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RFID-based Elderly Care Robot for Medication Management

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Abstract. Confronting the pressing need for precise medication management in aging societies, this study transcends the limitations of conventional visual and barcode technologies by proposing a multimodal sensing-enabled RFID-robot collaborative medication management system. To address three critical technical bottlenecks in dynamic caregiving scenarios—signal collisions in dense-tag environments, identification loss caused by complex stacking, and safety risks in human-robot collaboration—we innovatively establish a hierarchical analytical framework: the bottom layer utilizes optimized algorithms to enhance RFID multi-tag stacked reading stability, the middle layer implements YOLOv3 vision-assisted positioning for spatial mapping, and the top layer integrates a dual-protocol encryption mechanism (RAPP+LNCP) to ensure data security. This research aims to deliver a robust solution for home-based elderly medication management, reducing time costs compared to manual care. It further unveils novel pathways for the deep integration of IoT sensing technologies with healthcare domains and provides a quantifiable technical paradigm to address the "Silver Tsunami" crisis of the 21st century.

Keywords: Drug Management System, RFID, Elderly care robot, Aging society

1. Introduction

With the accelerating global aging population and the rising proportion of elderly patients with chronic diseases, the accuracy and timeliness of medication management have become a core challenge in smart elderly care systems. Currently, many elderly care robots employ computer vision or barcode technologies for medication identification; however, these methods are inherently limited by light sensitivity and high operational dependency (e.g., requiring precise alignment with labels). In recent years, radio frequency identification (RFID) technology, leveraging its non-contact reading and batch identification capabilities, has gradually been applied to medication inventory management in healthcare. Nevertheless, research on RFID in dynamic caregiving scenarios—particularly in interactive environments involving mobile robots—remains in its nascent stage. Existing literature indicates that critical gaps persist in multi-tag interference suppression, stability optimization for RFID reading in dynamic environments, and collaborative mechanisms between RFID and robotic motion control, which significantly restrict the practical utility of this technology in complex caregiving scenarios.

This study aims to explore how to enable caregiving robots to achieve real-time localization and identification of high-precision RFID medication tags, and further investigates the integration of

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RFID technology with other technologies to address identification inaccuracies in specific scenarios such as multi-drug stacking. Building on this, this paper seeks to construct a robot-sensor collaborative medication management system architecture to provide solutions for current and future medication management systems.

The research employs a literature review methodology with systematic search strategies. The search scope covers major international academic databases, including IEEE Xplore, ResearchGate, and ScienceDirect, focusing on relevant literature published between 2022 and 2025. Keywords include RFID, security protocols, authentication, elderly care, and medication identification. Literature types encompass journal articles and conference papers.

The anticipated research outcomes will: (1) provide a novel medication identification paradigm for smart elderly care robots and devices to reduce medication error rates; (2) advance IoT-robotics interdisciplinary technological convergence and offer new methodological references for dynamic RFID localization theory; (3) propose developmental insights for establishing sensor configuration standards in future caregiving robots. The findings may further extend to domains such as inventory management and smart warehousing, facilitating technological evolution in the "IoT + healthcare" ecosystem.

2. Core module design

2.1. Current technologies utilized in medication management systems

In terms of software, current medication management systems predominantly employ deep learning-based real-time object detection models such as YOLO. This model is primarily used for real-time object detection, object tracking, industrial inspection, and medical image processing. Taking YOLOv3 as an example, its core principle involves dividing input images into grids and detecting targets within each grid. Subsequently, multiple bounding boxes and corresponding class probabilities are predicted for each grid, followed by multi-scale feature extraction to detect objects at different hierarchical layers. Through the coordination of anchor boxes and the Non-Maximum Suppression (NMS) algorithm, the final retained bounding boxes, along with their corresponding classes and confidence scores, are obtained [1]. In this referenced study, YOLOv3 was integrated with a K210 camera module to achieve real-time recognition of ward numbers. However, this technology still relies on external systems (i.e., pharmacy departments and healthcare staff) to complete medication dispensing, with its primary role limited to drug transportation and delivery endpoint localization. In summary, there is currently a lack of software technologies capable of direct automated identification of medications themselves in the market.

In terms of hardware, existing systems enhance environmental perception through the integration of multiple sensors. For instance, the D415 depth camera provides RGB images, while the YDLIDAR X4 LiDAR generates 2D point cloud maps to enable drug shape recognition and robotic navigation route planning. Additionally, Mecanum wheels and lifting platforms are incorporated to assist robots in agile movement. The Raspberry Pi 3B's built-in WiFi module is configured to receive sensor data (e.g., from cameras) and facilitate real-time communication with external systems [2]. Furthermore, robotic arms equipped with flexible grippers effectively adapt to medications of varying shapes and sizes, whether bottled tablets or boxed drugs.

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2.2. Introduction to RFID and its current application domains

2.2.1. Fundamental principles of RFID

RFID is fundamentally a wireless communication technology. It automatically identifies target objects and retrieves data via radio frequency signals, enabling data interaction without human intervention or optical visual contact—unlike traditional optical technologies (e.g., cameras, lasers, barcodes) [3].

A typical RFID application system primarily consists of two components: a reader and an RFID tag. The reader, acting as a computer terminal, comprises a control unit, a high-frequency communication module, and an antenna, and is responsible for reading and writing data to RFID tags. The RFID tag, functioning as a passive transponder (i.e., battery-free), is composed of an integrated circuit (IC) chip and an external antenna. The RFID chip typically integrates circuits such as an RF front-end, logic control, and memory, with some designs even embedding the antenna on the same chip [4].

2.2.2. Current application scenarios and directions of RFID

Currently, this technology is widely employed for locating objects tagged with RFID labels. Passive RFID tags offer multiple advantages, such as low cost, minimal footprint, and the elimination of maintenance and battery replacement requirements. RFID tags are particularly suitable for diverse industrial scenarios where marking targets with multiple transponders is critical to ensuring optimal performance and enhanced reliability [5]. Additionally, RFID technology is integrated with real-time databases and programmable logic controllers (PLCs) to improve manufacturing automation [6].

In summary, this technology has gained extensive adoption in industrial and manufacturing sectors. Figure 1 illustrates the primary application scenarios of RFID technology. Beyond industrial applications, RFID can also be utilized for patient respiratory monitoring. For example, by integrating an embedded temperature sensor (Axzon Magnus-S3) with an RFID chip and deploying it on a face mask, users' respiratory rates can be predicted by detecting temperature variations in the air near the nasal passage. The discrepancies between temperature datasets detected via the RFID chip and flow datasets range between 4% and 12% [7].

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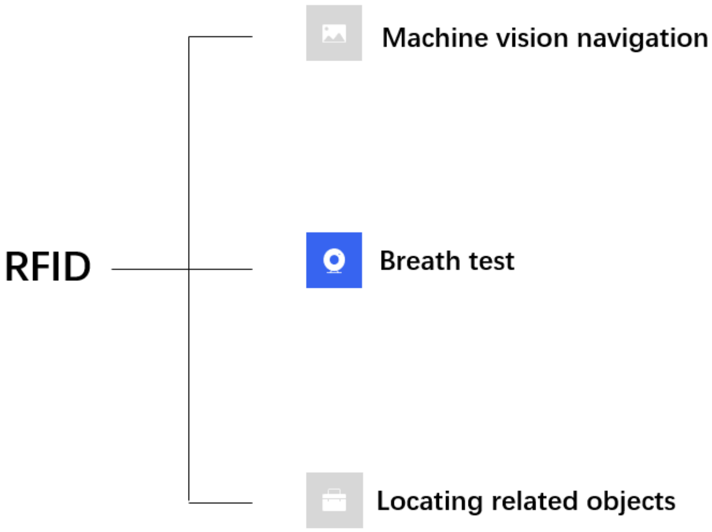

Figure 1: Existing application domains of RFID

2.2.3. Application design of RFID in medication identification for elderly care robots

Below is the flowchart (see Figure 2) summarizing the implementation of medication information verification and comparison via RFID, as well as the operational workflow of the entire system:

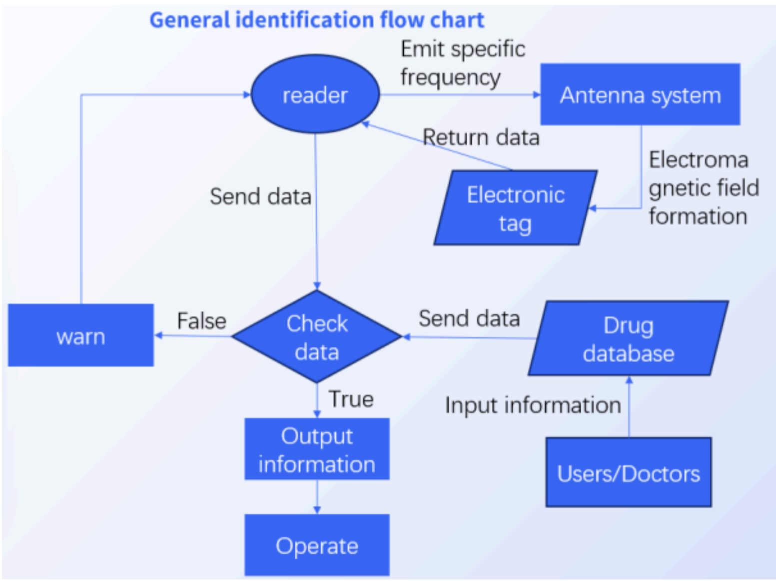

Figure 2: Process of RFID-based medication tag identification

The reader emits a radio frequency signal (e.g., 13.56 MHz) through its antenna to generate an electromagnetic field. Since the tag is passive, the chip converts energy from the electromagnetic field into electrical power to activate itself. Once activated, the tag transmits stored data (e.g., medication ID, dosage) back to the reader via its antenna. The reader antenna receives the reflected signal from the tag, which is converted into a digital signal by the RF module. A decoder extracts tag data (e.g., EPC code).

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After decoding, the reader transmits the data to the backend system for database cross-validation (e.g., checking medication expiration dates). Upon successful validation, the robot records the user's medication timing and dosage into a local database. If validation fails (e.g., triggered by prolonged non-adherence or incorrect drug retrieval), the robot issues a voice alert and sends warning messages to caregivers and the patient's family.

2.2.4. Optimization strategies for RFID in multi-tag stacking scenarios

In practical applications, signal collisions or identification errors may occur when multiple RFID tags coexist or are stacked. To address this issue, two strategies shown in Figure 3 can be adopted:

During the medication information verification process, if multiple tags and stacked medications are detected in the same area, the system combines the previously mentioned deep learning model (e.g., YOLOv3) with established QR code scanning to cross-validate discrepancies in the data. This multi-modal detection approach prevents identification errors caused by single-technology failures, thereby improving medication identification accuracy.

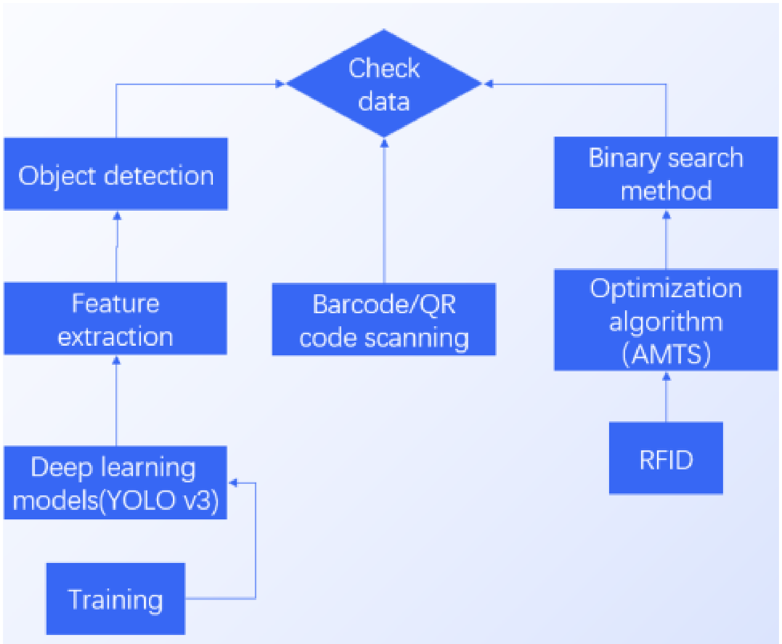

Figure 3: Strategies for optimizing RFID in stacked scenarios

In addition to integrating multiple technologies to assist RFID-based decision-making, optimizing RFID reading through algorithmic approaches is also a viable strategy. The application of the Adaptive M-ary Tree Slotted Aloha (AMTS) algorithm, based on Aloha and query tree-based algorithms, can effectively mitigate tag stacking issues. In AMTS, the reader first maps the tag set to distinct time slots using a framed slotted Aloha protocol, then employs a binary search method based on collision factors or mapping tables to resolve collided tags. Comparative experimental results from the literature demonstrate that AMTS achieves higher system throughput and superior performance (measured by average slots consumed per tag identification) compared to Dynamic Frame Slotted Aloha (DFSA), Enhanced Dynamic Frame Slotted Aloha (EDFSA), Splitting BTSA, and Dynamic Binary Search Algorithm (DBSA). As shown in Figure 4, the energy efficiency graph reveals that AMTS—particularly MT-AMTS—consistently outperforms other algorithms across tag quantities ranging from 0 to 1000 [8]. Therefore, implementing this algorithm in RFID systems not only alleviates tag collisions but also enables highly efficient tag identification.

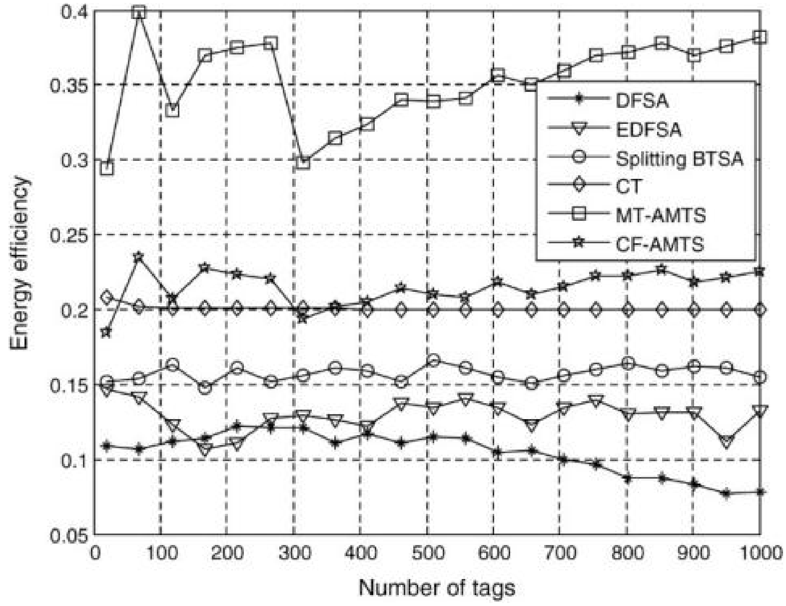

Figure 4: The changes in energy consumption of several optimization algorithms as the number of identified tags increases

3. Key technical challenges and future research directions

3.1. Environmental pollution concerns

With the recent development of the pharmaceutical industry, the variety of medications has increased significantly, while production volumes have surged due to technological advancements. Since this technology requires embedding RFID chips into medication packaging, the demand for such chips is immense. These tags often utilize PET substrates and other plastics. If discarded or improperly disposed of, these waste tags could exacerbate global plastic pollution, potentially expanding the "Seventh Continent"—a massive floating island of marine plastic debris.

Consequently, cost and environmental pollution issues cannot be overlooked. While paper-based tags may partially mitigate this problem, they are prone to failure in high-humidity environments. To address this, adopting biocompatible and fully biodegradable substrates, such as poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) polymer, for fabricating tag antennas and IC substrates could significantly alleviate environmental concerns. This approach employs thermal evaporation techniques and laser ablation of thin metal layers (500 nm) for tag manufacturing [9].

3.2. Privacy and information security concerns

Since medication data is directly stored within RFID tags, these tags are vulnerable to unauthorized scanning or leakage of users' private information. To address this, encryption technologies (e.g., the AES-256 algorithm) are combined with physical privacy switches (e.g., camera shielding mechanisms) to prevent illegal scanning and data tampering. Additionally, a permutated RFID authentication protocol, RAPP, involves three entities: tags, readers, and a backend database. Tags authenticate and update keys using pseudonyms (IDs) and three shared keys (K1, K2, K3). Protocol steps include message exchange, nonce generation, and key updates. The core innovation lies in the

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definition and application of permutation operations, which disrupt bit sequences to enhance security. RAPP requires only three lightweight operations—permutation, bitwise XOR, and left rotation—resulting in low communication overhead and meeting lightweight protocol requirements [10].

Beyond algorithmic safeguards, the NCross encryption algorithm employs bit concatenation and cyclic shifting to generate ciphertext, ensuring dynamic key security. Simultaneously, the LNCP protocol, validated using the Scyther tool and BAN logic, effectively resists replay attacks, reader impersonation attacks, tag impersonation attacks, and traceability attacks through informal formal verification methods [11].

3.3. Elderly acceptance challenges

Many elderly individuals exhibit reluctance or fear toward robots due to traditional beliefs and distrust in technology. Thus, enhancing elderly acceptance of such technologies is critical during their promotion. First, optimizing human-robot interaction design (e.g., simplified user-friendly interfaces) can significantly improve acceptance once elderly users experience tangible improvements in daily convenience [12]. Long-term trust-building further strengthens usage intentions. Second, incorporating anthropomorphic design into robots—though not altering human verbal behavior—influences non-verbal interactions, such as preferred interaction distance or response latency. The degree of anthropomorphism affects users' sense of familiarity with robotic systems, where human-like appearance encourages observers to engage with the robot, increasing its perceived welcome [13].

4. Conclusion

This study addresses the precision requirements of medication management in aging societies through a systematic exploration of RFID technology applications in elderly care robots. By integrating radio frequency identification, deep learning, and robotic motion control, a multimodal medication management system is proposed for dynamic caregiving scenarios. Passive RFID tags serve as core data carriers, combined with a YOLOv3 visual verification module to theoretically enable accurate identification in medication stacking situations. Hierarchical encryption protocols (RAPP+LNCP) and biodegradable PHBV substrates are implemented to ensure information security while mitigating environmental impacts. However, the current research faces three limitations: experimental validation remains confined to laboratory settings without realistic simulations of electromagnetic interference in nursing homes; large-scale production processes for PHBV substrates are not yet mature enough for commercial RFID tag applications; and multimodal data fusion algorithms lack empirical testing in extreme stacking scenarios (>5 layers), leaving their error reduction efficacy unverified. Future research should focus on three dimensions: technological integration of UHF RFID (860–960 MHz) with millimeter-wave radar to address deep-layer stacking through high-frequency signal penetration; material science advancements in fully biodegradable cellulose nanocrystal-based antenna materials with enhanced dielectric properties via molecular modifications; and human-robot interaction innovations incorporating affective computing modules for elderly acceptance prediction through voice intonation and micro-expression analysis. Notably, the EU's HORIZON-CL4-2024-HUMAN-01 initiative emphasizes ethical frameworks for care robots, opening interdisciplinary collaboration opportunities. This work demonstrates the feasibility of IoT-robotic architectures in smart elderly care, with potential extensions to chronic disease monitoring and emergency medication delivery scenarios.

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