Design of a Robotic-Based Multi-Packaging Machine

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Abstract: *This study presents the comprehensive design and architectural modeling of a robotic-based multi-packaging machine developed for high-speed and high-precision packaging processes. The system integrates a Delta robot-based pick-and-place unit, advanced servo-controlled horizontal packaging modules, and a modular conveyor design engineered for multi-product stream transfer. This work investigates the core operational challenges, including product flow management, optimized grouping strategies, dynamic conveyor synchronization, coordination of multi-axis servo movements, and the system's overall operational efficiency. The results indicate that the developed system operates with high stability, achieves superior precision, and significantly enhances production throughput by providing automatic parameter optimization based on product variety, thereby aligning with modern Industry 4.0 requirements.*
Keywords*: ROBOTIC PACKAGING, DELTA ROBOT, MULTI-FEEDING, SERVO CONTROL, INDUSTRIAL AUTOMATION.*

1. Introduction

Packaging machinery constitutes one of the most critical and performance-demanding components of production lines in the Fast-Moving Consumer Goods (FMCG) industry, necessitating rigorous standards for speed, precision, and operational stability. Traditionally, mechanically driven packaging solutions are optimized for limited product types, which results in significant and often unavoidable downtime, costly adjustments, and material waste during format changeovers or speed variations [1].

1.1. Problem Statement and Motivation

The proliferation of Industry 4.0 principles and the growing market demand for customized, low-volume, high-mix production have rendered conventional rigid automation systems inefficient and non-adaptive. The critical technological gap lies in the inability of these traditional systems to seamlessly handle the simultaneous grouping of diverse products from multiple feeder lines into a single package, known as multi-packaging, without sacrificing cycle time or precision [2]. This scenario necessitates the development of flexible, high-speed, and intelligent packaging solutions capable of on-the-fly reconfigurability.

1.2. Research Objectives and Contribution

In response to this technological deficit, this study presents the comprehensive design, architectural modeling, and performance analysis of a high-speed robotic-based multi-packaging machine. This novel system addresses the limitations of conventional systems by integrating parallel kinematics with advanced motion control.

The primary contributions of this work are manifold:

i. Architecture Design: Developing a robust, modular mechanical architecture centered around a high-speed Delta robot pick-and-place system integrated with servo-controlled horizontal packaging modules.

ii. Advanced Synchronization: Establishing a precise, low-latency (<0.1 s) synchronization control loop for dynamic tracking and coordination between the high-speed robot, the modular feeding conveyors, and the downstream sealing jaws.

iii. Process Optimization: Investigating and validating novel product flow management and grouping strategies (e.g., 2-, 3-, and 4- unit grouping) that utilize automatic parameter optimization based on the specific product recipe to maximize Operational Equipment Effectiveness (OEE).

This article details the machine's robotic structure design, control architecture, product flow management, system synchronization, mechanical frame specifications, and quantitative performance analyses. The results demonstrate that the developed system achieves high stability and significantly enhances production efficiency by providing automated adaptability to product variety.

2. Literature Review

The imperative for high-speed, flexible, and versatile packaging solutions in the FMCG sector has driven significant research into advanced robotic systems. Traditional mechanically linked packaging systems often struggle with the requirements of low-volume, high-mix production and necessitate significant changeover times for format transitions, highlighting the operational limitations discussed by Wang et al. (2015) in the context of Cyber-Physical Systems (CPS) [17].

2.1. The Role of Parallel Kinematic Robots (PKRs)

The study of multi-packaging and high-speed picking systems consistently demonstrates the superiority of robotic platforms—particularly Parallel Kinematic Robots (PKRs)—over conventional mechanical architectures in terms of production flexibility and speed [1]. Among PKRs, the Delta robot configuration, originally developed by Clavel (1991), is overwhelmingly preferred in the packaging industry [2].

Its prevalence stems from its inherent design advantages:
• Exceptional Acceleration and Speed: Delta robots can achieve high acceleration capabilities (often up to 15 m/s^2) and high cycle rates, with some commercial models capable of executing over 300 picks per minute [3, 4].
• Low Moving Mass and High Stiffness: The parallel architecture ensures actuators are mounted on the base, minimizing moving inertia and maximizing the stiffness-to-weight ratio [5].
• Superior Positioning Accuracy: The closed-loop kinematics of the Delta mechanism provide very high precision and repeatability, typically within +/- 0.1mm or better, which is critical for precision alignment tasks [6].
• Compact Footprint: These robots can be mounted above the workspace, allowing for easy integration into existing or modular line designs [7].
These core advantages position Delta robots as the industry standard for demanding pick-and-place and sorting applications [8, 9].

2.2. Servo Control and System Synchronization

A central technological pillar enabling the high performance of modern packaging lines is the sophisticated coordination of multi-axis servo systems. The integration of high-speed robotics with continuous product flow necessitates precise conveyor tracking [10]. Kragic and Christensen (2002) pioneered the development of algorithms for intercepting moving objects, forming the foundation for modern tracking mode operations [10].

In the context of multi-packaging, the precise synchronization of three main elements is paramount: the robot's end-effector, the product's moving coordinate on the conveyor, and the timing of the downstream packaging (sealing) module [11].

• Dynamic Coordinate Mapping: This involves receiving real-time speed and position feedback from the conveyor's encoder to dynamically adjust the robot's trajectory, a technique that significantly enhances picking efficiency [12].
• Multi-Axis Coordinated Motion: Contemporary packaging machines utilize networked servo drives (e.g., EtherCAT or PROFINET-based architectures) to ensure sub-millisecond synchronization between the robot controller, the feeding conveyor motors, and the servo-controlled sealing jaws [13, 14]. This precise coordination is essential for maintaining constant product pitch and achieving perfect sealing [15]. Research indicates that implementing such integrated servo-driven technology can improve overall line efficiency and cycle time by 20-40% compared to older mechanical cam-driven systems [16].

2.3. Flexibility and Industry 4.0

The design of a modular, robotic-based multi-packaging system aligns directly with the core tenets of Industry 4.0, which emphasizes decentralized control, real-time adaptability, and system interoperability [17]. The ability of the proposed system to handle various unit groups within a single machine demonstrates a high level of reconfigurability and flexibility, allowing manufacturers to rapidly switch between product recipes without extensive mechanical retooling [18]. This adaptability is crucial for achieving the "smart factory" ideal of customized, low-batch production [19]. Furthermore, the deployment of modular components and automated parameter optimization reduces both operational costs and the non-productive downtime associated with manual changeovers [20].

3. General System Design

The multi-packaging machine is engineered as a robust, modular system adhering to high industrial automation standards. The design philosophy centers on achieving maximal throughput and operational flexibility through the precise coordination of high-speed robotics and multi-axis servo technology.

3.1. Mechanical Structure and Modularity

The overall machine architecture is constructed from three primary, modular, and functionally distinct units:
Feeding Conveyor Modules: Responsible for delivering multiple product streams. They feature speed-controlled servo motors and integrated encoders for continuous, real-time positional feedback.

Delta Robot Pick-and-Place Unit: The high-speed core employing a 3-Degrees-of-Freedom (3-DOF) Delta mechanism for product singulation, grouping, and transfer.

Horizontal Form-Fill-Seal (HFFS) Packaging Module: Performs the final packaging operation, driven by synchronized servo controls, featuring servo-controlled jaw and disc assemblies for precise heat-sealing and cut-off.

The machine's structural integrity is secured by a robust carrier skeleton fabricated from AISI 304 stainless steel, ensuring compliance with food grade and hygiene standards (e.g., EHEDG guidelines). The developed multi-packaging machine's front, rear, and top general views are presented in Figures 1, 2, and 3, respectively

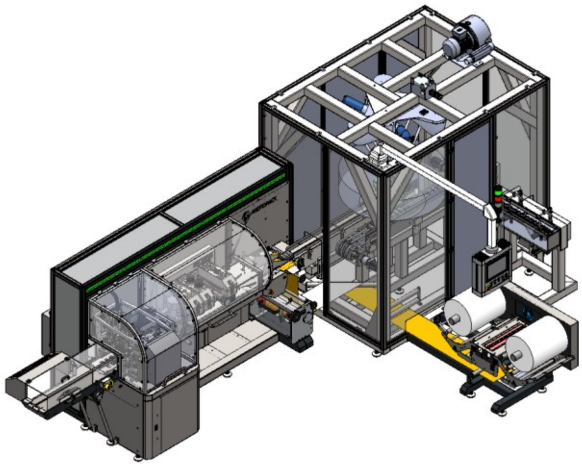

Figure 1: Front View of the Multi-Packaging Machine

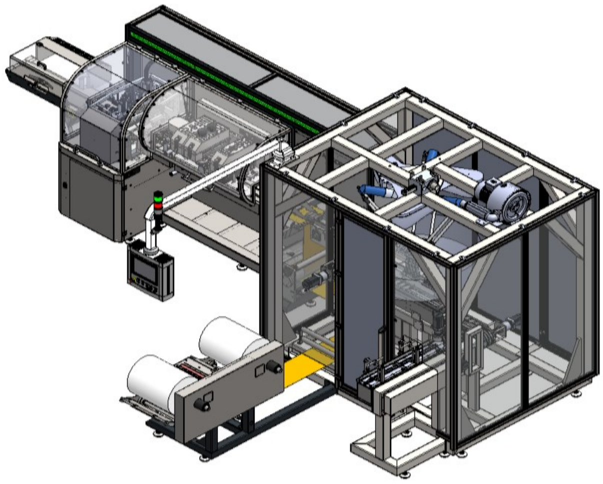

Figure 2: Rear View of the Multi-Packaging Machine

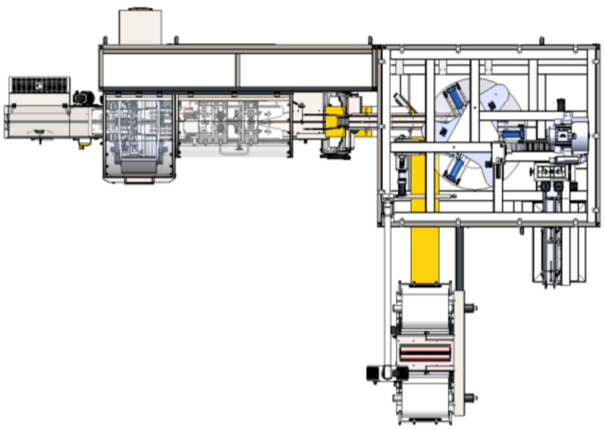

Figure 3: Top View of the Multi-Packaging Machine

3.2. Conveyor Tracking Algorithm and Synchronization Control

Achieving high-speed pick-and-place requires the seamless integration of the robot's motion with the continuously moving conveyor via a sophisticated real-time "Tracking Mode" algorithm. The robot controller dynamically calculates the necessary trajectory adjustments based on four critical data streams:

Table 1. Data streams for necessary trajectory adjustments

Data Stream	Function
Product x-y Coordinate	Defines the precise, instantaneous location of the target product
Conveyor Velocity (v)	Provides the instantaneous speed of the transport belt.
Product Arrival Time (t_a)	Predicts the time remaining until the product reaches the transfer zone
Packaging Jaw Synchronization Point (P_sync)	Defines the exact spatial coordinate for alignment with the sealing cycle.

4. Multi-Packaging Scenario and Grouping Strategy

The machine is capable of assembling and packaging multiple product groups simultaneously within a single wrapper, including: 2-Unit, 3-Unit, or 4-Unit Groups.

The operation is managed through a precise sequence: Product singulation > Robotic grouping > Product alignment > Servo jaw synchronization > Wrapper advancement and transfer. This high-level synchronization maximizes production throughput while accommodating high variability in packaging recipes.

5. Conclusion

The robotic-based multi-packaging machine developed and presented in this study represents a significant advancement in flexible industrial automation. By leveraging the dynamic capabilities of the Delta robot and the precision of multi-axis servo control, the system provides measurable improvements in both production efficiency and product quality stability across manufacturing lines.

5.1. Summary of Findings

The experimental and analytical results confirm the system's robust performance:

• Quality and Reliability: The high accuracy and repeatability ($\pm 0.1 \text{ mm}$) ensure correct grouping and damage-free transfer, increasing the consistency of packaging quality.

• Operational Efficiency: The integrated automatic grouping and synchronized transport capability drastically reduces manual intervention, resulting in shorter cycle times and a substantial increase in overall production speed.

• Flexibility and Adaptability: The robot-centric architecture allows the system to seamlessly accommodate variations in product size and form, confirming its suitability for modern flexible manufacturing requirements and enabling manufacturers to diversify their product offerings.

5.2. Strategic Impact and Future Work

The integration of a streamlined robotic system minimizes in-process waste and reduces the error rate, leading to a demonstrable reduction in overall manufacturing costs. These technical and economic gains collectively boost the operational efficiency of the enterprise and strengthen its market competitiveness.

In summation, the developed robotic-based multi-packaging machine is strategically positioned as a sustainable solution for modern industrial applications, delivering high efficiency, stable quality, low operating cost, and superior flexible manufacturing capabilities.

Future work will focus on incorporating advanced predictive maintenance routines using machine learning models trained on servo drive feedback data, and exploring the integration of collaborative robotics (Cobots) for complementary end-of-line secondary packaging tasks.

5. References

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