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Redefining Retail Automation: A Comprehensive Survey on Intelligent Shop- ping Carts with Sensing, Connectivity, and Decision Intelligence

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ABSTRACT

The rapid growth of retail automation has led to intelligent shopping systems that streamline inventory management, product identification, billing, navigation, and cus- tomer assistance. RFID-enabled automatic billing carts improve shopping efficiency by providing real-time item detection and elim- inating checkout delays, while later systems incorporate IoT platforms, mobile applica- tions, and cloud connectivity for synchro- nized transactions and enhanced user inter- action . Advanced carts now support self- following and autonomous navigation using computer vision, radar, UWB, SLAM, and sensor fusion frameworks , and AI-driven models enable personalized recommenda- tions, inventory forecasting, and behavioral analytics. Despite these advancements, chal- lenges such as scalability, multi-user inter- ference, item-removal detection, security, and high implementation cost remain. This review analyzes 14 studies to compare sens- ing methods, billing mechanisms, communi- cation models, and automation techniques while identifying gaps related to navigation reliability, interoperability, and privacy. The study further highlights future oppor- tunities in multimodal sensing, dynamic pricing, edge-AI cart autonomy, secure self-checkout, and LLM-based customer en- gagement for next-generation autonomous smart retail environments.

***Index Terms* - Smart shopping cart, RFID, IoT, autonomous navigation, sensor fusion, AI in retail, cloud computing, edge AI, real- time billing, UWB localization, SLAM, cus- tomer behavior analytics, self-checkout au- tomation.**

INTRODUCTION

Barcode scanning, manual product selection, and queue-based invoicing are all major com- ponents of the traditional retail shopping mod- el, which frequently leads to lengthy checkout times, a greater reliance on labor, and worse consumer satisfaction. Researchers have de- veloped smart shopping systems that combine RFID-based item recognition, embedded com- putation, Internet of Things connectivity, and autonomous navigation to overcome these drawbacks and provide a productive, contact- less, and user-friendly shopping experience [2][5][6][9]. Only RFID-based automatic bill- ing was the focus of the first smart cart sys- tems; each product tag is identified as it is placed inside the trolley, enabling real-time cost calculation without the need for human interaction [2][5]. Although these systems showed notable decreases in checkout time, they lacked scalable backend management, mobility intelligence, and consumer engage- ment features.

With the rise of the Internet of Things, re- searchers extended RFID carts into network- connected smart systems capable of sending purchase data to cloud servers, enabling fea- tures such as mobile app integration, live bill- ing visibility, and online receipt generation [1][7][10]. Further advancements included weight sensors, barcode scanning modules, mobile cart interfaces, and Wi-Fi-based com- munication, enabling multifunctional cart- based retail assistance [7]. However, these sys- tems still required customer-driven navigation and lacked autonomous movement.

Incorporating technologies like computer vi- sion, radar following, UWB indoor localiza- tion, and SLAM-based mapping, recent ad- vancements have shifted toward AI-driven and sensor-fusion-enabled smart shopping carts that can autonomously traverse shelves or fol- low users [11][14]. Higher-level retail intelli- gence is now possible through the application of machine learning models for inventory forecasting, dynamic product recommenda- tion, and customer behavior prediction [12][13][14]. These contemporary solutions assist unmanned supermarket concepts by go- ing beyond checkout automation to fully au- tomate the store.

Even though there has been a lot of improve- ment, issues including multi-tag RFID colli- sion, item removal detection, localization drift, complicated indoor navigation, security flaws, and a lack of universal retail compatibility still plague current solutions [3][8][11]. Further- more, a lot of systems are made for prototype- level demonstration and don't take into account full deployment requirements like backend monitoring, multi-cart coordination, database scalability, or fraud-proof checkout.

In order to compare smart shopping cart archi- tectures, sensor technologies, communication models, billing mechanisms, navigation meth- ods, AI integration, and user interaction mod- ules, this review article looks at 14 studies that were published between 2014 and 2025. In order to establish fully autonomous, secure, and commercially successful smart retail eco- systems, it is necessary to classify the devel- opment of smart shopping systems, highlight accomplishments and constraints, and pinpoint unresolved research gaps.

A. Problem Statement

Existing solutions are still constrained by prob- lems with item misdetection, lack of item- removal validation, unreliable indoor tracking, system scalability, cost feasibility, and inade- quate data security, despite the fact that nu- merous smart shopping cart systems have been proposed using RFID, IoT, sensor fusion, au- tonomous navigation, and AI-based retail intel- ligence. The majority of works concentrate on discrete features like cloud-based cart monitor- ing [1][7][10], autonomous movement [11][14], or automatic billing [2][5][6][9], but none offer a completely integrated, secure, and commercially deployable end-to-end sys- tem.Furthermore, most systems have only been tested in controlled or prototype settings, ig- noring real-world limitations including net- work instability, multi-cart interference, priva- cy laws, and customer usability considerations. A unified and scalable smart shopping frame- work that guarantees precise product detection, safe data processing, smooth user interaction, and dependable autonomous operation in dy- namic retail contexts is thus in need of further development.

B. Related Works

From RFID-based billing carts to IoT- connected smart trolleys and finally AI-driven autonomous retail systems, research on auto- mated shopping systems has progressed through several technological phases. The pri- mary focus of early installations was RFID billing automation, which does away with the need for manual checkout counters by scan- ning each product tag within the cart and up- dating the overall cost in real time. [2][5][6][9]. Although these systems showed that self-billing was feasible, they lacked dy- namic product management, network connec- tivity, and user identity.

Later systems included cloud platforms, mo- bile applications, and the Internet of Things to improve usability. This allowed consumers to examine cart data, receive notifications, and make digital payments [1][7][10]. Smarter shop workflows were supported by these con- nected smart carts' live item tracking, wireless data synchronization, and backend inventory updates. They limited automation, though, by still requiring users to push or maneuver the cart by hand.

In order to preserve privacy and stop billing manipulation, a new research path offered se- curity-enhanced and cryptographically protect- ed smart retail systems. These architectures encrypt data between RFID carts and servers utilizing TLS-based protocols or ECC [3][14]. These technologies demonstrated how crucial secure retail IoT environments are, particularly for deployments of unmanned stores.

Recent systems use radar, UWB location, SLAM mapping, load cells, or computer vision to enable carts that track client movement or explore shelves independently [7][11][14]. These systems go beyond billing and connec- tivity to include autonomous navigation, sen-sor fusion, and robotic following. With support for self-moving carts, obstacle detection, and indoor route planning, these projects moved the emphasis from basic cart-based invoicing to complete robotic retail automation.

By incorporating personalized suggestions, demand prediction, and consumer behavior- modeling, as well as by employing collabora- tive filtering algorithms, LSTM forecasting, or reinforcement learning to enhance retail deci- sion-making and user experience, AI-enabled systems further enhanced their capabilities [12][13][14]. By combining advanced analyt- ics with shopping assistance, these intelligent carts seek to change the cart's function from that of a passive carrier to that of an active re- tail assistant.

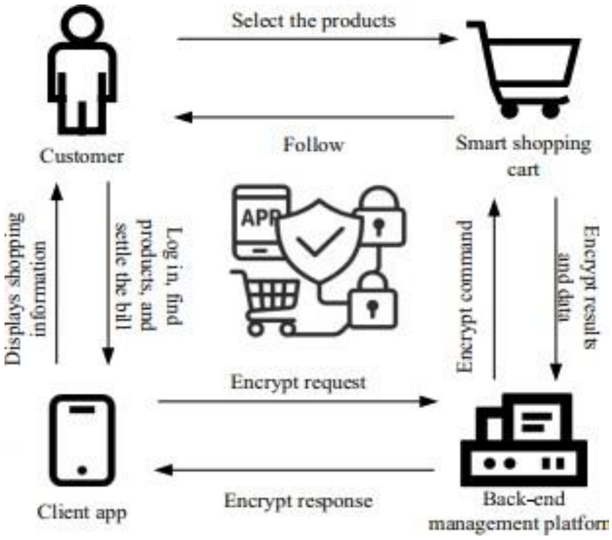

Fig. 1. Overall architecture of a full smart shopping system integrating smart cart, client app, and backend platform .

A whole smart shopping ecosystem intended for semi-automated or unmanned retail estab- lishments is depicted in Figure 1. The intelli- gent shopping cart at the center of the system is outfitted with embedded computer, commu- nication, product identification, and user- interaction modules. The smart cart handles item identification, cost calculation, and billing on its own without the assistance of conven-tional checkout counters. Depending on how it is implemented, the sensing system (RFID, barcode, or vision-based identification) recog- nizes the item as soon as the customer puts it in the cart and instantly updates the bill.

The main retail management platform, a cloud- based backend server, is in wireless communi- cation with the smart cart. Product databases, pricing guidelines, stock levels, and purchase records are all kept up to date on this server. For synchronization and analytics purposes, the server receives all cart-side transactions, including product scanning, cart status, and customer session data. Additionally, the backend manages automated bill generation, fraud detection, cart-server communication security, and authentication.

At the same time, a mobile application inter- face allows the user and the cart to communi- cate. Through the app, users may check re- wards or offers, see live billing, get product recommendations, and finish the purchase pro- cess. This completely does away with the need to wait in line and deal with a cashier. Addi- tionally, the software assists in locating digital receipts, purchase summaries, and store navi- gation routes.

Because of the architecture's full scalability, several carts connected to a single cloud plat- form can function within the same retail space. Additionally, the design makes it possible to integrate optional modules like automated in- ventory forecasting, interior navigation, AI- based recommendation systems, and customer behavior tracking. Therefore, the architecture serves as the technological basis for the next generation of unmanned smart stores, where autonomous retail technologies either replace or support human employees [14].

OBJECTIVES

This review paper's primary goal is to thor- oughly analyze the smart shopping cart sys- tems that have been created in the last ten years and categorize them according to the un- derlying technologies that underpin them, such as AI-driven decision-making, autonomous navigation, RFID-based billing, and IoT- enabled retail connectivity. This evaluation compares the design approaches, sensing tech- niques, communication models, and system intelligence levels of fourteen chosen research works in order to determine their advantages and disadvantages for practical implementa- tion. In order to provide a clear picture of the development trend in smart retail automation, another goal is to emphasize the technological evolution from early RFID-only systems to- ward multi-sensor, cloud-integrated, and AI-assisted autonomous carts.Finding the main research gaps that still exist, such as those in item-removal detection, multi-cart scalability, data security, localization accuracy, and com- mercial viability, is another objective. Based on these findings, future research directions for completely automated, safe, and user-adaptive smart shopping environments will be outlined. For academics and developers working on next-generation smart retail systems with en- hanced accuracy, usability, integration capabil- ity, and deployment readiness, this assessment ultimately seeks to provide a reference basis.

METHODOLOGY

This review follows a structured five-stage methodology to ensure a systematic, unbiased, and comprehensive analysis of existing smart shopping cart research. First, a literature search was conducted across IEEE Xplore, Spring- erLink, Elsevier ScienceDirect, and Google Scholar using keywords such as “RFID smart cart,” “automatic billing trolley,” “AI retail automation,” “IoT shopping system,” and “au- tonomous shopping cart.” A total of 48 papers were initially identified.

Second, a screening and filtering process was applied based on publication type, relevance, year (2014–2025), technical contribution, and availability of system architecture details, re- sulting in 14 final papers selected for review. Third, the selected papers were categorised into four thematic groups based on their prima- ry technological focus: RFID-based billing systems, IoT-enabled smart carts, autonomous and self-navigating carts, and AI-driven intel- ligent retail systems.

After classification, a comparative analysis was performed by examining parameters such as sensing method, communication protocol, hardware platform, intelligence level, user in- teraction model, and deployment feasibility. Finally, research gaps were identified by eval- uating unresolved challenges across all four categories, including security, item-removal detection, real-world scalability, navigation robustness, and system cost constraints.

COMPARACTIVE ANALYSIS

Smart shopping cart systems have clearly evolved from single-function RFID billing models to multi-modal, AI-enabled autono- mous carts, as evidenced by the examined works. Using passive RFID tags and microcon- troller-based displays, early systems mainly concentrate on automatic product recognition and on-cart billing, so doing away with manual checkout. However, they lack item-removal detection, theft prevention, and safe data man- agement. [2], [5], [6], [9]. By combining wire- less communication, cloud databases, and cus- tomer-linked mobile applications, IoT-based designs expand these capabilities and enable digital receipts and remote billing visibility. However, they still rely on constant internet availability and cause latency problems in real- time store environments [1], [7], and [10].

In order to achieve self-navigation and user- following behavior, autonomous cart systems use sensor fusion, radar tracking, SLAM, UWB localization, and onboard computation. This improves accessibility and physical assis- tance, but it still faces operational instability in crowded indoor layouts and dynamic store en- vironments [11], [14]. Through recommenda- tion engines, inventory forecasting, and adap- tive routing based on reinforcement learning or LSTM prediction models, AI-driven systems further improve retail intelligence; however, these solutions come with a higher hardware cost, necessitate extensive customer datasets, and raise privacy concerns [12], [13], and [14]. Security implementations are still uneven across all categories; only a small percentage of systems use secure payment channels, veri- fied product validation, or end-to-end encryp- tion [3], [14]. Similar to this, the majority of studies merely test prototypes rather than im- plementing them on a wide scale for commer- cial use, which leaves scalabili– [14]. In con- clusion, the comparative analysis demonstrates that no current system completely integrates AI-based personalization, autonomous mobili- ty, safe transaction flow, accurate product de- tection, and realistic deployment readiness into a single integrated solution.

RESEARCH GAPS IDENTIFIED IN EXISTING WORKS

Even though smart shopping systems have ad- vanced significantly, there are still a number of technical and useful gaps in the examined re- search works. Although early RFID-based bill-ing carts increased checkout speed, they were devoid of features like safe transaction han- dling, multi-tag collision avoidance, and real- time item validation [2][5][6][9]. Most RFID systems also fail to detect item removal after addition, making them vulnerable to billing errors and shoplifting — a problem still not fully addressed in later IoT-based systems [1][7].

Cloud connectivity and app-based billing were made possible by IoT-enabled carts, but their deployment in big supermarkets and underde- veloped nations is limited since they need con- stant network access and are not designed for offline or low-bandwidth retail settings [1][10]. Furthermore, the majority of these systems rely on single-sensor architectures (barcode, RFID, or weight sensor), which leads to poor accura- cy in cases where users mishandle or swap out goods without scanning.

Mobility problems are resolved by autonomous and self-navigating carts, but they also create new gaps in user tracking robustness, obstacle- dense movement, and indoor localization drift, particularly during peak retail hours [11][14]. Many of these works are only evaluated in controlled lab settings and do not take into ac- count real-world factors including wet-floor sensor failures, cart-to-cart interference, dy- namic shelf layouts, and crowds.

AI-driven designs integrate forecasting, rec- ommendation, and adaptive decision-making, but they rely heavily on large datasets and high-cost hardware, making them unsuitable for small-scale commercial deployment [12][13]. In addition, existing AI solutions do not address privacy-preserving analytics, alt- hough continuous customer tracking and pur- chase profiling may violate user data policies.

Security, scalability, and cost viability are still lacking in all four system classes. A complete end-to-end cybersecurity model for unmanned retail environments is not provided by any of the publications that propose encrypted com- munication or authentication layers [3][14]. Large-scale commercial adoption is also lim- ited because none of the studied systems offer a standardized architecture for interoperability between carts, store servers, and multi-vendor product databases.

CONCLUSION

This analysis examined fourteen studies that were published between 2014 and 2025 and covered topics such as AI-driven retail intelli- gence models, autonomous navigation sys- tems, IoT-enabled smart trolleys, and RFID- based billing carts. A fully integrated, scalable, and secure smart retail platform is not yet achieved by any of the current solutions, ac- cording to the comparative study. RFID solved checkout delays, IoT solved data synchroniza- tion, autonomous carts solved physical assis- tance, and AI solved customer-centric person- alization.

The research gaps identified include the ab- sence of universal product-validation stand- ards, limited real-world deployment testing, weak security models, and high implementa- tion cost. While current systems demonstrate strong prototype-level feasibility, large-scale commercial adoption will require interopera- bility, robust sensing, reliable indoor naviga- tion, and compliance with privacy and digital- payment regulations.

All things considered, smart shopping carts are a quickly expanding field of study with signifi- cant industrial implications. By transforming traditional retail into a completely automated, user-adaptive, and data-driven shopping expe- rience, edge computing, AI support, and secure IoT infrastructures could pave the way for the next generation of unmanned smart stores.

FUTURE SCOPE

Strong potential for additional developments in sensing precision, autonomous navigation, user engagement, and safe retail automation is indi- cated by the emergence of smart shopping cart systems. In order to prevent single-point fail- ure and ensure dependable item tracking in ac- tual store conditions, future systems are antici- pated to implement multi-sensor fusion, merg- ing RFID, computer vision, weight sensing, and UWB/SLAM-based localization. While cloud servers manage long-term analytics and inventory forecasting, edge-AI processing can minimize latency by completing billing, route planning, and product suggestion locally on the cart.

Dynamic obstacle management, multi-cart co- ordination, and self-mapping capabilities will be necessary for the full-scale implementation of autonomous carts in commercial supermar- kets. These features will allow carts to adjust to shifting store layouts without the need for human recalibration. Zero-knowledge custom- er authentication, blockchain-based billing, and encrypted retail IoT networks will all be inte- grated as security becomes a top focus. Fur- thermore, LLM-based voice interaction may be used by next-generation systems, enabling us- ers to query the cart for offers, product loca- tions, or customized recommendations.

Smart carts can function as mobile data- collection nodes for retail businesses, allowing for real-time shelf analytics, product heat map- ping, and customer behaviormodeling. The last phase of this evolution suggests completely automated smart retail environments, in which staff intervention is not necessary for autono- mous carts, robotic restockers, and AI-based pricing algorithms to function.

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