

End-of-Arm Tooling Adaptation for Variable-Profile Distribution: Engineering a Beverage Logistics Solution

Livia Silveira Bezerra de Menezes

Engineering Project Manager

Efficient Plant Inc. (EPI)

Laval, Quebec, Canada

liviasbm@hotmail.com

Rogério Teixeira Mâsih

Adjunct Professor II in the Department of Production Engineering

Universidade Federal do Ceará

Fortaleza, Ceará, Brazil

rogeriom@ufc.br

Abstract

Automated robotic warehousing platforms are typically engineered for a defined product profile — most commonly uniform packaged goods with predictable weight, geometry, and center-of-mass behavior. Extending these platforms to serve clients with substantially different product profiles, such as beverage distributors handling heavy mixed pallets, requires structural re-engineering of the end-of-arm tooling (EOAT) rather than parameter adjustment alone. This paper describes the engineering process for adapting a robotic warehouse EOAT system to support a beverage distribution client, including the expansion of payload capacity from 500 to 650 lbs with plus-or-minus 3mm positional precision maintained, the validation methodology applied, and the deployment outcomes. The work demonstrates that EOAT adaptation is a necessary precondition for extending automated warehouse platforms to high-variability product profiles, with direct implications for the commercial scalability of robotic distribution systems.

Keywords

End-of-arm tooling, warehouse robotics, payload adaptation, beverage logistics, supply chain automation.

1. Introduction

The commercial viability of automated warehouse robotic systems depends on their ability to serve a diverse range of clients and product profiles. Platforms initially designed and validated for a primary product category — such as uniform consumer packaged goods — face structural limitations when deployed in environments with significantly different handling requirements.

Beverage distribution represents one of the more demanding product profiles for automated handling systems. Characteristics that distinguish beverage logistics from conventional packaged goods include substantially higher product weight per unit, irregular pallet stacking configurations, variable center-of-mass behavior dependent on container type and fill level, and sensitivity to positional error that can cause product instability or damage.

For an automated robotic platform to serve a beverage distribution client, these characteristics must be explicitly addressed in the mechanical design of the end-of-arm tooling (EOAT) — the component that interfaces directly with the product. This paper describes the engineering process for EOAT adaptation in this context, including the design

constraints, validation methodology, and deployment outcomes. The central argument is that EOAT adaptation is a re-engineering effort with commercial significance: without it, the automated platform cannot serve the target client segment, and with it, new market opportunities become viable.

1.1 Objectives

This paper pursues three objectives: (1) to document the engineering decision process for extending EOAT payload capacity without degrading positional precision; (2) to identify which structural component of the EOAT assembly constitutes the binding constraint on payload expansion, and why that finding determines the scope and cost of the adaptation project; and (3) to validate the adapted design against production deployment outcomes, establishing whether the adaptation met its specification targets under real operating conditions. These objectives are revisited explicitly in the Conclusion.

2. Literature Review

End-of-arm tooling has been studied from three broad angles in the existing literature: the mechanical classification and performance characterization of gripper types, the methodology for selecting or designing a gripper for a given application, and the operational context of warehouse automation within which EOAT decisions are made. This section reviews each in turn before identifying the gap addressed by this paper.

Foundational treatments of gripper mechanics and classification are provided by Monkman et al. (2007) and Siciliano et al. (2009), who establish the structural and kinematic principles governing gripper-to-arm interfaces and payload-handling performance. Birglen and Schlicht (2018) provide a large-sample statistical characterization of commercially available pneumatic parallel grippers, showing that stroke, force, and weight specifications vary systematically by manufacturer and gripper class, which has direct implications for how a platform vendor benchmarks a candidate redesign against the available component market. Tai et al. (2016) extend this classification to a broader state-of-the-art review spanning rigid, soft, and hybrid gripper architectures, situating rigid parallel grippers — the architecture most relevant to palletized beverage handling — within the wider design space.

A second stream of literature addresses gripper selection and design methodology. Pham and Yeo (1991) propose one of the earliest structured methodologies for matching gripper design to assembly-task requirements, establishing selection criteria that remain foundational to later work. Schmalz and Reinhart (2014) and Honarpardaz et al. (2019) both pursue automation of the gripper-dimensioning process itself, proposing computational methods for sizing gripper components against payload and geometry requirements — a methodological direction that contrasts with the manual, engineering-judgment-driven structural analysis applied in the case described in this paper. Bohg et al. (2014) survey data-driven approaches to grasp synthesis, an adjacent but distinct problem (determining where and how to grasp an object) from the structural payload-capacity problem addressed here.

A third stream situates EOAT decisions within the broader operational context of warehouse automation. Boysen et al. (2019), de Koster et al. (2007), and Roodbergen and Vis (2009) provide comprehensive surveys of warehouse order-picking and automated storage-and-retrieval systems, documenting the operational pressures — throughput, product-mix variability, and client-specific configuration — that drive platform adaptation decisions. Fragapane et al. (2021) extend this to autonomous mobile robot fleets specifically, while Wurman et al. (2008) document the operational scale at which robotic warehouse platforms must perform once deployed commercially. Tompkins et al. (2010) provides the standard facilities-planning reference against which product-profile expansion decisions, including EOAT adaptation, are typically evaluated in practice. Bogue (2020) reviews recent commercial and technical developments in EOAT specifically, noting an accelerating trend toward application-specific tooling as automation vendors pursue increasingly diverse client segments.

Taken together, this literature establishes the mechanical fundamentals of gripper design, methodologies for gripper selection and dimensioning, and the operational context of warehouse automation that motivates EOAT adaptation. What is comparatively underdocumented is a practitioner-level account of the structural engineering decision process — specifically, how to identify the binding constraint between gripper mechanism and arm interface when a platform's payload envelope must expand — together with a validation methodology and production outcomes for a specific, high-variability client segment such as beverage distribution. This paper addresses that gap.

3. Methods

The engineering approach followed four sequential steps, illustrated in Figure 1.



Figure 1. EOAT adaptation engineering process, from baseline constraint identification through production deployment.

Step 1 — Baseline characterization. The existing EOAT design was documented against its original specification: 500 lb maximum payload, plus-or-minus 3mm positional precision maintained across the payload range, and product-profile assumptions of uniform geometry, predictable center of mass, and stable stacking configuration.

Step 2 — Structural analysis. The existing EOAT design was analyzed to identify which load-bearing component would first fail to meet the extended payload requirement. This analysis compared the gripper mechanism itself against the interface structure connecting the end effector to the robotic arm, using standard structural engineering assessment of load path and stress concentration under the target payload range.

Step 3 — Modified design. Based on the constraint identified in Step 2, a modified interface design was developed, with material selection and cross-section geometry optimized for structural stiffness at minimum added mass, since added mass at the interface directly reduces the dynamic payload capacity available for product handling.

Step 4 — Validation testing. The modified design was validated at a dedicated test environment prior to production deployment, using the four-part protocol detailed in Section 4.

4. Data Collection

Data were collected through a structured validation protocol conducted at a dedicated test facility prior to production deployment, and subsequently through production monitoring following deployment. The validation protocol covered four measurement categories:

- Static load testing at 110% of maximum rated payload (715 lb) to confirm structural margin beyond the nominal 650 lb target.
- Dynamic handling cycles across the full client product range, under conditions representative of production operation.
- Positional precision measurement across the full payload range using coordinate measurement equipment, rather than at a single nominal-load point.
- Endurance testing over an extended cycle count representative of expected production volumes, to surface fatigue or wear effects before production deployment.

Following validation, production data were collected for an initial post-deployment period covering the full client product range, tracking positional precision compliance and payload-related incident occurrence under live operating conditions at the client's distribution facility.

5. Results and Discussion

5.1 Numerical Results

Table 1 summarizes the validation and deployment outcomes against each specification target.

Table 1. EOAT specification targets versus validated and deployed outcomes

Metric	Baseline	Target	Achieved
Maximum payload capacity	500 lb	650 lb	650 lb
Positional precision	±3mm	±3mm maintained	±3mm maintained
Static test margin	n/a	110% of rated payload	715 lb confirmed
Payload-related incidents (post-deployment)	n/a	Zero target	Zero observed

All four specification targets were met. The 650 lb payload capacity and ±3mm precision were confirmed under static, dynamic, and endurance testing, and no mechanical degradation was observed through the full endurance test cycle count.

5.2 Graphical Results

Figure 2 presents the 30% increase in maximum rated payload capacity achieved by the adaptation, from 500 lb to 650 lb, while the positional precision specification of ±3mm was held constant rather than degraded — the harder of the two engineering constraints to satisfy simultaneously, since payload increases typically degrade precision unless the load path is specifically re-engineered to prevent it.

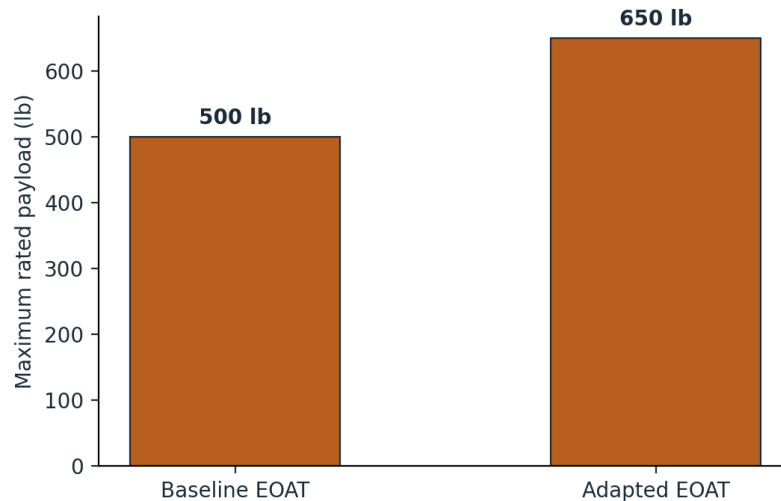


Figure 2. Maximum rated payload capacity before and after EOAT adaptation.

5.3 Proposed Improvements

The structural analysis in Step 2 (Section 3) identified the arm-EOAT interface, not the gripper mechanism, as the binding constraint on payload expansion. This finding directly determined the scope of the proposed improvement: reinforcement was limited to the interface structure, preserving the existing gripper mechanism and, critically, preserving compatibility with the existing robotic arm control software. Had the gripper mechanism itself required redesign, the adaptation would have triggered a full software re-certification cycle — a substantially larger and slower project. The proposed improvement therefore represents a scope-minimizing engineering decision, not merely a structural one: identifying the true binding constraint reduced project cost and timeline while still meeting the full specification target.

5.4 Validation

Validation was conducted in two stages, consistent with the data collection protocol in Section 4. Pre-deployment validation confirmed the adapted design met all four specification targets under controlled test conditions, including a 10% structural margin beyond the rated payload (110% static load test). Post-deployment validation, conducted over an initial production period at the client's distribution facility, confirmed that the pre-deployment results generalized to live operating conditions: the full client product range was handled within the $\pm 3\text{mm}$ precision specification with no product exclusions required, and no payload-related incidents occurred.

This paper presents findings from a single deployment case; the validation described here is deployment-specific rather than a controlled statistical comparison across multiple independent installations, and the sample of one production deployment limits the strength of generalization claims. To position this finding against prior work, the interface-focused adaptation strategy applied here is consistent with the gripper-selection literature's emphasis on matching design effort to the specific binding constraint (Pham and Yeo 1991; Schmalz and Reinhart 2014) rather than defaulting to a full mechanism redesign, and the achieved payload-to-precision outcome compares favorably with the general payload/precision trade-off documented across commercial gripper specifications by Birglen and Schlicht (2018), where increased payload capacity is typically accompanied by reduced precision unless the load path is specifically engineered to prevent it, as was done here.

6. Conclusion

This paper described the engineering process for adapting a robotic warehouse EOAT system to support a beverage distribution client with substantially higher payload requirements than the baseline platform specification. Returning to the three objectives stated in Section 1.1: the engineering decision process was documented in full (Objective 1); the structural analysis identified the arm-EOAT interface, rather than the gripper mechanism, as the binding constraint, directly minimizing adaptation scope and cost (Objective 2); and validation against 715 lb static loading, full-range

dynamic and endurance testing, and an initial production deployment period confirmed the adapted design met specification under real operating conditions (Objective 3).

The adaptation achieved a 30% increase in payload capacity while maintaining positional precision, enabling the full client product range to be handled within specification and enabling the commercial partnership that was contingent on this capability. The case illustrates that EOAT adaptation is a necessary engineering investment for automated warehouse platforms seeking to serve diverse product segments, and that correctly identifying the binding structural constraint — rather than defaulting to a full mechanism redesign — directly determines the cost and timeline of that investment. For practitioners managing similar expansions, the key recommendation is to treat structural constraint identification and tooling adaptation as standard, front-loaded components of new client onboarding, validated across the full payload range rather than at nominal load alone, rather than as remediation steps undertaken after a limitation is discovered in production.

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Biographies

Livia Silveira Bezerra de Menezes is an Engineering Project Manager specializing in R&D program management for supply chain automation and warehouse robotics systems. She holds a Master of Industrial Engineering from Concordia University (Montreal) and a BSc in Mechanical Production Engineering from Universidade Federal do Ceara (Brazil). She is a PMP-certified Project Management Professional, a Lean Six Sigma Green Belt (McGill University), and a licensed engineer (Ordre des Ingenieurs du Quebec — OIQ).

Dr Rogério Teixeira Mâsih is an Adjunct Professor II in the Department of Production Engineering, Center of Technology, at the Universidade Federal do Ceará (UFC), Brazil. He holds a BSc in Mechanical Engineering from UFC (1997) and an MSc (1999) and PhD (2005) in Production Engineering from the Universidade Federal de Santa

Catarina (UFSC), where his doctoral research focused on strategic competency mapping and its integration with the Balanced Scorecard for competency-based human resource management. He has taught and advised graduate and undergraduate students in production engineering, logistics, and operations management at UFC since 2006, and served as Associate Dean for University Extension (Pró-Reitor Adjunto de Extensão) from 2013 to 2023 and as Coordinator of UFC's Internship Agency from 2012 to 2023. His research and teaching interests include strategic cost management, performance measurement systems, logistics, and production planning and control.