Journal of computer science and software applications
https://www.mfacademia.org/index.php/jcssa
ISSN:2377–0430
Vol. 5, No. 4, 2025

Design and Research of a Rotating Packing Device with AI IntegrationMiles Whitaker

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Abstract:

This paper presents the design and research of a novel rotating packing device aimed at improving packaging efficiency, operational flexibility, and automation potential. The device is composed of a first and a second rotating shaft, each equipped with multiple suspended shaft arms and attached box bodies. Through the coordinated rotational movement of these components, the device enables rapid, stable, and organized item placement and retrieval. The mechanical structure is carefully optimized to enhance stability under dynamic loads, maximize spatial utilization, and support high-frequency operations in industrial settings.In terms of motion control, the system employs synchronized rotational mechanisms that ensure precise angular positioning and smooth trajectory planning, minimizing potential collisions and mechanical wear. Detailed analysis of the device's kinematic behavior, load distribution, and structural dynamics is conducted to verify its performance and reliability under various operating conditions. Experimental validations demonstrate that the proposed design significantly improves throughput and reduces manual handling time compared to conventional fixed packing systems.Moreover, this study discusses the future integration of artificial intelligence (AI) technologies to further elevate system intelligence and adaptability. Potential AI applications include real-time object recognition, predictive maintenance, adaptive path optimization, dynamic load balancing, and anomaly detection. By embedding AI-driven modules into the control architecture, the rotating packing device can achieve autonomous decision-making, fault-tolerant operation, and continuous performance improvement, ultimately supporting the broader goal of intelligent manufacturing and smart logistics. Future work will focus on the implementation of these AI enhancements and their evaluation in real-world production environments.

Keywords:

Packaging Box, Rotating Device, Structural Design, AI Integration

1. Introduction

Efficient packaging mechanisms are critical to modern logistics and manufacturing industries, where the demand for high throughput, operational flexibility, and reduced labor costs continues to grow. As global supply chains become increasingly complex and consumer expectations for fast delivery rise, the ability to package, sort, and transport goods rapidly and reliably has become a key determinant of competitiveness. However, traditional static packaging methods, which rely on fixed-position box arrangements and manual intervention, often face significant limitations in terms of efficiency, scalability, and adaptability to diverse product types and varying production speeds.

Recent studies have focused on enhancing packaging systems through innovative mechanical design and the adoption of automation technologies [1,2]. Techniques such as robotic arms, conveyor-based packaging lines, and modular automated systems have been proposed to improve packaging throughput and reduce human labor. Nevertheless, many existing solutions still encounter challenges related to spatial constraints, mechanical complexity, and difficulties in achieving seamless integration with intelligent monitoring and control systems. Therefore, there remains a pressing need for new packaging devices that offer not only higher operational efficiency but also greater adaptability and intelligence.

In response to these challenges, this study introduces a novel rotating packing device capable of dynamically adjusting the positions of multiple packing boxes through controlled rotational movement. The system is composed of a first and second rotating shaft, each equipped with suspended shaft arms and attached box bodies. By coordinating the rotational motion of these components, the device enables rapid and flexible item placement and retrieval, optimizing spatial utilization and supporting continuous high-speed operation. The mechanical design emphasizes structural stability, dynamic balance, and durability under repetitive loading conditions.

Furthermore, the future integration of artificial intelligence (AI)-based optimization and monitoring systems is considered to further enhance the device's operational performance. AI technologies such as machine vision, predictive maintenance, adaptive motion planning, and real-time decision-making can provide the system with the ability to autonomously adjust to changing operational conditions, detect and diagnose potential faults, and optimize packaging strategies based on real-time data. The incorporation of AI aims to transform the rotating packing device from a purely mechanical system into an intelligent, self-optimizing unit capable of supporting smart manufacturing and logistics operations.

The remainder of this paper is organized as follows: Section 2 describes the detailed mechanical design and motion control strategy of the rotating packing device. Section 3 discusses the potential AI-based enhancements and their integration into the system architecture. Section 4 presents experimental validation results, and Section 5 concludes the study with a summary of findings and future research directions.

2. Design Strategies

2.1 Overall Structural Design

The rotating packing device is designed to achieve efficient, flexible, and continuous packaging operations through a carefully engineered mechanical structure. It primarily comprises four key components: a first box body, a first rotating shelf, a second box body, and a second rotating shelf. Each component is designed to fulfill specific functional roles while ensuring seamless integration into the overall system.

The first box body serves as the main stationary container for initial item placement. It features a strategically positioned opening at its top surface, enabling direct access for item insertion and retrieval. The dimensions and structural material of the first box body are optimized for mechanical strength, load-bearing capacity, and durability under high-frequency operation.

Mounted above the first box body is the first rotating shelf, which acts as the primary dynamic mechanism of the device. The first rotating shelf includes a rotating button for manual or automated activation, a first rotating shaft positioned vertically at the center, and multiple first suspended shaft arms radially arranged along the shaft. These shaft arms are designed with lightweight, high-strength materials to minimize inertial load while maintaining structural rigidity. The radial arrangement ensures uniform distribution of forces during rotation, enhancing system stability and reducing mechanical wear.

Complementing the first rotating shelf is the second rotating shelf, which operates in a synchronized manner to maintain precise alignment and coordination. The second rotating shelf similarly comprises a second rotating shaft and several second suspended shaft arms, also distributed radially. To ensure synchronization, mechanical linkages or electronic control systems can be employed, depending on the desired level of precision and system complexity.

Each second box body is connected between a corresponding pair of first and second suspended shaft arms, forming a suspended, dynamically adjustable container. The design of these connections allows each second box body to maintain a stable orientation during rotation while offering a degree of flexibility to absorb minor shocks and vibrations. Importantly, the suspended configuration enables the opening of each second box body to sequentially align with the opening of the first box body as the system rotates. This sequential alignment facilitates smooth and efficient transfer of items between the containers without the need for complex robotic manipulation [3].

To further enhance performance, the structural design incorporates several engineering optimizations. Bearings and low-friction rotational interfaces are utilized at critical joints to reduce mechanical resistance and extend service life. Modular design principles are adopted to enable easy maintenance and component replacement. In addition, sensors can be integrated along the rotating shafts and arms to monitor position, angular velocity, and mechanical stress in real-time, providing critical data for both control and predictive maintenance systems.

Overall, the structural design of the rotating packing device balances mechanical robustness, operational efficiency, and the potential for future integration with intelligent control systems. This foundation enables the device to meet the rigorous demands of modern logistics and manufacturing environments while remaining adaptable to evolving technological advancements.

2.2 Shaft Arm Mechanism

The shaft arm mechanism plays a critical role in ensuring the smooth, stable, and precise operation of the rotating packing device. Each shaft arm is meticulously designed to support dynamic movement while minimizing mechanical stress and maintaining overall system integrity.

Each suspended shaft arm is connected through a combination of bearings and a connecting shaft, forming a flexible yet robust linkage between the rotating shelf and the box body. Specifically, the first suspended shaft arm is attached to the first rotating shelf via a first bearing and a connecting shaft. The first bearing is strategically located at the end of the first suspended shaft arm, differentiating it from the connecting part block to allow relative rotational movement. This configuration ensures that as the first rotating shelf turns, each first suspended shaft arm can slightly adjust its orientation to accommodate minor misalignments and dynamic loads without transmitting excessive stress to the shaft or the shelf.

Similarly, the second suspended shaft arm is connected to the second rotating shelf through a second bearing positioned at its end. The second bearing fulfills the same function as the first bearing, providing rotational stability and mechanical flexibility. Together, the first and second suspended shaft arms form a supporting framework for the second box body, suspending it securely while allowing it to rotate synchronously with the motion of the rotating shelves.

The use of high-precision bearings at the ends of the shaft arms is essential for reducing friction, minimizing wear, and ensuring the long-term durability of the device. Bearings are selected based on load capacity, rotational speed, and environmental conditions such as dust, temperature, and humidity. Additionally, the connecting shafts are designed to offer a balance between stiffness and compliance, preventing excessive vibration or deformation during high-speed rotation.

From a mechanical perspective, the shaft arm mechanism is subjected to complex dynamic forces, including centrifugal forces generated during rotation and the gravitational forces acting on the suspended box bodies. Finite element analysis (FEA) and dynamic simulation tools can be employed during the design phase to optimize the geometry, material selection, and bearing placement, ensuring that the shaft arms maintain structural integrity under all expected operating conditions.

Moreover, the design allows for modular assembly and maintenance. Each shaft arm, bearing, and connecting shaft can be individually inspected and replaced if necessary, minimizing downtime and improving maintainability. Future enhancements may include the incorporation of smart bearings equipped with sensors to monitor parameters such as temperature, vibration, and load in real time, enabling predictive maintenance and further improving the operational reliability of the entire device.

Overall, the shaft arm mechanism is fundamental to the successful operation of the rotating packing device. It provides the necessary support and flexibility to enable efficient, stable, and precise movement of the packing boxes, while its modular and robust design ensures long-term performance in demanding industrial environments.

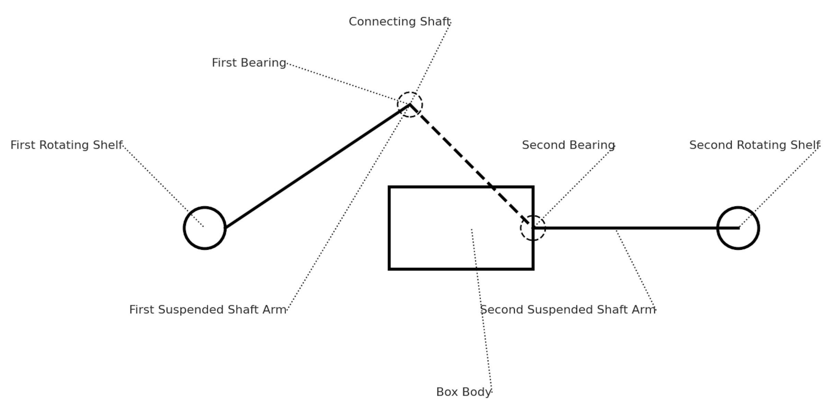


Figure 1. Shaft arm mechanism

3. Operational Flow

The operational sequence of the rotating packing device is designed to achieve high-efficiency item handling with minimal manual intervention. The workflow integrates mechanical rotation, precise alignment, and controlled timing to ensure seamless packaging operations.

The process begins with the activation of the rotating button, which initiates the motion of the first rotating shaft. The first rotating shaft, in turn, drives the rotation of the attached first suspended shaft arms. Due to the mechanical or electronic synchronization mechanisms embedded within the system, the rotation of the first rotating shaft is precisely coordinated with that of the second rotating shaft located on the second rotating shelf. This synchronization is critical to maintaining the proper relative positions of the suspended shaft arms and ensuring consistent alignment throughout the operation.

As the first and second rotating shafts rotate, the suspended shaft arms carry the second box bodies along a controlled circular path. Through this movement, each second box body sequentially positions its opening directly above the opening of the stationary first box body. This alignment process is both continuous and cyclic, enabling the device to operate without requiring intermittent stops, thereby maximizing throughput.

During alignment, once a second box body reaches the target position over the first box body, the system temporarily stabilizes the rotation to allow for precise item insertion or retrieval. This stabilization may involve active braking mechanisms, such as electromagnetic brakes, or passive damping methods to reduce rotational inertia and minimize misalignment caused by overshoot or vibrations. Sensors, such as position encoders or proximity detectors, can be utilized to accurately detect the position of each box body and confirm successful alignment before item transfer begins.

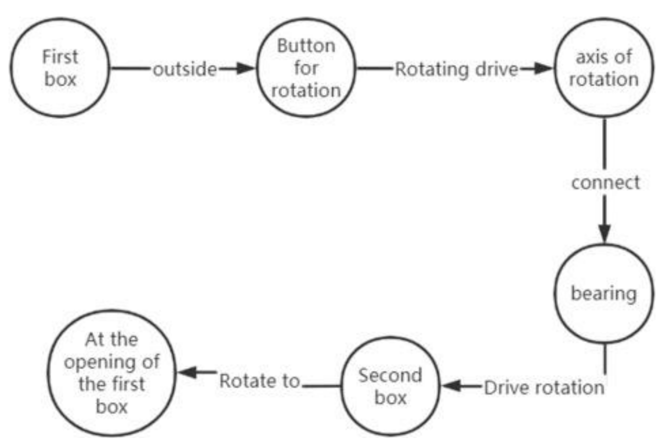
Once the item is inserted into or retrieved from the second box body, the rotating shafts resume motion, advancing the next second box body into alignment. This operational cycle repeats continuously, enabling a high degree of automation and reducing the need for human supervision.

To further enhance operational efficiency and adaptability, the system can be programmed with different rotational speeds and stop durations based on item size, weight, or process requirements. For instance, heavier items may require longer stabilization times, while smaller or lighter items can be processed at higher speeds. Such flexibility makes the device highly suitable for a wide range of packaging scenarios, from small parcel sorting in logistics centers to component handling in automated manufacturing lines [4].

Additionally, the control system architecture is designed to monitor operational parameters in real time, including shaft rotation speed, alignment accuracy, and load status. Alerts or automatic adjustments can be triggered if deviations from expected performance are detected, thereby ensuring consistent and reliable operation.

Overall, the operational flow of the rotating packing device integrates precise mechanical control, intelligent motion planning, and real-time monitoring to deliver efficient, flexible, and reliable item handling, meeting the evolving demands of modern logistics and industrial automation environments.

Table 1: Use flow chart of rotary box used for packaging



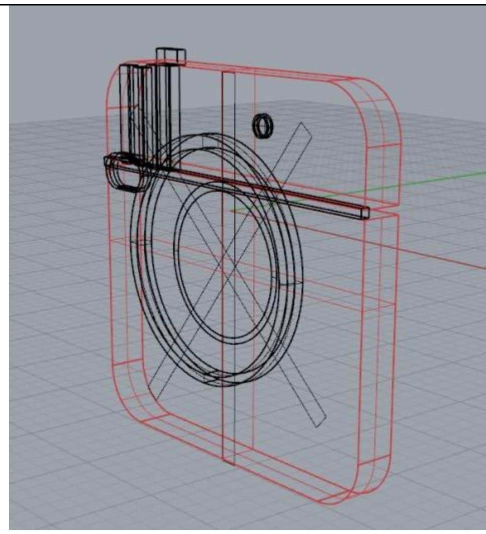


Figure 2. Rotatable structure

4. Specific Implementation

4.1 Structural Composition

Each second box body in the rotating packing device is designed as a regular hexahedron with an open top surface, structurally resembling a drawer. This open-top design facilitates convenient and efficient item insertion and retrieval during operation. The walls of each second box body are constructed from lightweight yet durable materials, such as reinforced polymers, aluminum alloys, or composite panels, balancing the need for mechanical strength with minimal weight to reduce rotational inertia.

The first and second suspended shaft arms are rigidly connected to two opposite lateral faces of each second box body. These connection points are carefully selected and reinforced to ensure uniform load distribution during rotation. The connecting interfaces typically employ mechanical fasteners or welding, combined with bearing assemblies at the joints, to provide both structural support and rotational flexibility. This dual-connection configuration significantly enhances the stability of the box bodies while allowing them to remain securely oriented as the rotating shelves move.

The suspended design, where each box body hangs between a pair of shaft arms, offers multiple engineering advantages. First, it ensures that gravitational forces are evenly distributed across the supporting arms, minimizing stress concentrations that could lead to mechanical fatigue or failure. Second, the suspended configuration provides natural damping of vibrations and oscillations during rotation, which is critical for maintaining smooth and precise operational flow, especially at higher rotational speeds.

During the operational cycle, as the first and second rotating shafts turn synchronously, the openings of the second box bodies are guided into sequential alignment with the opening of the first box body. This precise alignment enables seamless transfer of items without the need for complex active adjustment mechanisms. The spatial arrangement of the box bodies around the rotating shafts is optimized to maximize packing density while preserving sufficient clearance for smooth movement and item handling.

Further structural optimizations include the addition of guide rails or stoppers on the box bodies to limit excessive swing during rotation and improve positional accuracy. If necessary, passive locking mechanisms

ISSN:2377-0430
Vol. 5, No. 4, 2025

can be incorporated to temporarily stabilize the box body during the item transfer phase, releasing automatically once the rotation resumes.

In terms of manufacturability and maintenance, the modular design of the second box bodies and shaft arms allows for easy assembly, disassembly, and replacement. Standardization of box dimensions and connection interfaces facilitates mass production and interchangeability, which is advantageous for scaling the system or adapting it to different operational environments.

Overall, the structural composition of the second box bodies and their integration with the suspended shaft arms provide a robust, flexible, and efficient foundation for the rotating packing device. This design supports not only high-speed and high-volume operations but also adaptability for integration with future intelligent control and monitoring systems [5].

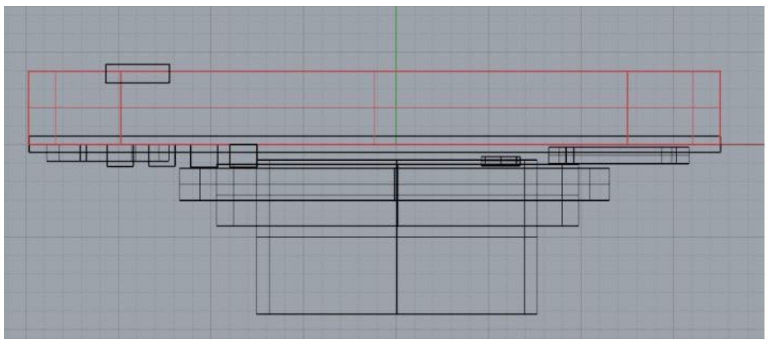


Figure 3. Rotatable attachment mechanism

4.2 Synchronization Mechanism

The synchronization mechanism is a critical component of the rotating packing device, directly influencing the precision, stability, and efficiency of the operational process. It ensures that the first and second rotating shelves, along with their associated shaft arms and second box bodies, move in a coordinated and balanced manner throughout the packaging cycle.

To maintain mechanical balance and minimize dynamic instability during operation, the shaft arms are uniformly distributed around their respective rotating shafts. This radial arrangement ensures that the mass around each shaft is evenly balanced, effectively reducing centrifugal imbalances that could otherwise cause vibrations, mechanical wear, or misalignment of the box bodies during rotation. Careful consideration is given to the number, length, and weight distribution of the shaft arms to achieve an optimal center of mass alignment with the axis of rotation.

Synchronization between the first and second rotating shelves is achieved through either mechanical linkages or electronically coordinated drive systems, depending on system requirements and complexity. In a mechanical configuration, gears, chains, or timing belts can be employed to physically couple the two rotating shafts, ensuring fixed phase relationships and synchronized angular velocities. Such systems are relatively simple, robust, and suitable for environments where operational consistency is prioritized over flexibility.

In more advanced implementations, electronic synchronization is adopted. Each rotating shaft is driven by an independent motor equipped with high-precision encoders. A central control system continuously monitors the angular position and rotational speed of each shaft, dynamically adjusting motor inputs to maintain perfect synchronization. This electronically controlled approach offers greater flexibility, allowing for real-time adjustments to account for load variations, minor misalignments, or external disturbances. It also enables the system to implement advanced motion profiles, such as controlled acceleration and deceleration phases, to reduce mechanical stress and enhance system longevity.

To further ensure operational smoothness, feedback control mechanisms such as Proportional-Integral-Derivative (PID) controllers are integrated into the drive system. These controllers fine-tune the rotational motion based on continuous sensor inputs, minimizing synchronization errors and dynamically compensating for any deviations. In safety-critical applications, redundancy can be built into the control system, including dual encoders and backup power supplies, to maintain synchronization even in the event of component failures.

Additionally, mechanical dampers or vibration isolators can be installed at strategic points along the rotating shafts and shelves to absorb residual oscillations and reduce transmission of vibrations to the supporting structure. These measures contribute to a quieter, more stable, and more durable operation, especially under high-speed or heavy-load conditions.

The effectiveness of the synchronization mechanism directly affects the accuracy with which the openings of the second box bodies align with the opening of the first box body. High synchronization accuracy ensures that item insertion and retrieval processes are smooth and reliable, preventing operational delays or mechanical damage.

Overall, the design and implementation of the synchronization mechanism reflect a careful balance between mechanical simplicity, control precision, and operational reliability. Whether through mechanical coupling or intelligent electronic control, the synchronization system ensures that the rotating packing device operates efficiently, stably, and in perfect coordination, meeting the rigorous demands of modern industrial automation environments [6].

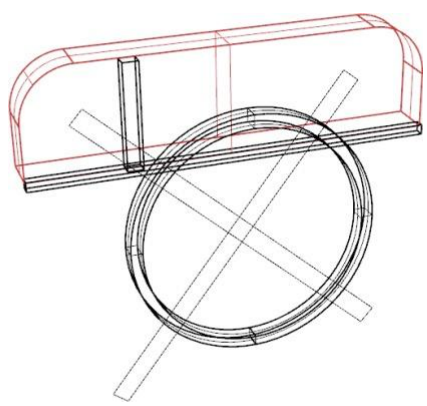


Figure 4. Schematic diagram of rotating mechanism

4.3 Connection Details

The connection details between the second box bodies and the suspended shaft arms are critical to ensuring both the rotational flexibility and the structural integrity of the rotating packing device. These connections must reliably support the dynamic loads experienced during operation while allowing sufficient freedom of movement to accommodate precise rotational alignment.

Each second box body is equipped with a first connecting block and a second connecting block, positioned on two opposite lateral faces of the box body. These connecting blocks serve as the primary structural interfaces for attaching the box body to the suspended shaft arms. The connecting blocks are fabricated from high-strength materials, such as reinforced steel or aluminum alloy, to provide the necessary durability and resistance to repeated mechanical stresses.

The first connecting shaft is linked to the first connecting block at a defined distance from the first bearing located at the end of the first suspended shaft arm. This spatial separation between the bearing and the connecting block is intentionally designed to optimize the mechanical leverage, allowing for smooth rotational flexibility while minimizing bending moments on the shaft arm. The geometry ensures that rotational forces are transmitted efficiently through the bearing-connecting shaft-connecting block assembly, reducing stress concentrations that could otherwise lead to mechanical fatigue or deformation over prolonged use.

Similarly, the second connecting block on the opposite side of the box body is attached to the second connecting shaft, which links to the second suspended shaft arm through a corresponding bearing. This symmetrical connection design not only balances the forces exerted on the box body during rotation but also ensures that the box body remains level and stable throughout the operational cycle.

To further enhance mechanical performance, flexible couplings or damping inserts may be incorporated between the connecting shafts and the connecting blocks. These components help absorb minor shocks and vibrations generated during rotation, improving system stability and extending the service life of both the box bodies and the connecting assemblies.

Precise alignment during assembly is crucial to maintaining system performance. Alignment jigs or fixtures are typically used during the installation process to ensure that the connecting blocks, shafts, and bearings are positioned accurately relative to one another. Any misalignment could result in uneven load distribution, increased friction, and accelerated wear, ultimately compromising the operational reliability of the device.

In addition, all critical connection points are designed for ease of maintenance. The use of standardized fasteners, modular components, and accessible mounting points allows for quick inspection, adjustment, or replacement of worn or damaged parts. To further support operational safety and longevity, periodic maintenance schedules can be established, including lubrication of bearings, torque checking of fasteners, and inspection of coupling elements.

Overall, the detailed connection design between the second box bodies and the suspended shaft arms plays a pivotal role in the overall functionality of the rotating packing device. It ensures that the system maintains a balance between the necessary rotational freedom for dynamic operation and the mechanical robustness required for long-term, high-frequency use in demanding industrial environments.

Figure 5. Local magnification diagram

ISSN:2377-0430
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The openings of the second box bodies are standardized in size, facilitating sequential item placement and retrieval [7].

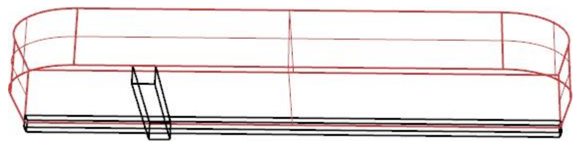

Figure 6. Second box use

5. AI Integration Prospects

To further enhance the functionality, adaptability, and intelligence of the rotating packing device, the application of artificial intelligence (AI) technologies is proposed as a critical direction for future development. By leveraging advanced machine learning and real-time data analysis capabilities, the system can evolve from a purely mechanical operation into a self-optimizing, intelligent packaging solution capable of meeting the dynamic demands of modern logistics and manufacturing environments.

One promising avenue is structural optimization through machine learning algorithms. By collecting and analyzing operational data—such as rotational speed, vibration patterns, load distribution, and stress concentration points—machine learning models can identify patterns and correlations that may not be immediately evident through traditional engineering analysis. These models can then be used to iteratively optimize structural parameters, including the dimensions and materials of the shaft arms, the positioning and specification of bearings, and the mass distribution of the second box bodies. Such data-driven optimization can lead to significant improvements in the device's durability, performance, and energy efficiency over time, while also reducing material costs and maintenance requirements [8].

Real-time monitoring represents another critical application area. By integrating a lightweight convolutional neural network (CNN) trained on image and sensor data streams, the system can achieve continuous, non-invasive monitoring of key operational parameters. The CNN can process video feeds or sensor signals to track the rotation status of the shafts, the alignment precision of the box bodies, and the overall mechanical health of the device. Early detection of anomalies such as misalignment, bearing wear, or unexpected vibration can trigger immediate alerts or automatic adjustments, preventing minor issues from escalating into major system failures. This capability not only enhances system reliability but also significantly extends the operational lifespan of the device by enabling proactive maintenance interventions [9].

In addition to structural and operational enhancements, AI technologies offer significant potential for intelligent management of the packing system. By integrating AI-driven predictive models with Internet of Things (IoT) technologies, the device can dynamically adjust box usage based on real-time workload demands, forecast maintenance needs, and autonomously schedule downtime for repairs or component replacements. Predictive maintenance models, trained on historical performance data, can accurately estimate the remaining useful life of critical components, allowing operators to optimize maintenance schedules and minimize unplanned disruptions. Furthermore, intelligent resource allocation algorithms can prioritize the use of second box bodies based on factors such as load balance, wear level, and current task urgency, further improving operational efficiency and resource utilization [10,11].

Overall, the integration of AI technologies into the rotating packing device presents a transformative opportunity to redefine its capabilities, positioning it as a key component of future smart manufacturing and logistics systems. These advancements not only promise to enhance the device's performance, reliability, and adaptability but also open up new possibilities for autonomous operation, seamless integration with larger industrial networks, and continuous system evolution through self-learning mechanisms. Continued research and experimental validation will be essential to fully realize these prospects and to ensure that AI-enhanced rotating packing devices can meet the increasingly complex and demanding requirements of next-generation industrial environments.

6. Conclusion

This study presents the design, implementation, and prospective enhancement of a novel rotating packing device characterized by a dual-frame, multi-box structure that enables dynamic, efficient, and continuous packaging operations. Through the coordinated rotation of the first and second rotating shelves, each equipped with suspended shaft arms and second box bodies, the device achieves rapid item placement and retrieval while maintaining high structural stability and operational precision. The mechanical design emphasizes ease of use, structural simplicity, and reliability, ensuring that the device can operate effectively under the demanding conditions of modern logistics and manufacturing environments.

The shaft arm mechanisms, connection details, and synchronization strategies have been carefully optimized to balance rotational flexibility with mechanical robustness, providing a foundation for long-term durability and minimal maintenance requirements. The modular and standardized construction further enhances the device's scalability and adaptability, making it suitable for a wide range of application scenarios, from automated warehousing systems to smart production lines.

In addition to the core mechanical innovations, the study explores the future integration of artificial intelligence (AI) technologies as a means to further elevate the device's capabilities. By leveraging machine learning for structural optimization, convolutional neural networks for real-time operational monitoring, and AI-driven predictive models combined with IoT technologies for intelligent management, the rotating packing device can evolve into a self-optimizing and autonomous system. Such integration is anticipated to significantly improve system performance, enhance fault tolerance, reduce operational costs, and enable seamless interaction with broader smart manufacturing ecosystems.

The findings of this study demonstrate that the proposed rotating packing device holds substantial potential for advancing the efficiency, flexibility, and intelligence of packaging operations in industrial settings. Future work will focus on prototyping the AI-enhanced version of the device, conducting extensive experimental validations under real-world conditions, and exploring its integration into large-scale automated logistics networks. With continued development, the rotating packing device is expected to contribute meaningfully to the evolution of intelligent, adaptive, and high-performance industrial automation systems.

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