed for hexahedral spaces, demonstrating high accuracy and adaptability in complex indoor environments.

III. 3-D Localization scheme

This localization method estimates the location of an object in a hexahedron, regarding reference to a predetermined coordinates system by using RFID tags and readers. In this section, present the design of the system. Design an efficient algorithm for 3D `sensitive to environment variations. Furthermore, they neither require any expensive reader nor any tedious landmark deployment and maintenance.

a. System Deployment

To cover the whole space, as shown in Fig. 1 number of readers with known coordinates are placed on the ceiling of a room at regular intervals *S*. The positions of deployed readers are selected carefully so that they together can cover the entire region when the maximum separated between readers is by $\sqrt{2}R$ according to[2].

The length, width, and height of the room are *L*, *W*, and *H*, respectively. Spreading the largest number of readers may increase the precision, while it may lead to a higher cost and longer computing time. Therefore, in case that approach needs the readers capable of multiple transmission power levels, here each RFID reader is supposed to have Φ_k transmission power levels, and the transmission power levels are calibrated so that there is a linearly increasing reply range with the increase of power level. The relationship between the beacon transmission ranges and the maximum transmission range is given by:

$$R_{\Phi_k} = \sqrt{\frac{\Phi_k}{\Phi_m}}\,\mathrm{R} \qquad (1)$$

Where Φ_m denotes the total number of different beacon power levels; Φ_k is the beacon number starting from the lowest power level (or transmission range); *R* denotes the maximum range that a reader can transmit at the corresponding maximum power level as the first step each RFID reader is assumed to have the same transmission power level. Assume signal transmission from the RFID reader forms a sphere, due to the lack of a good propagation model for RFID connectivity information used. Those readers can have a power control algorithm and a novel MAC protocol for the RFID system that embeds both collision detection and singulation mechanisms.

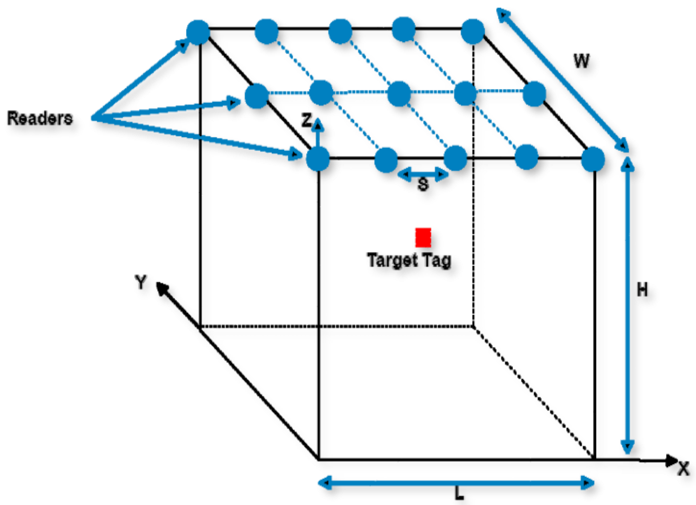


Figure 1: The schematic of our approach.

b. Proposed localization method

The proposed 3D localization method achieves position estimation using only connectivity information determining which readers detect a tag and which do not. This eliminates the need for direct distance or angle measurements, which are typically required in many existing methods, where Fig. 2 shows the flowchart of the 3-D localization algorithm. The approach involves three key steps:

1. **Constructing Hypothetical Tag Space:** Instead of relying on the deployment of physical tags, which require meticulous setup, maintenance, and increased system costs, the method simulates real tags by constructing a 3D matrix of hypothetical tag coordinates. This enables a cost-efficient alternative to densely distributed physical tags, a significant improvement over methods like 3D-LANDMARC [2] that require dense physical tag deployment for accuracy.

2. **Environmental Parameter Estimation:** By analyzing the detection status (inclusion or exclusion) of tags by readers, the method deduces spatial restrictions. For instance, if a reader Ri detects a tag T, the tag must be within the reader's range, creating an "inclusion restriction" (Fig. 3a). Conversely, if Rj cannot detect T, it infers an "exclusion restriction" (Fig. 3b). These restrictions collectively refine the spatial volume where T is located (Fig. 3c).

3. **Positioning Coordinates of Tracking Tags:** A hypothetical tag space is sampled at predetermined intervals within the refined volume. This process ensures that the localization method maintains high granularity without physical tag overhead. Algorithms based on topological constraints and spatial refinement are applied to determine the 3D coordinates of the target tag.

Comparison with Comparable Works: Compared to E3DinSAR , which relies on complex hardware and synthetic aperture techniques, the proposed method achieves similar accuracy without additional hardware costs. In contrast to optimization-based methods like [4], which rely on neural networks and require extensive training data, the proposed method simplifies computations and deployment. Unlike the frequency-stepped continuous-wave approach [5], which struggles with multipath effects, our method inherently mitigates such challenges by leveraging connectivity constraints rather than signal phase information [6].

The proposed method introduces a scalable and cost-effective solution for high-complexity environments. Simulation results demonstrate its robustness, achieving competitive accuracy in 3D localization with significantly reduced deployment and maintenance efforts.

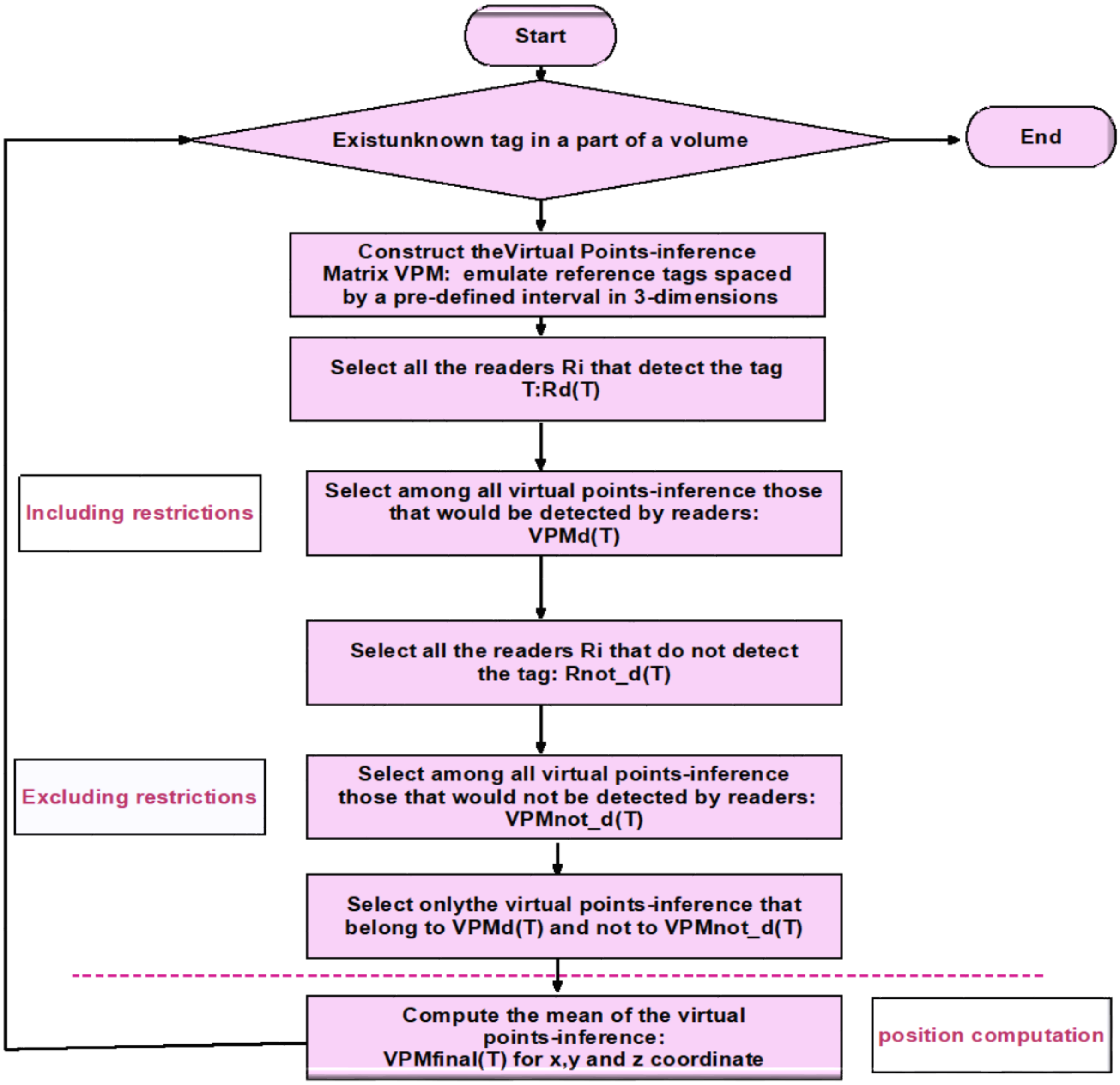


Figure 2: Flow chart of new algorithm for localization.

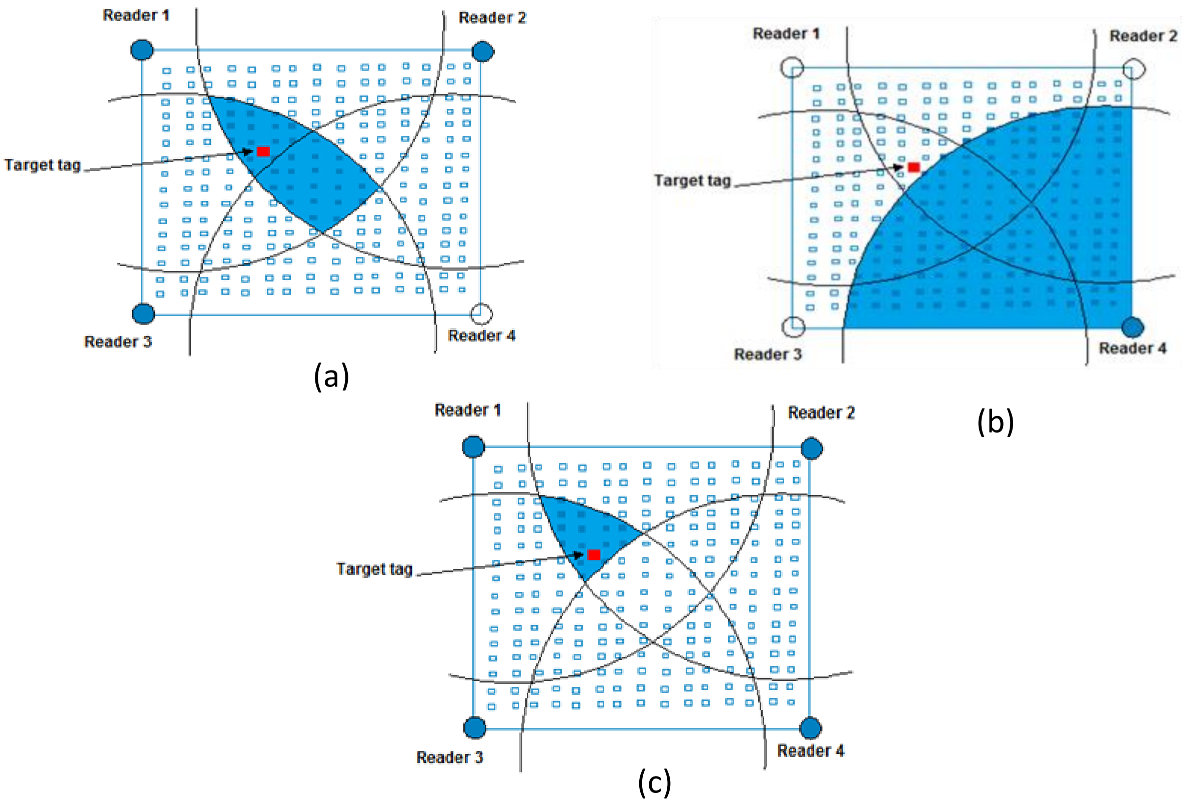


Figure 3: (a) Including restrictions defined by the readers 1, 2, 3. (b) Excluding restrictions defined by the reader 4. (c) Refine the volume defined by the topological restrictions for the four readers.

Simulate real tags by building a 3-D matrix that contains the coordinates of the hypothetical tags as we would have placed them in reality. Sample the volumes with hypothetical tags spaced with a pre-determined interval and, by this way, refine the volume that is defined by the topological restrictions. To evaluate the accuracy, define different error measurements

• The mean error in 2 dimensions:

$$\epsilon_{2D} = \sqrt{(x_{real} - x_e)^2 + (y_{real} - y_e)^2} \tag{2}$$

• The mean error regarding the estimated height:

$$\epsilon_h = \sqrt{(z_{real} - z_e)^2} \tag{3}$$

• The mean error in 3 dimensions:

$$\epsilon_{3D} = \sqrt{(x_{real} - x_e)^2 + (y_{real} - y_e)^2 + (z_{real} - z_e)^2} \tag{4}$$

IV. Simulation and Discussion:

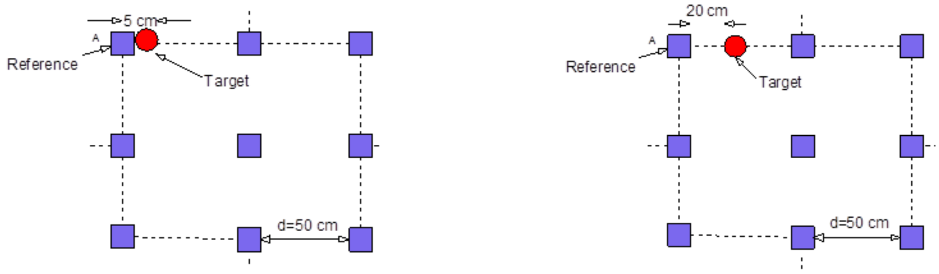
a. Environments

Carried out extensive simulations in MATLAB to evaluate the proposed 3-D positioning scheme. Since the localization can be performed in any room, office, warehouse, or container model these volumes are by a hexahedron whose dimensions are chosen to include every kind of shape:

$L = 20m,\ W = 20m,\ H = 3m,$

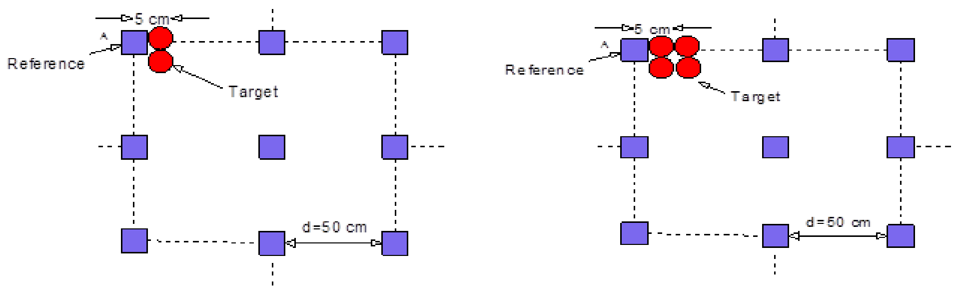
Where L, W, and H are the length, width and height, respectively. The proposed method can be applied also if readers have different read ranges. However, at first, we set the read range R for all readers: $R = 5m$

We select 100 cm x 100 cm cells from the localization system for analysis. Fig. 4 (a) and Fig. 4 (b) show the tag placements in the selected area for different reference-target spacings. A single target tag is 5 cm and 20 cm away to the right of Reference A in Case 1 and Case 2 respectively. Fig. 5(a) and Fig. 5(b) show the tag placements in the selected 100 cm x 100 cm cell when 2 targets and 4 targets are close to reference A, respectively.



(a) Case 1 (b) Case 2

Figure 4: Tag placement for different reference-target spacings.



(a) 2 targets (b) 4 targets

Figure 5: Tag placement for different numbers of targets.

b. Results

Studying the impact of several parameters of interest, such as the reference node density and the fraction of localized tags may dictate the accuracy of the positioning schemes. As shown in Fig. 6, if the inter-reader spacing is short, the volumes formed by the intersection of the read ranges are very small. Furthermore, if virtual points-inference are too much space they do not adequately delimit these volumes. This is why the fraction of localized nodes is under 92% when the inter-virtual points-inference spacing is equal or larger than 0.2 m and readers are densely deployed. Consequently, propose to perform the localization using an interval of 0.1 m particularly when the localization error is bellow 0.3 m.

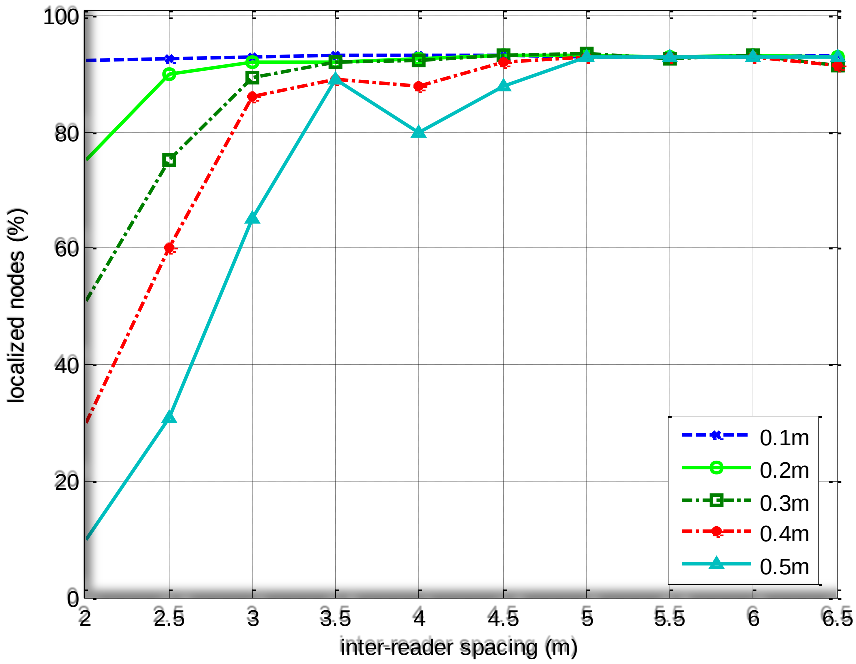


Figure 6: fraction of localized nodes for different inter-virtual tag densities

The impact of inter-reader spacing on the localization error is shown in Fig. 7. The precision in 2 dimensions goes from 0.31 m to 0.48 m when the interval is between 2 m and 3.5 m. Then, it increases suddenly because of the shapes formed by the intersections of read ranges which are very irregular when the interval is near *R*. The localization error is around 0.78 m until 5 m and increases after. Indeed, when the interval becomes larger, the volume of the presence of a tag increases too. The localization error regarding height is bound between 0.34 m and 0.77 m and could be improved if was around or superior to R. Finally, the curb for the 3-D precision has almost the same shape as the one for 2 dimensions since the error on height is bound. The 3-D localization error goes from 0.39 m to 0.66 m, then increases until 0.98 m and is stable before rising until 1.70 m.

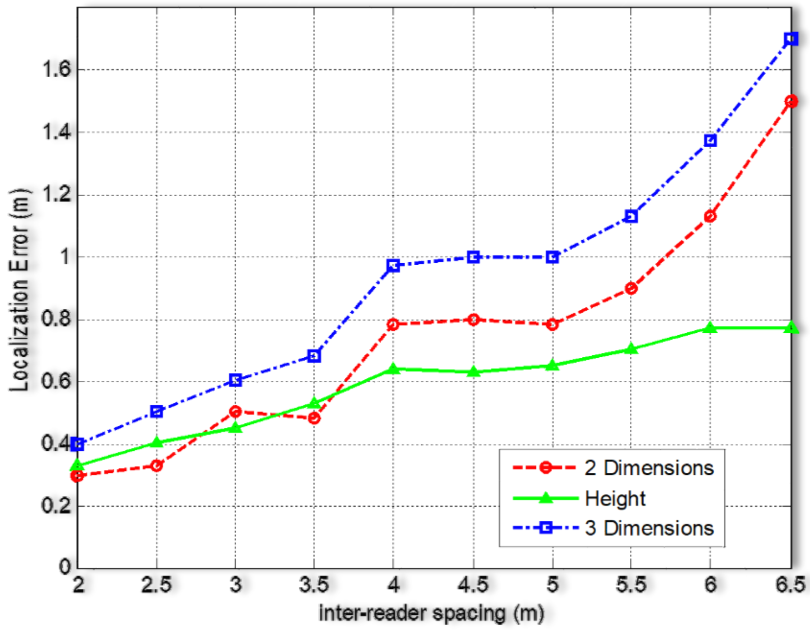


Figure 7: Localization error in relation to the inter-reader spacing.

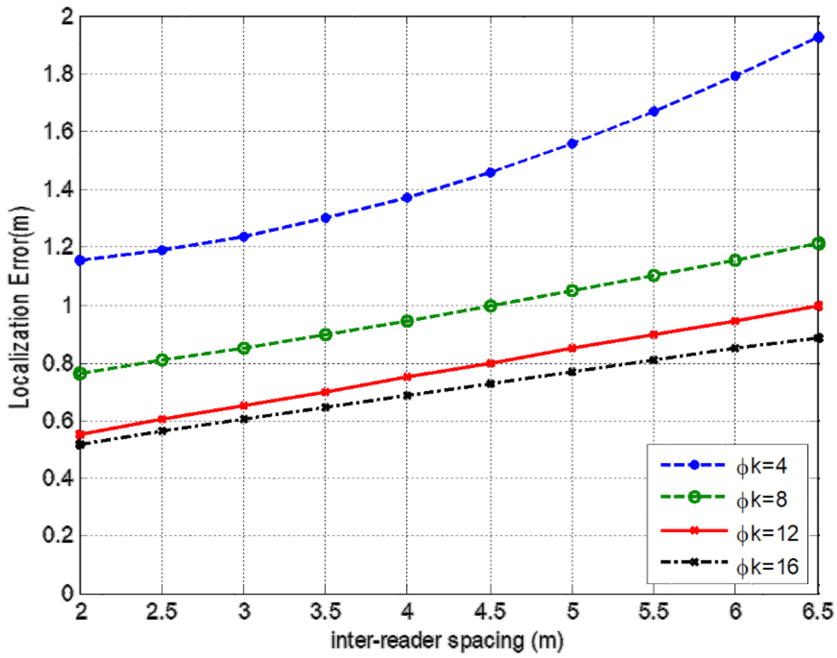


Figure 8: Impact of the number of power levels (Φ_k) on localization error in relation to inter-reader spacing.

As can be seen in Fig. 8, the Localization errors decrease with more readers deployed. Besides the number of readers, the number of power levels (Φ_k) available to each reader is usually a dominating factor in the accuracy of the scheme. The results show that more accurate coordinates are yielded with more power levels.

This is reasonable because a larger Φ_k results in a finer increase in the readers' transmission power and thus more accurate estimation of distances from the target tag to the readers. Study the impact of the 3-D localization algorithm under different numbers of target books are used as the target objects are shown in Fig. 9. The targets are placed together in 2 x 2, 3 x 3, 4 x 4 and 5 x 5 arrays for 4, 9, 16 and 25 targets, respectively. The 3-D localization reduces the estimation error to 40 cm for the single target case. The estimation error increases significantly by 50% from 1 target to 4 targets due to high RSSI variance led by severe target-target interaction. Its estimation error then increases slowly for more than 4 targets, which can be reasoned from the target-target interaction analysis.

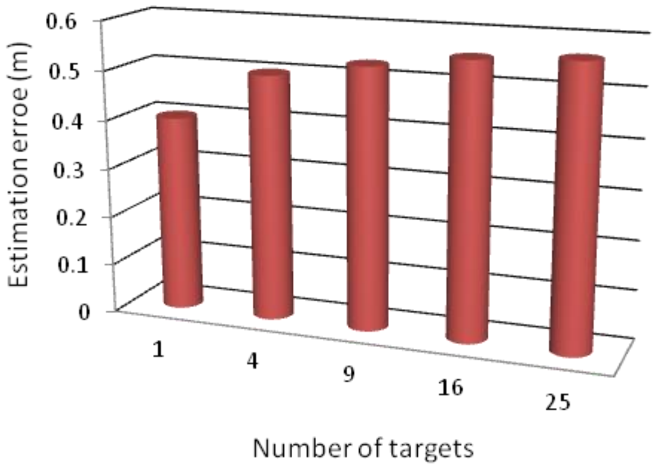


Figure 9: Estimation error under different numbers of targets.

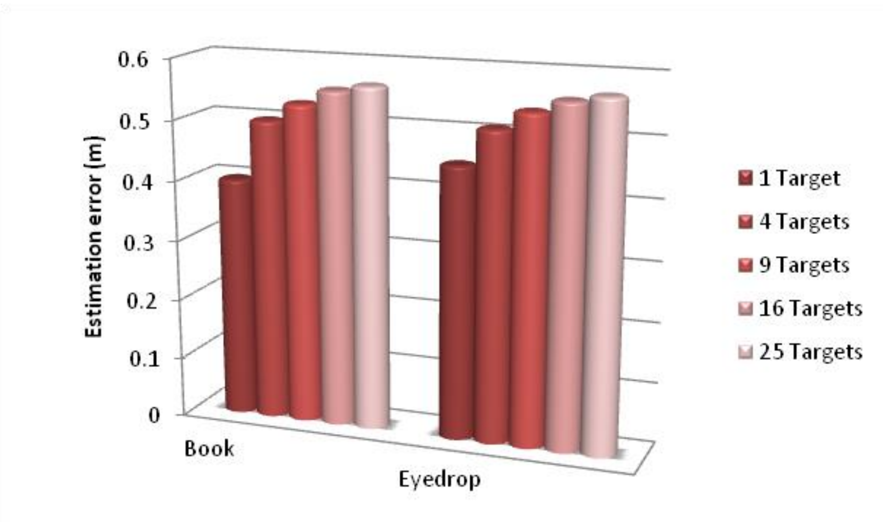


Figure 10: estimation error for objects made of different materials

Figure 10 shows the estimation error for objects made of different materials. The materials have a significant influence on the estimation error of the proposed 3-D localization error algorithm, e.g., compared with the target tags attached on Books and the target tags attached on Eyedrop backscatter weaker signals because of high attenuation from water. Therefore, for a single target, the estimation error increases from 40 cm to 45 cm when the object is changed from Book to Eyedrop. For 4 close books, the target tags have already had high RSSI variance because of sever target-target interaction. The degradation of signal strength due to materials does not have further significance on the estimation error of the proposed algorithm for close targets.

V. Conclusion and Future Work

This study presented a novel three-dimensional localization method employing a range-free approach for RFID-based positioning in high-complexity indoor environments. By utilizing virtual point inference and connectivity information, the proposed method achieves efficient and cost-effective localization without the need for dense physical tag deployments. The method demonstrates significant advantages, including scalability, robustness, and adaptability to varying reader configurations. Simulation results validate its accuracy, showing fine precision with dense reader deployments and satisfactory performance even with reduced reader density. Additionally, the analysis identified the optimal interval for virtual reference tags and highlighted the role of reader power levels in enhancing localization accuracy.

The primary novelty of this work lies in its use of virtual tag spaces and topological constraints, which eliminate the need for physical tag setups while maintaining high localization precision. Unlike existing methods that rely on complex hardware or computationally intensive algorithms, this approach offers a streamlined, low-cost solution tailored for practical deployment in real-world scenarios.

Future research will focus on enhancing the proposed method by integrating advanced positioning techniques, such as channel diversity, to improve accuracy in challenging environments with multipath interference, as discussed by Yang et al. [7]. Additionally, positioning algorithms tailored for wireless sensor networks, such as those outlined by Yu and Sharp [8], could provide insights into optimizing reader and tag configurations in RFID systems.

Another promising direction is the incorporation of mathematical to modeling approaches, such as those presented by Seco et al. [9], to refine spatial estimation and reduce computational complexity. Leveraging insights from broader surveys on wireless indoor positioning systems [10, 11] may also guide the development of hybrid localization systems that combine RFID with other technologies, such as UWB or Bluetooth.

Finally, experimental validation of the proposed method in diverse real-world settings, including dynamic environments where objects and readers may move, will be essential. Enhancing the algorithm to mitigate the impact of multipath effects and interference in cluttered environments will also be explored. Additionally, integrating machine learning techniques to dynamically optimize the placement and power levels of readers could further improve accuracy and scalability. Testing the method in warehouses, offices, and industrial environments will further demonstrate its practical applicability and effectiveness.

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نظام تحديد الموقع ثلاثي الأبعاد لبيئات علامات RFID الداخلية المعقدة

الخلاصة: تُعد تقنية تحديد الهوية بموجات الراديو (RFID) تقنية لتبادل المعلومات تعتمد على الاتصال عبر الموجات الراديوية. يتيح نظام RFID التعرف التلقائي على الأفراد والمنتجات وتعقبهم، حيث يتكون من عنصرين رئيسيين: القارئ والبطاقة (العلامة). كما يوفر حلاً فعالًا لتحديد المواقع في البيئات الداخلية. في هذه الدراسة، نقترح مخططًا جديدًا منخفض التكلفة وغير معتمد على النطاق لتحديد المواقع ثلاثية الأبعاد (3D) داخل بيئات RFID الداخلية عالية التعقيد. يعتمد هذا المخطط على شبكة من علامات RFID ذات مواقع معروفة كنقاط مرجعية لتقدير الإحداثيات الثلاثية الأبعاد لجسم مستهدف موجود داخل فضاء سداسي الأوجه ومزود بعلامة .RFID علاوة على ذلك، نقوم بتقييم خطأ تحديد الموقع لضمان أداء قوي. تُظهر نتائج المحاكاة أن خوارزميتنا تحقق دقة ملحوظة، مما يبرز فعاليتها في مواجهة تحديات تحديد المواقع ثلاثية الأبعاد. تسهم هذه الدراسة في تقديم نهج قابل للتطوير وفعال من حيث التكلفة لتحديد المواقع المستند إلىRFID ، مما يمهد الطريق لتطور البيئات الداخلية الذكية.

الكلمات المفتاحية:RFID ، تحديد المواقع، الاتصالات الداخلية.