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A Review of Research on RFID-Based Automatic Identification Systems for Mixed-Model Production

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Abstract

With the continued advancement of intelligent manufacturing strategies and the sustained growth of demand for personalized customization, manufacturing enterprises are accelerating the transformation of their production modes from traditional high-volume, single-variety production lines to flexible mixed-model production with multiple varieties and small batches. While improving flexibility, mixed-model production introduces a series of management difficulties, including diverse workpiece types, intersecting process routes, and frequent material distribution. Traditional barcode and quick response (QR) code identification technologies are gradually showing limitations in long-distance reading, parallel processing of multiple targets, and adaptation to harsh environments. Radio frequency identification (RFID) technology has become a core supporting technology for solving these problems because of its contactless operation, long reading distance, penetration-based identification of multiple targets, and strong resistance to interference. This paper systematically reviews research progress on RFID technology in multi-variety, small-batch mixed-model production. It first describes the fundamentals of RFID technology and the core characteristics of the mixed-model production mode. It then compares the three mainstream identification technologies of barcodes, QR codes, and RFID. On this basis, a layered system architecture comprising a perception layer, network layer, data layer, and application layer is constructed, and the integration of RFID middleware with digital twin technology is discussed. The evolution of key technologies is reviewed, with emphasis on multi-tag anti-collision algorithms, including ALOHA-based, tree-based, hybrid, and machine-learning-based algorithms, as well as high-precision positioning and tracking methods based on received signal strength indicator (RSSI), phase, and holography. Typical cases in bearing manufacturing, garment production, and automotive mixed-model assembly are used to analyze practical application results. Finally, the paper discusses trends in the deep integration of RFID with artificial intelligence, digital twins, passive Internet of Things technologies, and green low-carbon manufacturing, and identifies current research challenges and open problems, with the aim of providing a scientific basis for decision-making by manufacturing enterprises undertaking digital and intelligent production-line transformation.

Keywords

RFID, mixed-model production, automatic identification, multiple varieties and small batches, anti-collision algorithm, positioning and tracking, digital twin

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1. Introduction

1.1 Research Background

With the advancement of the "Made in China 2025" and industrial internet strategies, the order structure faced by the manufacturing industry is undergoing changes: the varieties customers want are becoming more and more, while the quantity of a single batch is becoming smaller and smaller. The past organizational mode in which one line runs only one variety for a long time and relies on large batches to dilute costs has already been difficult to adapt to this change, and many enterprises have begun to turn to multi-variety, small-batch flexible mixed-line production. Flexibility has improved, and management troubles have also followed: on the same line several kinds of workpieces are circulating at the same time, process routes cross each other, and the frequency and complexity of material distribution have both risen markedly. In such a workshop with very strong dynamics, whether the production process can be "seen clearly and recorded" is directly related to line efficiency and yield rate.

Traditional automatic identification and data capture means, when placed in mixed-line scenarios, have relatively prominent shortcomings. Manual scanning one by one with a barcode gun is slow, and missed scanning is almost the norm; QR codes are low in cost and easy to deploy, but they are relatively sensitive to lighting conditions and to oil stains and dust on the workpiece surface, and can only read one at a time, making it difficult to perform batch reading of multiple targets in motion. What mixed-line production needs is precisely an identification technology that can keep a distance, be non-contact, identify multiple targets simultaneously, and still work stably under conditions such as oil stains, dust and metal reflection.

1.2 Research Purpose and Significance

The requirements of mixed-line production on the identification link can roughly be grouped into three points: workpieces must be recognized quickly, status must be tracked reliably, and logistics scheduling must be able to respond at any time. The reason why radio frequency identification (RFID) is being used more and more in industrial sites lies precisely in its natural advantages in these aspects: no line-of-sight contact is required, the reading distance can reach several meters, multi-tag parallel reading is supported, and it can still work under working conditions such as oil stains, dust and metal interference.

Looking at the existing literature, what is discussed more is the individual underlying technologies of RFID, for example the improvement of a certain type of anti-collision algorithm, the design of anti-metal tags and antennas, the optimization of reader layout, and so on. Research that truly takes "multi-variety, small-batch mixed-line production" as an independent business scenario, discusses from the system level how the architecture should be built and where the key links are stuck, and places it together with other identification means for horizontal comparison is still not common at present. This is precisely the part that this paper hopes to supplement.

Around this goal, this paper sorts out the research progress of RFID technology in multi-variety small-batch mixed-line production, and places the foothold on specific scenarios such as workpiece verification, product tracking and logistics scheduling, in the hope of providing, for manufacturing enterprises when implementing digital transformation of production lines, a referable judgment basis on practical issues such as system architecture construction, hardware selection and deployment.

1.3 Research Status in China and Abroad

In recent years, scholars in China and abroad have conducted extensive and in-depth research on the application of RFID in industrial manufacturing. In terms of research topics, the relevant results can be summarized in the following areas.

(1) RFID fundamentals and standards. Finkenzeller's RFID Handbook systematically describes the physical principles, system composition, and frequency-band characteristics of RFID and is a classic work in this field [1]. Haoshi Jiang et al. reviewed the development and application trends of radio frequency identification technology [2]. At the standards level, the ultra-high-frequency Electronic Product Code Generation 2 (EPC Gen2) protocol developed by EPCglobal and its corresponding international standard, ISO/IEC 18000-63, have become the de facto standards for ultra-high-frequency RFID worldwide [3, 4].

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(2) Multi-tag anti-collision algorithms. Early research mainly focused on basic hardware design and simple data acquisition in warehousing and logistics. As the identification scale expanded, ALOHA-based and tree-based anti-collision algorithms and their optimization became research hotspots, and parallel identification and machine learning methods were gradually introduced [5, 6, 7].

(3) RFID positioning and tracking. From the signal-strength-based LANDMARC system to phase-based holographic methods such as Tagoram, RFID positioning accuracy has improved from the meter level to the centimeter and even millimeter level [8, 9].

(4) Application of RFID in manufacturing execution. With the maturation of intelligent manufacturing systems, the research focus has gradually shifted toward real-time scheduling in RFID-based manufacturing execution systems (MESs) [10, 11].

Most existing reviews focus on individual RFID technologies. Few start with the requirements of multi-variety, small-batch mixed-model production and examine system architecture and technical challenges alongside a comparison with other identification technologies. This paper takes that production setting as its focus to address a gap in the review literature.

1.4 Structure of the Paper

Section 2 introduces the main characteristics of mixed-model production and the principles of RFID identification. Section 3 compares commonly used automatic identification technologies. Section 4 develops a layered architecture for an RFID identification system suited to mixed-model production. Section 5 reviews research on key RFID technologies under complex operating conditions, including anti-collision methods, positioning, and tracking. Section 6 examines the results of RFID implementation through representative cases. Section 7 discusses future directions and unresolved problems, and Section 8 concludes the paper.

2. Relevant Theory and Technical Foundations

2.1 Fundamentals of RFID Technology

2.1.1 RFID System Composition and Operating Principle

Radio frequency identification is a contactless automatic identification technology. A complete RFID system basically consists of three core components. The first is the electronic tag, which consists of a coupling element and a chip and stores relevant electronic data to identify a target object. The second is the reader, which is mainly responsible for reading information from the electronic tag. The third is the data processing system, which receives the data transmitted by the reader and performs subsequent processing. In the core operating process, the reader sends a radio-frequency signal of a specified frequency through an antenna. When an electronic tag enters the magnetic-field region, the antenna inside the tag generates an induced current, thereby obtaining energy and becoming activated. The activated tag then uses its antenna to transmit stored information such as its code. After the reader antenna receives the carrier signal returned by the tag, it sends the signal to the reader for demodulation and decoding. Finally, the data are sent to a back-end computer system for the corresponding business processing [1, 2].

2.1.2 Classification of RFID Systems

According to the operating frequency band, RFID systems can be divided into four categories: low frequency (LF, 125-134 kHz), high frequency (HF, 13.56 MHz), ultra-high frequency (UHF, 860-960 MHz), and microwave (2.45 GHz and above). LF and HF systems are mainly based on electromagnetic inductive coupling. They have relatively short reading distances and relatively strong resistance to interference from metals and liquids and are commonly used for short-range identity identification. UHF systems are based on electromagnetic backscatter, provide long reading distances and high multi-tag reading rates, and are the most widely used frequency band in industrial and logistics applications [1, 3]. According to the tag power-supply method, electronic tags can be divided into active, passive, and semi-active tags. Passive tags are activated by the radio-frequency energy emitted by the reader. They are inexpensive and maintenance-free, but their reading distance is limited. Active tags contain their own batteries and provide long reading distances, but they are larger and more expensive. Semi-active tags provide a compromise between the two [1].

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2.2 Introduction to the Mixed-Model Production Mode

2.2.1 Definition and Core Characteristics

Mixed-line production refers to continuously and alternately producing products of multiple specifications on the same production line, with line-change time negligible or very short, and the industry habitually summarizes it as “multiple varieties, small batches”. This mode can be regarded as the concrete landing of the concepts of flexible manufacturing system and mass customization in the assembly link, and is basically the same concept as the “mixed-model assembly line” commonly seen in the literature. Its flexibility mainly falls in three places: the differences between different workpieces are relatively large; resources such as equipment, tooling and software need to be shared among multiple varieties; the process route is not fixed and can be adjusted with orders.

2.2.2 Core Business Requirements

The first is the automatic identification of workpieces. When large batches of workpieces circulate on the line, what must be answered first is “which one is this”, and the identity verification must be fast and accurate.

The second is the whole-process production tracking. Work-in-process must circulate across processes, and the process route may also be changed temporarily; the processing status and circulation status both need to be collected in real time, otherwise the subsequent scheduling loses its basis.

The third is the dynamic scheduling of logistics. Materials must be delivered to the position where they should go, checked once more at key nodes, and the material flow of the whole line must also be kept within a controllable range.

2.2.3 On-Site Identification Difficulties

Coming down to the site, the problems of the information collection link are more concentrated. There are many kinds of workpieces and the circulation density on the line is high, it is very common for multiple tags to enter the reading range at the same time, and data collision and identification conflict are therefore difficult to avoid. The process route is not fixed and materials are frequently scheduled, so where the physical object has gone and where it is recorded in the system are easily inconsistent; once the physical flow and the information flow are disconnected, the subsequent tracking and scheduling all fall through. In addition, there are many metal structure blockages and heavy oil stains and dust in the workshop, and the reading accuracy of automatic identification equipment will further decrease. Superimposed together, these points actually put forward a composite requirement for identification technology: the distance must be far enough, multiple targets must be read at the same time, and it must also work stably under harsh working conditions — this is exactly the strength of RFID.

3. Horizontal Comparison of Mainstream Identification Technologies

Looking at the results of the literature review, the automatic identification technologies used relatively more in the field of item identification at present are mainly of three categories: barcode, QR code and radio frequency identification (RFID). The differences among the three in working principle and basic application characteristics are quite obvious [12].

3.1 Characteristics of Barcode Technology

(1) High dependence on optical visibility: Barcode identification mainly relies on a scanner emitting light and obtaining a signal from the difference between the absorption of light by black bars and the reflection of light by white spaces. The effective identification distance is relatively short, and optical visibility must be maintained during identification.

(2) Weak resistance to physical interference: Because barcodes depend strongly on the optical reflection characteristics of their surfaces, contamination or damage to the label surface destroys the optical characteristics, prevents the scanning equipment from obtaining an accurate signal, and consequently causes identification errors.

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(3) Limited information capacity: Although barcode technology has the advantage of low cost, it encodes information only through combinations of one-dimensional lines and spaces, so its information storage capacity is extremely limited.

3.2 Characteristics of QR Code Technology

(1) Large information capacity, but decoding has to go through a whole set of image processing procedures. The QR code encodes data into black and white squares, which are laid out on a two-dimensional plane according to specific rules, and its capacity and coding complexity are one to two orders of magnitude higher than those of the barcode. The price is that the decoding chain becomes longer: first an image acquisition device is used to capture the graphic, then preprocessing such as grayscale conversion, filtering and denoising, and binarization is performed, after which the algorithm locates the positioning patterns and corrects the distortion, and only then can the code be read out. If any step in the middle goes wrong, for example uneven illumination or serious contamination, the reading will fail.

(2) It has a built-in error correction mechanism, and can still be read out when locally damaged. Dedicated error correction code elements (Reed-Solomon error correction) are reserved in the coding structure of the QR code, and according to different error correction levels, a certain proportion of code area occlusion or contamination can be tolerated, and at the highest error correction level this proportion is about 30%. This is also the reason why it has more advantage in identification reliability than the barcode: for the barcode, as long as there is one break, the whole code often cannot be read out.

3.3 Characteristics of Radio Frequency Identification Technology

(1) Non-contact interaction is completed by radio frequency signals, and the working distance is farther. A bidirectional data channel is established between the reader and the electronic tag through radio frequency signals, which both supplies energy to the tag and completes the exchange of commands and data. Compared with optical schemes that need to be first aligned, then imaged, and finally decoded, its identification distance can be extended to several meters, a single interaction is at the millisecond level, and the storage capacity and service life of the tag also have more room.

(2) It does not need to be “visible”, and it does not pick the reading angle. The tag does not have to stop when it is read, and can be read both when stationary and when in motion, as long as the reader antennas cover it from different directions. Non-metallic packaging such as cartons, plastic boxes and wooden pallets hardly constitutes an obstruction to the radio frequency signal, and the tag can still be identified when sealed inside the packaging; the “visible” premise on which optical identification relies no longer holds here.

(3) It can still remain stable under harsh working conditions. Information is carried by electromagnetic fields or electromagnetic waves and does not depend on an optical window, so factors such as high temperature, high humidity, dust and oil stains, which have a great influence on lenses and code surfaces, interfere with RFID much less. However, the influence of metal and liquid on radio frequency signals is still a problem that needs to be handled separately.

RFID also has limitations. Tags generally cost more than printed barcodes, metal and liquids can weaken radio signals, and communication between tags and readers may raise security and privacy concerns. These trade-offs should be assessed against the needs of each application [10, 13].

Table 1 compares barcodes, QR codes, and RFID by operating principle, reading distance, ability to read multiple targets, visibility and penetration requirements, resistance to environmental interference, data capacity, read/write capability, tag cost, and typical applications.

Table 1: Comparison of the Characteristics of Three Mainstream Automatic Identification Technologies

Comparison dimension	Barcode	QR code	RFID
Operating principle	Difference in optical reflection	Black-and-white block image coding	Electromagnetic induction/backscatter
Reading distance	Short range (contact-based)	Short range (imaging required)	Long range (up to several meters or more)
Multi-target reading	Not supported	Not supported (one code per scan)	Parallel batch reading supported

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Comparison dimension	Barcode	QR code	RFID
Penetration/visibility requirement	Optical visibility required	Optical visibility and suitable lighting required	Can penetrate packaging; no line-of-sight requirement
Resistance to environmental interference	Weak (easily disabled by contamination)	Moderate (error correction available)	Strong (resistant to oil, high temperature, and metal interference)
Data capacity	Very small	Relatively large	Relatively large and dynamically writable
Read/write capability	Read-only	Read-only	Readable, writable, and reusable
Tag cost	Very low	Low	Relatively high
Typical scenario	Retail checkout	Mobile payment and anti-counterfeiting traceability	Industrial tracking, logistics, and asset management

4. Layered Architecture of an RFID-Based Automatic Identification System for Mixed-Model Production

Electronic equipment assembly lines are a relatively typical application scenario of this kind of system. Looking at the existing design and deployment schemes, RFID-based automatic identification systems for mixed-line production mostly do not adopt a single structure, but are split apart by layers [14]. This paper sorts them out in the order of "perception layer—network layer—data layer—application layer", and the relationship among the four layers is a bottom-up data flow.

4.1 Perception Layer

What this layer has to solve is "how things in the physical world become data usable by the system". The materials, material boxes and turnover boxes flowing on the production line first carry identity information through electronic tags; the reader takes out the tag content when the workpiece passes through the reading area, and the data thereby enters the system. The identification action itself does not require manual intervention, and the collection, uploading and subsequent management are all completed in this one link.

4.2 Network Layer

The collected data must be sent to the upper layers, and this relies on the network layer. The connection modes inside the workshop are not unified: fixed stations mostly use wired industrial Ethernet; mobile equipment and areas inconvenient for wiring use Wi-Fi; sensor nodes can use ZigBee; scenarios with higher requirements on delay and coverage will consider 5G. Going further up, when docking with existing systems such as MES and WMS, industrial internet of things protocols such as MQTT and OPC UA are usually adopted, putting real-time performance and reliability in a priority position.

4.3 Data Layer

The data layer, on the one hand, establishes a bidirectional data link by means of the perception terminals, and on the other hand, must clean, filter and fuse the large number of raw records generated by RFID. The workload of this layer is often underestimated: a tag will be read repeatedly within the range of the reader, and the same material will be repeatedly reported within a short period; direct storage not only occupies space but also interferes with judgment. Therefore, in engineering an RFID middleware is generally introduced: application-level events (ALE) are used to filter out repeated reports, complex event processing (CEP) is used to combine scattered read/write events into state changes with business meaning, and then the data is shared externally in a unified format through EPC information services (EPCIS) [1]. After the tag is bound to the material, the system will establish a tracking object for the work-in-process, recording the tag number, material information and current state; the state is updated once it changes, and which step the material box has reached can be found in the data layer. These real-time data can also be supplied to the digital twin model, so that the production line in the virtual space keeps synchronized with the workshop site [10].

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4.4 Application Layer

At the application layer, RFID is truly embedded into the business, and the footholds are mainly two blocks, material control and outward delivery. The material control module combines tag sensing with remote refreshing of the ink screen, covering the whole process from warehouse preparation, picking, boxing, outbound, arrival at the station, production consumption to recycling; every step is recorded and can be traced afterwards. The practices at manual stations and automatic stations differ slightly, but the logic is the same: the operator reads once with the reader, the control system automatically records the code, the correspondence between the person and the material is thereby determined, and the station identity and the resource are bound together. The outward delivery link relies on the ink screen: the server issues a command to refresh the screen content, and the tag information corresponds to the outward delivery box and the components in the box; when the loaded box passes the antenna sensing gate erected at the door, the reader on the gate reads the box tag, and the outward delivery action is completed thereupon [14].

5. Review of Advances in Key RFID Technologies

5.1 Multi-Tag Anti-Collision Technology

When the material boxes on the same work order enter the field of view of the reader at the same time, multiple tags will seize the channel at the same moment, the signals superimpose on each other, and the reader cannot decode any of them; this is multi-tag collision. In mixed-line scenarios the tag density is high and the flow is fast, collision is almost unavoidable, and anti-collision algorithms therefore become the key to whether the system can be used. Existing work advances roughly along two threads: one is to improve on the classical ALOHA-type and tree-type algorithms, and the other is to bring in parallel identification and intelligent optimization [5, 15, 16]. Divided by technical route, the existing algorithms can be grouped into four kinds: ALOHA type, tree type, hybrid type and machine learning type.

5.1.1 ALOHA-Based Anti-Collision Algorithms

The idea of ALOHA is very direct: since it is not known when speaking is appropriate, let the tags randomly choose a time slot to send a response, and reduce the probability of collision by dispersing the sending time. This pedigree starts from pure ALOHA, goes through slotted ALOHA and framed slotted ALOHA (FSA), and finally evolves to dynamic framed slotted ALOHA (DFSA); the Q algorithm in the EPC Gen2 standard is a typical implementation of the DFSA idea [3]. This kind of algorithm is easy to implement, and its adaptability to tag movement is also not bad, but its shortcoming is “tag starvation”: individual tags may fail to select an available time slot for several consecutive rounds and cannot be read for a long time; in addition, whether the frame length matches the actual number of tags directly determines the level of throughput [5]. The DFSA approach is to estimate the number of tags in the field before each frame begins [17, 18] — counting the probabilities of the three states of idle, successful identification and collision in the time slots, and then combining the Bayesian method with the Poisson distribution to calculate the probability distribution of the number of tags, and accordingly adjusting the frame length of the next frame to a suitable level, so as to press down the collision probability [16].

5.1.2 Tree-Based Anti-Collision Algorithms

The tree-type algorithm takes another road: it divides the tag set layer by layer downward until only one tag remains in each subset. This belongs to deterministic identification, and the common forms are binary tree (BT), query tree (QT) and collision tree. Compared with the “random avoidance” of ALOHA, it does not miss tags, and the price is more query rounds and larger delay. The improvements in recent years mainly revolve around this point, that is, bringing in parallel identification so that multiple branches can be processed at the same time in one round:

Parallel identification collision tree algorithm based on Walsh code (PWCT). It borrows the idea of code division multiple access (CDMA), and performs spread spectrum processing on tag signals with Walsh codes when multi-bit collision occurs; each tag carries a mutually different Walsh code, which is equivalent to occupying a sub-channel of its own, so that parallel transmission is possible within the same time slot. The identification delay therefore drops markedly, and the anti-interference capability is also improved.

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Lock-bit based adaptive parallel identification collision tree algorithm (LAPCT). It targets the problem that the communication complexity between the reader and multiple tags is too high, and adopts a "single query—multi-cycle response" mechanism: first Manchester coding is used to find the differences on the characteristic bits of the tags, a common query prefix is generated accordingly, and then the response process is cut into several sub-cycles according to the prefix, so that multiple tags can be read out in parallel with one query.

Blind source separation parallel identification collision tree algorithm based on tag grouping (GPCT). This scheme combines the multi-antenna system with blind source separation, first works out the optimal number of groups and divides the tags in the field into several groups; when the number of tags in a group does not exceed the number of antennas, blind source separation is used directly to separate the mixed signals, and when it exceeds, the process falls back to the collision tree [15].

5.1.3 Hybrid and Machine-Learning-Based Anti-Collision Algorithms

The hybrid type joins the strengths of the previous two: the randomness of ALOHA guarantees throughput, and the determinism of the tree type guarantees no missed reading [6]. The machine learning type appeared somewhat later; researchers no longer only stare at "how to queue", but try to separate the individual tags directly from the aliased signals, using means including blind source separation, independent component analysis (ICA) and deep neural networks, with relatively obvious effects in high-density scenarios [7]. One of these ideas transforms the multi-tag identification within the same time slot into the problem of electronic code encoding generation: what the antenna collects is the superimposed observation of multiple tag signals, and after removing the mean and processing the amplitude, the mixed signals are unmixed and the respective tag signals are restored, so that multiple EPC codes can be read out in parallel in one time slot, without having to avoid congestion by staggered sending [16].

In summary, Table 2 compares the representative algorithms, advantages, and shortcomings of the four categories of multi-tag anti-collision algorithms: ALOHA-based, tree-based, hybrid, and machine-learning-based algorithms.

Table 2: Comparison of Multi-Tag Anti-Collision Algorithm Categories

Algorithm category	Representative algorithms	Advantages	Shortcomings
ALOHA-based	FSA, DFSA, and EPC Gen2 Q algorithm	Simple implementation; adaptable to tag movement	Tag starvation and throughput fluctuations
Tree-based	BT, QT, collision tree, PWCT, LAPCT, and GPCT	Deterministic identification; no tag starvation	Long identification latency and high communication complexity
Hybrid	Algorithms combining ALOHA and tree-based methods	Balance between throughput and reliability	High algorithmic complexity
Machine-learning-based	Blind source separation, ICA, and deep networks	Adaptable to complex, high-density scenarios	High computational overhead and dependence on training data

5.2 High-Precision Positioning and Trajectory Tracking Technology

Signal strength, phase, and other information obtained through RFID technology can be used for continuous dynamic trajectory sensing and dynamic trajectory tracking. According to their positioning principles, RFID positioning methods can be divided into three categories: methods based on the RSSI, methods based on phase and holography, and methods based on synthetic aperture radar (SAR).

5.2.1 RSSI-Based Positioning Method

RSSI methods estimate the distance between a tag and a reader from the strength of the received signal. The LANDMARC system introduced reference tags to support positioning with meter-level accuracy and became an early model for RFID indoor positioning. Multipath propagation and fluctuations in signal strength, however, make further gains in accuracy difficult [8].

5.2.2 Phase- and Holography-Based Positioning Method

Compared with RSSI, phase is more sensitive to distance changes, and its resolution is also finer. The differential augmented hologram (DAH) method proposed by the Tagoram system belongs to the

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representative of this route: with commercial devices alone it brought the dynamic tracking accuracy to the millimeter level, and in a real airport baggage sorting scenario it reached the centimeter level [9]. Its approach is to use a multi-antenna array to continuously collect the phase during the movement of the tag, and to hand the difference between the theoretical phase and the measured phase to algorithms such as the hyperbolic differential hologram; the interference brought by multipath in the environment and by the device itself can just be cancelled out through the difference, and what remains is the position constraint of the tag on each hyperbola, and the intersection of multiple curves is the trajectory point. When three-dimensional information is needed, the authors arranged a dual-tag array on the operating tool, and with the spatial curved surface hologram localization algorithm, in addition to the planar trajectory, the elevation angle and azimuth angle can also be given, and the three-dimensional tracking is likewise kept at the centimeter level [9].

5.2.3 Synthetic-Aperture-Radar-Based Positioning Method

SAR methods move the reader along a known path to form a synthetic aperture. By coherently combining the signals backscattered from a tag at different points on that path, they can improve positioning accuracy and reduce the effects of multipath propagation. Used alongside holographic methods, SAR is a major approach to centimeter- and, in some settings, millimeter-level RFID positioning [9].

Table 3 compares the principles, reported accuracy, and representative systems of RSSI-based, phase- and holography-based, and SAR-based positioning methods.

Table 3: Comparison of RFID Positioning Methods

Positioning method	Basic principle	Accuracy level	Representative system/work
RSSI method	Distance measurement based on signal-strength attenuation	Meter level	LANDMARC
Phase and holography method	Phase-difference probability grid and holography	Centimeter-millimeter level	Tagoram
SAR method	Coherent accumulation with a synthetic aperture	Centimeter-millimeter level	Tagoram and TDE-Loc

5.3 Anti-Metal Tags and Antenna Design

In the mixed-line workshop, metal workpieces and metal pallets can hardly be avoided. The metal surface will reflect the radio frequency signal back and form a shield, and will also shift the resonant frequency of the tag antenna (detuning); after an ordinary tag is attached, the reading distance often shrinks to a fraction of the original, and in serious cases it cannot be read at all. The solution of the anti-metal tag starts from the structure: a separation layer is added between the tag and the metal to keep a certain distance between the two; or a substrate with a high dielectric constant is used to compress the thickness of the tag; there are also those using a special slot antenna structure, letting the metal surface itself become a part of the antenna. All these practices can bring the reading performance under the metal environment back to a usable level, and therefore a separate item has to be listed for it in tag selection [1]. It can be said that the metal occlusion problem mentioned in Section 2.2.3 is precisely solved step by step by this kind of design.

6. Typical Cases

6.1 Bearing Manufacturing

The processing chain of the bearing is long, the models are many and the batch size changes frequently, so it belongs to typical flexible production. Its requirements are very high both on whether the parts can arrive on time and on whether auxiliary tools such as grinding wheels and cutters are available at any time: once the grinding process waits for material, the machine tool can only stand idle. The original workshop relied on manual monitoring, and the accounts and the actual situation often did not match; what should be replenished was not replenished, and what was piled up in the warehouse could not be moved, so the two kinds of waste, inventory and line stoppage, existed at the same time. During the transformation, the workshop deployed RFID electronic tags and readers on the bearing inner and outer rings, rollers, AGV vehicles and tooling cutters; the manual inventory link was basically cancelled, and material consumption, position circulation and machine tool status were all collected in real time by the system and traceable throughout the process; the use status

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and remaining life of the tools were also within the monitoring range, and the distribution route was planned according to the shortest cycle. The data after the transformation are: the total cost of product material distribution decreased by 17%, the inventory in the line-side buffer area decreased by about 35%, the production bottleneck caused by material shortage was basically eliminated, and the average utilization rate of machine tools increased by 22.24% [19].

6.2 Garment Manufacturing

A garment manufacturer in Suzhou deployed RFID to improve how it collected production information. The workshop installed wireless network relay stations and equipped each workstation with an RFID reader and display. Order and size information was stored on RFID material cards that moved with the fabric, while employees received separate RFID identity cards. Employees swiped their identity cards when starting work. When a workstation computer read a material card, it displayed the sewing instructions for the relevant operation. If a cut piece reached the wrong workstation, the system showed a warning in red text. Card-swipe records at entry and exit points allowed managers to follow production progress in real time and calculate employees' piece-rate pay automatically. The enterprise reported a 25% increase in production-line efficiency [20].

6.3 Automotive Mixed-Model Assembly

On the automobile final assembly line, the cars to be assembled at the same station before and after may be completely different: this one is a two-wheel-drive low configuration, and the next one is a four-wheel-drive high configuration. To make such a line run smoothly, the key is that the station must know in advance "which one is coming". The engineering practice is to install an RFID tag on the skid, and write the vehicle model, configuration and order number into it together; when the skid enters the station, the reader reads out the tag content and directly sends it into the PLC, and the PLC switches the program and process parameters of the corresponding robot, so that the assembly action changes automatically with the vehicle model and no longer depends on the worker raising his head to look at the sheet. Error prevention is also completed on the same set of data: the part also has a barcode on it, and the system compares whether the vehicle model and configuration read by RFID are consistent with the part identified by the barcode; once they do not match, an alarm is given, so that wrong assembly, missed assembly and mixed material are blocked at the station link. There are also studies that connect RFID with wireless networks such as ZigBee to build a reconfigurable mixed-model assembly system, and both the changeover time and the assembly errors can be pressed down [10]. From the actual effect, the changeover time generally drops from several tens of minutes to several minutes, and the flexibility and takt of the production line are also improved accordingly.

6.4 Comparison of Case Results

Table 4 compares the main difficulties, key solution elements, and quantitative results of three typical cases: bearing manufacturing, garment manufacturing, and automotive mixed-model assembly.

Table 4: Comparison of Application Results in Typical Cases

Industry	Main difficulties	Key solution elements	Quantitative results
Bearing manufacturing	Information disconnection, excess inventory, and machine-tool shutdowns	Comprehensive tagging of workpieces, AGVs, and fixtures; real-time tracking and route planning	Distribution cost decreased by 17%; line-side inventory decreased by 35%; machine-tool utilization increased by 22.24%
Garment manufacturing	Difficulty tracking production progress and cumbersome piece-rate wage settlement	Material cards, employee identity cards, and workstation readers	Production-line efficiency increased by 25%
Automotive mixed-model assembly	Mixed production of multiple vehicle models, slow changeover, and assembly errors	Carrier RFID, coordinated PLC switching, and error-prevention comparison	Substantially shorter changeover time and fewer assembly errors

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7. Development Trends and Prospects

With the in-depth advancement of Industry 4.0, the role of RFID in mixed-line production is also changing: in earlier years it mainly solved the problem of recording data; now it is more and more like the infrastructure of the production line, which must both supply data and participate in judgment and control. The changes in the following aspects are relatively obvious.

The combination with artificial intelligence is the most direct one. In the past, when RFID read a code, its role basically stopped at "a certain workpiece has arrived at a certain station", and what to do next was still decided by people and the upper system. After connecting to an AI Agent, this link can go one step further: while reading the electronic code, the attributes of the workpiece and the process differences are parsed out at the same time, and what should be done is issued directly. In the mixed-line workshop, temporary insertion of orders, diversion of defective products and process errors or omissions occur almost every day, and the agent can call out an alternative scheduling strategy when it identifies that the material does not match the station, switch the processing parameters over, and correct itself when an error occurs [21]. The role of machine learning is more at the bottom layer; it has been applied in links such as tag number estimation, signal decoding and anomaly detection, and RFID has therefore taken a step from a collection tool toward a decision infrastructure [7].

On the digital twin side, what is often missing is not the model, but the real-time data that can be continuously fed in. The identity and status provided by RFID exactly fill this piece: after the material flow data is connected to the twin model, the production line in the virtual space can change in synchronization with the site, and real-time monitoring, predictive maintenance and resource configuration optimization also have an input to rely on. Existing research has proposed a digital twin architecture for RFID material flow (DTRMF), from data ingestion, processing and analysis to storage and visualization, with a relatively clear division of labor among the layers [10], and the fine control of mixed-line production therefore has one more implementation path.

Changes in the passive direction are also worth attention. Ambient backscatter communication allows the tag not to depend on a dedicated excitation source, and to directly borrow the radio frequency signals already existing in the environment to complete communication, and it is regarded as one of the key technologies of 6G passive internet of things [22]; once the tag end no longer needs batteries and maintenance, the deployment cost and operation and maintenance burden will both drop markedly, and this is precisely the precondition for RFID to be rolled out on a large scale in mixed-line production [22]. Another line is carbon accounting. The calculation of product carbon footprint requires energy consumption to be placed on specific products, and the circulation duration and processing path recorded by RFID exactly provide such a basis for allocation: after the equipment energy consumption collected by the internet of things gateway is split according to the actual time and processes of the workpiece on the line, every tagged workpiece can be given a carbon emission detail, and the green compliance of the enterprise also has data support.

However, from the demonstration line to plant-wide coverage, there are still several hurdles in between. Although the unit price of tags is falling, the total investment calculated per piece is still not low, and how much to deploy and to what granularity needs to be judged according to input and output; the influence of metal and liquid on reading performance has been mentioned earlier, and at present it is still avoided by anti-metal tags and antenna layout, without a fundamental solution; when equipment of different manufacturers and different protocols is placed on the same line, the interoperability is poor and the standardization lags behind, and the integration cost is often underestimated; the security and privacy protection mechanisms of RFID data at industrial sites are also not yet sound [23]. These problems will not disappear in the short term, and they are also directions that subsequent research can continue to advance.

8. Conclusion

This paper focuses on the urgent need for rapid workpiece identification, real-time status tracking, and dynamic logistics scheduling under a multi-variety, small-batch, flexible mixed-model production mode and systematically reviews the research status and core advances of automatic identification systems based on RFID technology. The research shows that, compared with traditional barcodes and QR codes, RFID technology is well suited to mixed-model production scenarios in which physical and information flows are

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highly dynamic and intertwined because of its contactless operation, long-distance batch reading, strong penetration, and excellent resistance to harsh operating conditions. The constructed four-layer architecture comprising the perception layer, network layer, data layer, and application layer enables closed-loop management from underlying material binding to upper-level life-cycle control. Multi-tag anti-collision technologies represented by ALOHA-based and tree-based algorithms, together with high-precision positioning and tracking technologies based on phase and holography, effectively address data conflicts and positioning difficulties in industrial environments. In typical manufacturing cases involving bearings, garments, and automobiles, these technologies significantly reduced distribution costs and line-side inventory and improved equipment utilization. Looking ahead, with the continued development of Industry 4.0, RFID technology will be deeply integrated with AI agents and digital twins, advancing from "passive recording" to "autonomous decision-making and execution." It will also combine with passive Internet of Things and carbon-reduction trends to support green low-carbon manufacturing and provide stronger core support for manufacturing enterprises undertaking digital and intelligent production-line transformation.

References

[1] Finkenzeller K. RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and Near-Field Communication [M]. 3rd ed. Chichester: John Wiley & Sons, 2010.

[2] Haoshi Jiang, et al. Radio Frequency Identification Technology and Its Applications and Development Trends [J].

[3] EPCglobal. EPC Radio-Frequency Identity Protocols Class-1 Generation-2 UHF RFID Protocol for Communications at 860 MHz-960 MHz, Version 1.2.0 [S]. 2008.

[4] ISO/IEC 18000-63:2015. Information technology - Radio frequency identification for item management - Part 63: Parameters for air interface communications at 860 MHz to 960 MHz Type C [S].

[5] Shih D H, Sun P L, Yen D C, et al. Taxonomy and survey of RFID anti-collision protocols [J]. Computer Communications, 2006, 29(11): 2150-2166.

[6] A Review of RFID Multi-Tag Anti-Collision Algorithms [J]. Computer Integrated Manufacturing Systems, 2014.

[7] Wang L, Luo Z, Guo R, et al. A review of tags anti-collision identification methods used in RFID technology [J]. Electronics, 2023, 12(17): 3644.

[8] Ni L M, Liu Y, Lau Y C, et al. LANDMARC: Indoor location sensing using active RFID [J]. Wireless Networks, 2004, 10(6): 701-710.

[9] Yang L, Chen Y, Li X Y, et al. Tagoram: Real-time tracking of mobile RFID tags to high precision using COTS devices [C]//Proceedings of the 20th Annual International Conference on Mobile Computing and Networking (MobiCom 2014). New York: ACM, 2014: 237-248.

[10] Zhu X, Mukhopadhyay S K, Kurata H. A review of RFID technology and its managerial applications in different industries [J]. Journal of Engineering and Technology Management, 2012, 29(1): 152-167.

[11] Design and Implementation Results of an Intelligent Footwear and Apparel Warehousing and Production Traceability System Based on RFID-MES Collaboration [J]. Chemical Fiber & Textile Technology, 2026.

[12] Jiapeng Liu. Research on an Object Identification System Based on UHF RFID [D].

[13] Weis S A, Sarma S E, Rivest R L, et al. Security and privacy aspects of low-cost radio frequency identification systems [C]//Security in Pervasive Computing (SPC 2003). Berlin: Springer, 2004: 50-59.

[14] Lei Guo. Design and Implementation of Information-Based Control for an Electronic Equipment Assembly Line Based on the Internet of Things [D].

[15] Xuan Luo. Research on Multi-Tag Parallel Identification and Anti-Collision Technology for UHF RFID [D].

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[16] Fengsheng Zeng. Research on an Anti-Collision Algorithm for RFID Broadcast Channels in the Internet of Things Based on Framed Slotted ALOHA [D].

[17] Schoute F C. Dynamic frame length ALOHA [J]. IEEE Transactions on Communications, 1983, 31(4): 565-568.

[18] Vogt H. Efficient object identification with passive RFID tags [C]//Proceedings of the First International Conference on Pervasive Computing (Pervasive 2002). Berlin: Springer, 2002: 98-113.

[19] Hongyan Li. Research on Material Distribution Methods for an RFID-Based Flexible Intelligent Bearing Manufacturing Workshop [D].

[20] Yaping Xu. Construction and Engineering Practice of an RFID-Based Information Acquisition System for Garment Production [D].

[21] Xing Li. Design and Implementation of a Discrete Manufacturing MES Based on AI Agents [D].

[22] Van Huynh N, Hoang D T, Lu X, et al. Ambient backscatter communications: A contemporary survey [J]. IEEE Communications Surveys & Tutorials, 2018, 20(4): 2889-2922.

[23] Ohkubo M, Suzuki K, Kinoshita S. Cryptographic approach to “privacy-friendly” tags [C]//RFID Privacy Workshop. Cambridge: MIT, 2003.

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Conflicts of Interest

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