HAHN Automation Semi Flexible Tube Pick System

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Problem Definition and Background

At HAHN Automation, customers often request automated machines capable of handling various tasks involving semi-flexible tubes. To address this, the company employs an easy-to-load system, allowing operators to place a batch of parts into the machine and initiate an uninterrupted run. However, the current tube isolation system, designed to separate individual tubes from larger bundles, suffers from notable inefficiencies. Frequent failures in the vacuum system lead to inadequate suction, resulting in inconsistent isolation attempts and extended cycle times. These issues are worsened by an improperly optimized "V"-shaped tray design, which causes misalignment above the vacuum tool. Additionally, the weight of the part batch puts strain on the actuator, hindering its ability to move smoothly through the stack. Furthermore, the actuator controlling the motion arm with the vacuum tooling has suboptimal stroke length and speed, making it difficult to capture parts effectively. Finally, the vacuum tip tooling itself plays a critical role in suctioning one part for isolation, the current profiles are littered with air leak paths which add to the problems seen across the system. Together, these inefficiencies contribute to inconsistent performance and reduced system reliability.

These challenges place a strain on operators, programmers, and toolmakers, requiring frequent intervention and adjustment. Engineering and maintenance teams must also allocate significant time to addressing the recurring issues, diverting resources from other critical projects. The resulting inefficiencies hinder HAHN's production capabilities and negatively affect their ability to meet customer requirements and remain competitive.

The goal of this project is to develop a semi-flexible tube pick testing system that can be used to improve performance and reliability. The proposed solution will address the root causes of these issues by optimizing the seal of the vacuum system, improving the pick presentation and the material finish of the motion body connected to the actuator, and develop a new tray design. This hopes to show new ways to test and improve the system for future implementation into main systems.

Research: Technology and Existing Products

Understanding the challenges faced by HAHN Automation required a deeper examination of the technologies and products currently used in automated part-handling systems. The inefficiencies in the tube isolation process at HAHN reflect broader issues seen across industries relying on similar methods. By analyzing the strengths and limitations of existing solutions, such as vacuum-based systems, mechanical grippers, and vision-guided robotics, this research identifies opportunities to optimize HAHN's current setup. This section explores these technologies, providing insights into their application, challenges, and potential modifications to address the specific needs of HAHN Automation's semi-flexible tube picking system.

Vacuum Systems

Vacuum-based systems are widely used in industries such as electronics, packaging, and automotive manufacturing due to their simplicity, speed, and ability to handle delicate parts gently. However, consistent performance heavily depends on maintaining proper suction levels and ensuring a secure seal between the vacuum tool and the part. HAHN Automation has experienced frequent issues with the vacuum system failing to adequately seal, leading to inconsistent tube isolation attempts and increased cycle times. Similar challenges have been observed industry-wide; for example, in an IConnect007 (1) study emphasizes that poorly designed or maintained nozzles can lead to picking failures and operational delays. These findings highlight the need for improved vacuum tooling at HAHN, focusing on better sealing performance to enhance suction reliability and minimize failed picks.

Tray Design Optimization

The geometry and alignment of the tray play a critical role in the efficiency of tube isolation systems. At HAHN, the current "V-shaped" tray contributes to part misalignment, which not only increases the likelihood of picking failures but also risks damaging parts during the process. According to Assembly Magazine (2), precise alignment is essential for ensuring consistent part handling in automated systems, as it directly impacts quality and efficiency. To address this, redesigning the tray to better match the geometry of the semi-flexible tubes is a key consideration. For instance, transitioning to a "Check Mark" configuration with optimized angles (e.g., 70°-20°) could provide greater stability for the tubes, reduce misalignment, and improve system reliability during picking.

Actuator Movement

The actuator responsible for moving the vacuum tooling is another critical component contributing to inefficiencies in the system. At HAHN, issues such as excessive stroke length and improper speed settings create delays and inconsistencies during tube isolation. Research from Agilian Tech (3) underlines the importance of optimizing the actuator settings to achieve better cycle times and reliable operation. By fine-tuning the actuator’s stroke length and speed, and ensuring its location aligns with the tray design, the system can deliver smoother and more consistent picking performance. These adjustments are essential to reducing the overall cycle time and increasing the reliability of the isolation process.

Transitioning from technology to existing products involves examining real-world implementations that illustrate both the potential and limitations of current systems. Understanding how these products perform offered insights into what adjustments are necessary for improvement at HAHN Automation. This section will explore existing product types and highlight their strengths and weaknesses to better inform targeted modifications to HAHN's system.

Current automated part-handling systems vary in complexity and application, with vacuum cup suction systems, mechanical grippers, and vision-guided robotics being some of the most prevalent. Vacuum cup suction systems are widely used across industries such as packaging, automotive, and electronics due to their simplicity, compact design, and cost-effectiveness. They are suitable for high-speed operations and can handle delicate components gently. However, challenges arise when part surfaces are irregular or when there are fluctuations in vacuum pressure, which can lead to inconsistent suction and operational delays. As noted in Pneumatic Tips (4), vacuum cups are essential for high-speed part handling but are susceptible to failures if maintenance is neglected. This concern aligns with the issues experienced at HAHN Automation, where inadequate sealing in the vacuum system results in inconsistent tube isolation and extended cycle times. Enhancing the vacuum tooling to ensure better sealing performance could mitigate these challenges.

Mechanical grippers are another type of part-handling tool that offers precision and consistency, especially for predictable, heavier, or rigid parts. These systems use clamping or finger-like mechanisms to grasp and transport parts, ensuring secure handling. However, mechanical grippers are more complex, involving multiple moving parts that require regular maintenance, and they can be slower compared to vacuum systems (5). This can be a limitation in high-speed production environments, which is why they may not be ideal for HAHN's goals of efficiency and cost-effectiveness.

Vision-guided robotic arms represent an advanced solution with the capability of using cameras and algorithms to detect a part's size, shape, and position, allowing dynamic adjustments during operation. This makes them highly adaptable for varied and irregular parts, eliminating the need for constant reconfiguration. However, the costs associated with installation and maintenance, as well as the potential for slight delays due to processing times, make these systems less practical for applications where cost and speed are priorities (6). While vision systems offer significant advantages in flexibility, they come with a trade-off of increased complexity and expense. This makes them unsuitable for HAHN's needs, where simplicity and cost-efficiency are valued immensely.

By analyzing these existing products and their respective strengths and weaknesses, it becomes evident that a more targeted approach is necessary. Instead of adopting advanced and costly systems like mechanical grippers or vision-guided robotics, enhancing the current vacuum system and optimizing tray design at HAHN Automation provides a feasible path forward. Addressing issues with inconsistent vacuum performance, suboptimal tray geometry, and actuator calibration through focused improvements will enhance the system's reliability and overall operational efficiency without introducing unnecessary complexity or cost.

Customer Features

The semi-flexible tube pick system at HAHN Automation must meet a variety of needs and expectations to be effective in automated manufacturing processes. The primary users rely on the system to provide consistent, efficient, and safe tube isolation with minimal manual intervention. The following overview of customer needs includes insights drawn from both user feedback and the prioritization of system features based on survey results:

Note: The survey was conducted using a scale from 1 (low, bad) to 5 (high, good) to assess the importance and satisfaction levels of various system features.

1. **Reliability**
   Ensuring consistent and accurate tube isolation without frequent manual adjustments is vital. Reliability in the system's operation affects production flow and reduces downtime. The survey data from HAHN colleagues indicated that uniform tube picking was highly valued, with an average importance rating of 4.0. This need emphasizes the requirement for robust vacuum tooling and reliable part-handling mechanisms.
2. **Efficiency**
   Reducing cycle times and production delays is essential for meeting manufacturing targets. Operators prioritize fast and efficient part handling to maximize system throughput. The survey revealed that cycle time reduction was a significant concern, with an average importance rating of 4.1. Streamlining tray design, optimizing actuator movement, and improving vacuum performance will be key to achieving this goal.
3. **Durability**
   The system should be robust enough to endure long operational hours with minimal maintenance. A durable design minimizes downtime and repair costs while ensuring continuous operation. The survey highlighted system durability as a top priority, receiving an average importance rating of 4.2. The use of high-quality materials and components will be essential to meeting this requirement.
4. **Ease of Use**
   The system must be user-friendly, enabling operators to use it with minimal training. An intuitive and easy-to-operate system helps operators maintain productivity and reduces the time needed for

onboarding new staff. The importance of operator safety and ease of maintenance, reflected in survey responses with average ratings of 4.0 and 3.3, respectively, demonstrates that user-friendliness and straightforward operation are highly valued.

5. **Safety**
   Safety is a non-negotiable aspect of any manufacturing system. The system should incorporate safety mechanisms that prevent accidents and reduce operational risks. The survey put a strong emphasis on safety, with an average importance rating of 4.0. This includes features such as automated safety shut offs and protective guards that comply with industry safety standards.
6. **System Compatibility and Flexibility**
   The system should be adaptable to various tube sizes and types to handle diverse manufacturing needs. Compatibility with different part geometries ensures the system's versatility and utility across different production runs. The survey results showed that this aspect holds significant value, with an average importance rating of 3.8.

Customer Features and Survey Insights

The feedback collected from a survey of 11 colleagues with direct experience in operating the current system provided valuable insight into the features that matter most:

Customer Features	Average Importance Rating	Average Satisfaction Rating
Uniform Pick of Tube	4.0	3.2
Cycle Time	4.1	3.1
Compatibility with Different Sizes	3.8	3.1
Operator Safety	4.0	3.6
Ease of Maintenance	3.3	2.8
System Durability	4.2	2.9
Overall System Footprint	2.8	3.2

Table 1 - Table summarizing customer feature importance and satisfaction ratings, highlighting key priorities such as system durability, reliability, and cycle time for targeted design improvements.

These ratings show the priority placed on system reliability, efficiency, safety, and durability. Features such as uniform pick capability, reduced cycle time, and robust system durability received high importance ratings, indicating that meeting these needs should be central to the new design. Conversely, areas such as ease of maintenance, though important, were rated lower in satisfaction, suggesting room for improvement.

Focusing on the features with the highest importance ratings as seen are reliable picking, reduced cycle time, safety, and durability will guide the design of the semi-flexible pick system. By aligning the design with these core needs, the proposed solution will enhance production efficiency, reduce operational disruptions, and improve overall satisfaction among operators and end users. This approach ensures that HAHN Automation can achieve its goal of developing a system that meets the demands of modern automated manufacturing environments while maintaining a competitive edge in the market.

Product Objective

The objective of this project is to design and develop a semi-flexible tube pick test system that will addresses some of the current inefficiencies at HAHN Automation while meeting the needs and expectations of its users. The primary goals are to enhance system reliability and efficiency as well as to ensure user-friendliness and safety. The system should be capable of handling tube isolation with minimal manual intervention and optimized for long-term operational performance. Specifically, the product objectives include:

1. **Improved Vacuum System Performance**
   Enhance the vacuum tooling to eliminate air leak paths and improve the seal, ensuring reliable suction and consistent tube isolation. This will minimize failed picks and reduce cycle times, addressing the high importance placed on system reliability and efficiency.
2. **Optimized Tray Design**
   Redesign the “V”-shaped tray to improve part alignment and reduce misalignment-related issues. The new tray design, potentially incorporating a "Check Mark" configuration with optimized angles (e.g., 70°-20°), will provide better stability and prevent part damage during picking. This adjustment aims to meet the high priority of reliable part handling and improved cycle times.
3. **Enhanced Actuator Configuration**
   Fine-tune the actuator’s stroke length and speed to enable smoother, more consistent movement through the stack. Aligning the actuator’s location with the tray design will contribute to better cycle times and more effective part isolation. The improvements to actuator performance aim to increase the overall efficiency of the system while reducing strain on the components.

In conclusion, by addressing these objectives, this machine will be capable of identifying potential issues with various parts, enabling HAHN Automation to build a comprehensive database. This database can then be utilized for design improvements and future implementation of other machines, enhancing the company’s ability to optimize their automated systems.

Design Analysis

Design Alternatives and Selection

This section evaluates and selects design alternatives based on their potential to address inefficiencies in the current system while aligning with HAHN Automation's operational goals. The analysis incorporates a comparison of the existing design against proposed solutions and an evaluation process using a structured Design Evaluation Table. Each alternative is discussed in detail, with final selections justified based on scoring metrics and alignment with project objectives.

Tray Design

Current Design

- **Specification:** A fixed V-shaped tray holds tubes in place for isolation.
- **Limitations:** The fixed angle causes tubes to stack taller, resulting in increased weight at the bottom. When parts are picked, this weight can destabilize remaining parts, leading to suction failures and higher cycle times due to repeated attempts.

Proposed Alternatives

1. **Fixed "Check Mark" Tray (70°-20° Angle)**

    - **Description:** The tray is redesigned with a "Check Mark" profile to distribute tube weight more evenly.
    - **Benefits:** Reduces weight at the suction point, improving stability and pick success rate.
    - **Challenges:** Less flexible, as the fixed angles may not accommodate all tube geometries or testing scenarios.
    - **Score:** This option achieved a total score of **17**, with high marks in user-friendliness, company vision, and scalability, making it a strong candidate.

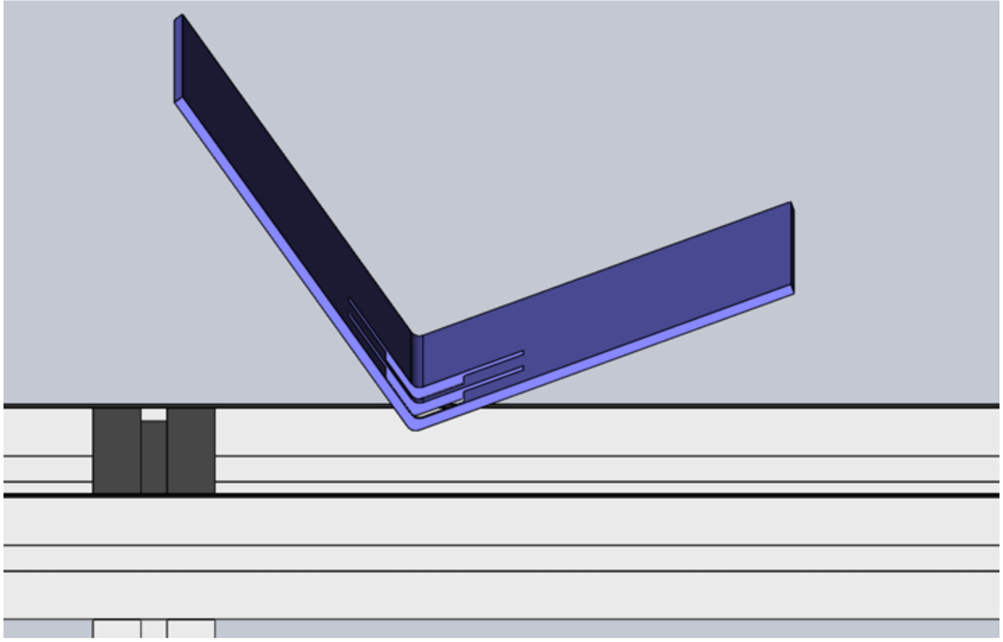

Figure 1 - Proposed "Check Mark" tray design with 70°-20° angles for improved part stability and alignment during the tube isolation process.

2. **Shake Tray Mechanism**
    - **Description: Incorporates a shaking mechanism to realign tubes dynamically, reducing the impact of stacking and promoting even weight distribution.**
    - **Benefits: Can mitigate misalignment caused by tube flexibility and uneven stacking; provides better handling of a wide variety of tube shapes and sizes.**
    - **Challenges: High mechanical complexity and cost; potential for wear overtime due to moving parts.**
    - **Score: Despite its innovative approach, the shake tray scored lower (7) due to its cost and limited alignment with project priorities.**

Selected Design: The **Fixed "Check Mark" Tray** was selected for its balance of simplicity, cost-efficiency, and alignment with project goals, with an estimated price of $1,600.

Vacuum Sealing Mechanism

Current Design

- **Specification:** Vacuum tooling is held in place by magnets.
- **Limitations:** Magnetic attachment results in poor seal quality and vacuum pressure loss, leading to inefficiencies in part suction and isolation.

Proposed Alternatives

1. **Add O-Ring Around the Tool Boss**
    - **Description:** Integrates an O-ring to enhance the seal between the tool and the part.
    - **Benefits:** Improves vacuum reliability without significant changes to the tooling.
    - **Challenges:** Requires regular maintenance or replacement of O-rings due to wear.
    - **Score:** Achieved a total score of **14**, with strong performance in testing innovation and cost.

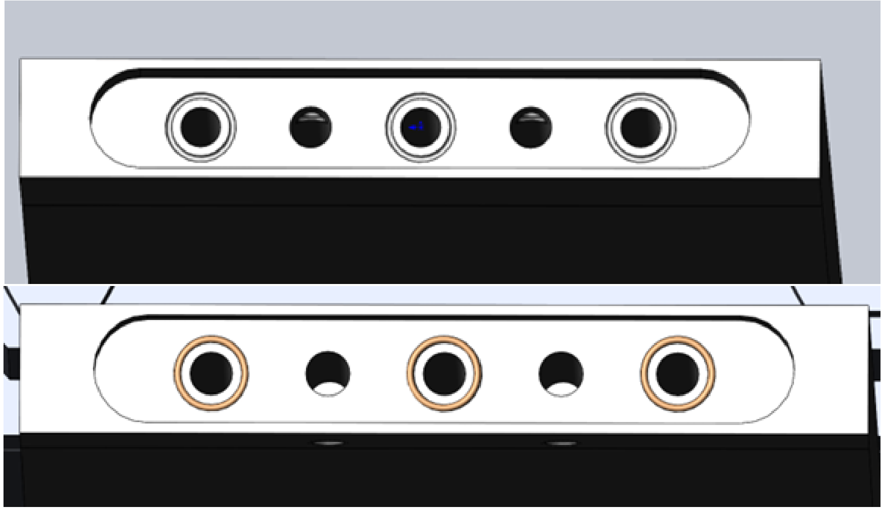

Figure 2 - Proposed O-ring vacuum seal design to eliminate air leak paths and ensure consistent suction performance for reliable tube isolation.

2. **Thumb Screw with O-Ring for Positive Seal Engagement**
    - **Description:** Uses a thumb screw to apply controlled force onto the O-ring for a tighter seal.
    - **Benefits:** Ensures a positive seal and maximum vacuum performance.
    - **Challenges:** Increased setup time and the risk of damage due to overtightening.
    - **Score:** This option scored lower, at **9**, due to reduced user-friendliness and a higher cost.

3. **Custom Gasket in Tool Pocket**
    - **Description:** A custom gasket is designed to fit snugly in the tool pocket, providing a durable and consistent seal.
        - **Benefits:** Offers a low-maintenance solution that enhances sealing without requiring frequent adjustments.

    - **Challenges:** Initial fabrication of the gasket may involve higher upfront costs and precise tolerances.
    - **Score:** This alternative scored **10.5**, as it balances improved sealing performance with moderate scalability.
4. **Spring-Loaded Seal with Ball Engagement**

    - **Description:** Incorporates a spring-loaded ball mechanism to create a dynamic seal that adjusts to variations in tube geometry or tooling.
    - **Benefits:** Provides a secure and adaptable seal, improving vacuum consistency across different tube sizes.
    - **Challenges:** Increased mechanical complexity and potential wear on moving parts, requiring periodic inspection.
    - **Score:** This option scored **11.5**, demonstrating strong potential for scalability and moderate user-friendliness.

Selected Design: The **O-Ring Vacuum Seal** was selected for its simplicity, low cost ($600), and effective performance enhancement.

Actuator Orientation and Stroke Distance

Current Design

- **Specification:** A vertical actuator located beneath the tray with a long stroke distance for picking parts.
- **Limitations:** Excessive stroke length applies unnecessary force on tubes, reducing part retention and increasing the likelihood of detachment from the vacuum tool.

Proposed Alternatives

1. **Teflon-Impregnated Coating and Improved Presentation Distance**

    - **Description:** Combines Teflon coating on the actuator body to reduce friction with adjustments to the actuator's stroke for better part alignment and retention.
    - **Benefits:** Reduces part detachment during pick-up and improves overall system performance.
    - **Challenges:** Involves moderate cost and redesign considerations.
    - **Score:** This combined approach scored the highest at **18**, demonstrating strong alignment with company vision and system flexibility.

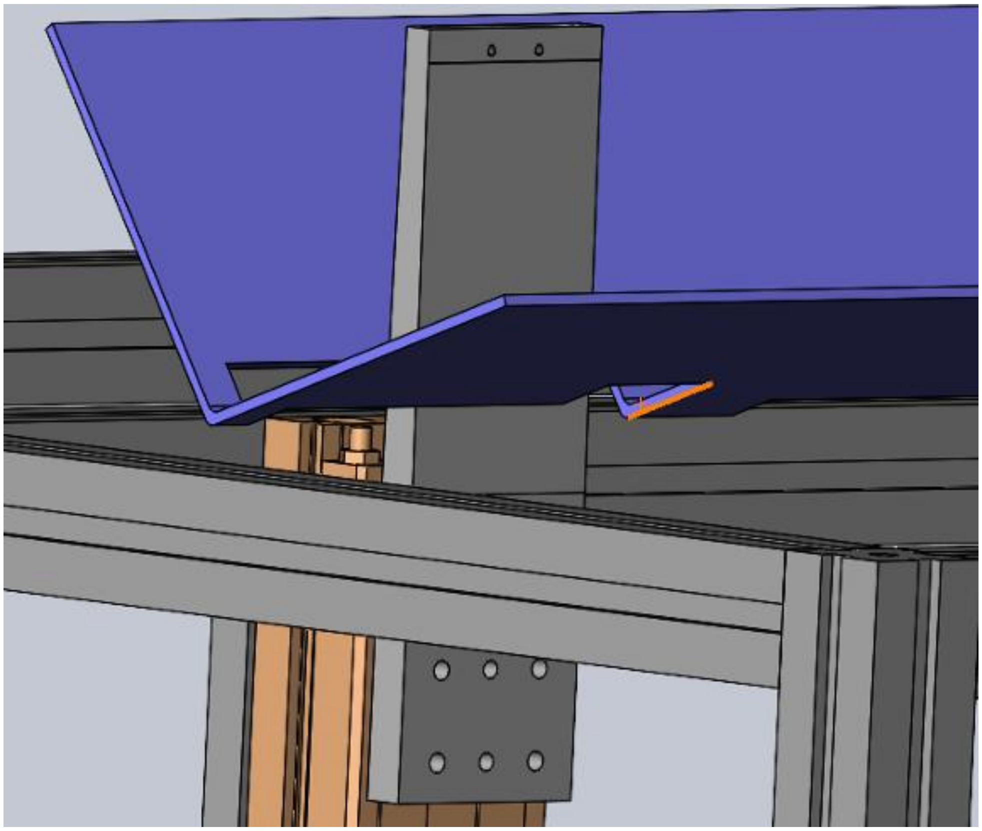

Figure 3 -Enhanced actuator design featuring a Teflon-coated motion body to reduce friction and improve durability during extended operation.

2. **Reorient Actuator to the Top**

   - **Description:** Changes the actuator's position to the top of the system, picking parts from above.
   - **Benefits:** Provides better control of force application and alignment with parts.
   - **Challenges:** Requires significant system redesign and increased complexity.
   - **Score:** Although innovative, this alternative was not selected due to its lower score in scalability and a higher estimated cost.

Selected Design: The **Teflon Coating and Improved Presentation Distance** combination was selected for its effectiveness and alignment with project goals, with a cost of $4,750.

Vacuum Tip Design

1. **Delrin Profiles**

   - **Description:** Vacuum tips designed with Delrin profiles for lightweight, precise suction.
   - **Benefits:** Balances durability with ease of manufacturing and lower cost.

- **Score:** Total score of **14**.

2. **Polycarbonate Profiles**

- **Description:** Vacuum tips made from polycarbonate for enhanced durability and versatility.
- **Benefits:** High strength-to-weight ratio and compatibility with various tube geometries.
- **Score:** Total score of **15**, making it the highest-ranked alternative.

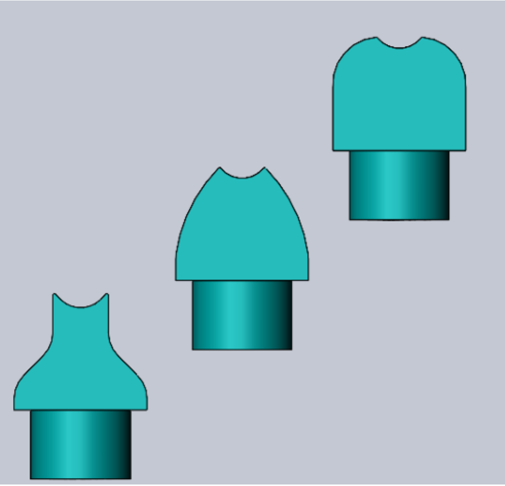

Figure 4 - Redesigned polycarbonate vacuum tips highlighting three distinct profiles to be used for testing the ability to seal around the part, each optimized for one tube size.

3. **Aluminum Profiles**

- **Description:** Vacuum tips made from aluminum for maximum strength.
- **Benefits:** Ideal for high-stress applications.
- **Score:** Despite its strength, aluminum profiles scored lower (**11**) due to higher costs and reduced flexibility.

Selected Design: The **Polycarbonate Profile** was chosen for its balance of strength, flexibility, and cost, with an estimated price of $3,500.

The selected alternatives, including the **Fixed "Check Mark" Tray**, **O-Ring Vacuum Seal**, **Teflon Coating with Improved Presentation Distance**, and **Polycarbonate Vacuum Tip**, provide targeted improvements to HAHN Automation's system. These choices were made based on a detailed evaluation of their performance, scalability, and cost, ensuring alignment with the project's goals and budget. The total estimated cost for the selected components is $10,450.

Solid Model Assembly

The solid model assembly provides a comprehensive visualization of the proposed semi-flexible tube picking system, integrating all selected design improvements. This assembly features the Fixed "Check Mark" Tray, optimized for weight distribution and stability, along with the enhanced vacuum tooling utilizing an O-ring seal for reliable suction performance. The actuator system has been updated with Teflon-impregnated coatings and improved presentation distance to ensure smooth and precise part handling. Additionally, the vacuum tips are designed using polycarbonate profiles for durability and compatibility with a variety of tube geometries. This fully integrated assembly represents a refined solution, balancing performance, simplicity, and cost-effectiveness while addressing the inefficiencies observed in the current system.

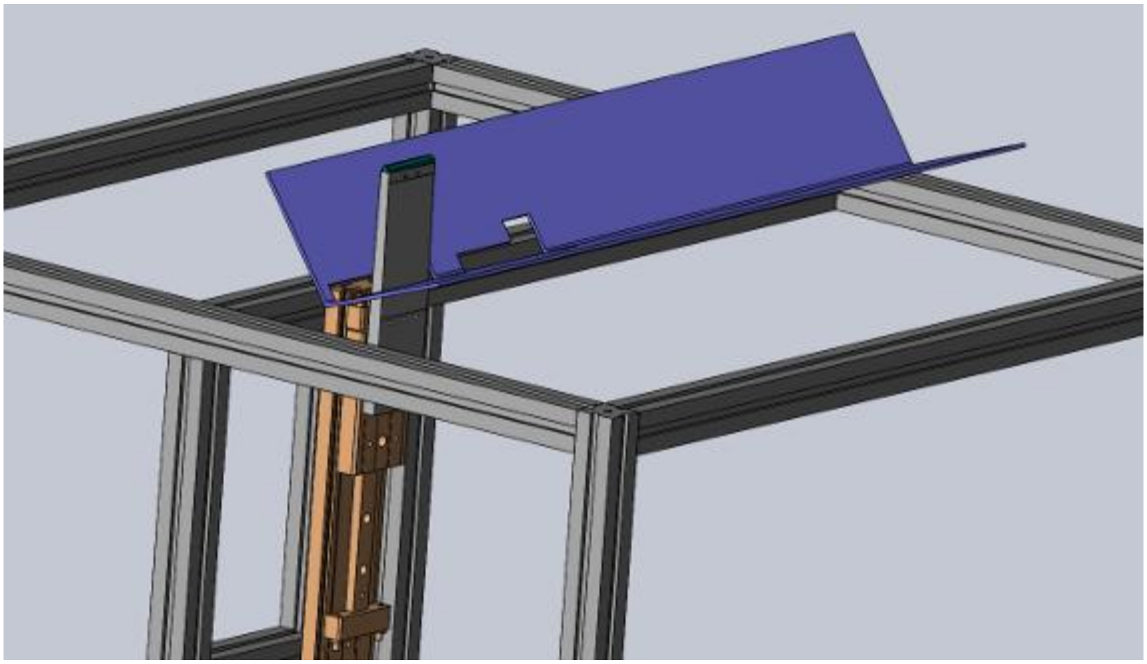

Figure 5 - 3D solid model assembly illustrating the integration of the updated vacuum seal, actuator, and vacuum tip designs, providing a detailed overview of the proposed system enhancements.

Supporting Calculations

Vacuum Loss Through Tubing

Vacuum pressure loss through the ¼" tubing was calculated to ensure the tubing would not cause significant suction loss during system operation. The tubing analyzed was approximately 4 feet in length, with a ¼" internal diameter, operating at a flow rate of 1.5 CFM. The Darcy-Weisbach equation was used to estimate pressure loss through tubing.

Calculations

$$\Delta P = f * \frac{L}{D} * \frac{pv^2}{2}, with\ v = \frac{Q}{A}, A = \pi(\frac{D}{2})^2$$

$$Q = 1.5CFM = 0.000708\frac{m^3}{s}, D = 0.00635m, L = 1.2192m, p = 1.2kg/m^3$$

$$A = \pi(\frac{0.00635}{2})^2 = 3.175e^{-5}\ m^2$$

$$v = \frac{0.000708}{3.175e^{-5}} = 22.35\ m/s$$

$$\Delta P = 0.02 * \frac{1.2192}{0.00635} * \frac{1.2 * (22.35)^2}{2} \approx 1151\ PA = 0.34\ inHg$$

The pressure drop was calculated to be approximately 1151 Pa, or 0.34 inHg. Compared to the vacuum generator's output of approximately 20 inHg, this loss is negligible (~1.7% reduction). Therefore, tubing friction was determined not to be a limiting factor in system performance, and attention was focused on other sources of vacuum loss, such as seal quality at the picking tip.

Factors of Safety of Concern

The factors of safety (FoS) for the semi-flexible tube pick system are calculated to ensure that critical components can withstand the forces and stress experienced during operation. The factors of safety are determined by comparing the material properties and maximum load capacities with the calculated forces from the loading conditions. The primary components of concern are the tray, part pusher, and vacuum tip tools.

Material Properties

1. Tray (300 Series Stainless Steel)
    - Yield Strength: 205 MPa (29,732 psi)
    - Ultimate Tensile Strength: 515 MPa (74,679 psi)
2. Part Pusher (6061-T6 Aluminum)
    - Yield Strength: 276 MPa (40,015 psi)
    - Ultimate Tensile Strength: 310 MPa (44,962 psi)
3. Vacuum Tip Tools (Polycarbonate)
    - Yield Strength: 55 MPa (7,977 psi)
    - Ultimate Tensile Strength: 70 MPa (10,153 psi)

Calculations

1. Tray

The distributed load on the tray from the batch of parts is $0.581\ lbs/in$ (calculated in Load Case 1). Assuming the tray is simply supported and considering its length of 32 inches, the total force on the tray is:

$$Total\ Force = Distributed\ Load * Length = 0.581\frac{lbs}{in} * 32in = 18.6\ lbs$$

The bending stress in the tray is calculated using the formula:

$$\sigma = \frac{M\ * c}{I}$$

Where:

- M = Maximum bending moment = $\frac{wL^2}{8}$ for a simply supported beam
  - $w = 0.581\frac{lbs}{in}, L = 32in$
  - $M = 0.581 * \frac{(32)^2}{8} = 74.4\ in - lbs$
- c = Maximum distance from the beam's center axis to the outermost face of the beam
- I = Moment of inertia (assuming $0.052in^4$ for the 5-inch-wide tray section)

$$\sigma = \frac{74.4 * 0.25}{0.052} = 357.69\ psi$$

The factor of safety for the tray is:

$$FoS = \frac{Yield\ Strength}{\sigma} = \frac{29{,}732}{357.69} \approx 83.1$$

2. Part Pusher

The force action on the part pusher during operation includes the distributed load from parts in contact. Assuming the part pusher interacts with 50 tubes at a time:

$$Force = 50\ tubes * 0.124\frac{lbs}{tube} = 6.2\ \text{lbs}$$

The stress in the part pusher is calculated using its cross-sectional area of $2.5\ in * 0.345\ in = 0.8625\ in^2$:

$$\sigma = \frac{F}{A} = \frac{6.2}{0.8625} = 7.19\ psi$$

The factor of safety for the part pusher is:

$$FoS = \frac{Yield\ Strength}{\sigma} = \frac{40{,}015}{7.19} \approx\ 5{,}566$$

3. Vacuum Tip Tools

The vacuum tip tools experience the force of lifting one tube, including friction. The force due to the tube's weight and friction is calculated as follows:

$$Weight\ Force = 0.124\ lbs$$

Assuming the coefficient of static friction (μ_s) of 0.3 between the tube and the vacuum tip:

$$Friction\ Force = Weight\ force *\ \mu_s = 0.124\ lbs * 0.3 = 0.0372$$

The total force acting on the vacuum tip is:

$$Total\ Force = Weight\ Force + Friction\ Force = 0.124\ lbs\ 0.0372\ lbs = 0.1612\ lbs$$

With a contact area of $0.0609\ in^2$ the stress can be calculated on the vacuum tip:

$$\sigma = \frac{Force}{Area} = \frac{0.1612}{0.0609} = 2.647\ psi$$

The factor of safety for the vacuum tips tooling is:

$$FoS = \frac{Yield\ Strength}{\sigma} = \frac{7{,}977}{2.647} \approx 3{,}014$$

In summary, these factors of safety demonstrate that all components are significantly overdesigned relative to their calculated loads, ensuring robust performance and reliability. FEA analysis will further validate these results by modeling the actual loading conditions.

Component	Calculated Stress (psi)	Material Yield Strength (psi)	Factor of Safety (FoS)
Tray	357.69	29,732	83.1
Part Pusher	7.19	40,015	5,566

Vacuum Tip Tools	2.647	7,977	3,014

Table 2 - This table summarizes the calculated stresses, material yield strengths, and factors of safety for critical components of the semi-flexible tube pick system, ensuring robust performance and reliability under expected loading conditions.

Application of industry Codes, Specifications, and Standards

The design and development of the semi-flexible tube picking system are guided by established industry codes, specifications, and standards to ensure safety, reliability, and compliance with best practices. These standards provide a framework for the system's mechanical, electrical, and operational design, guaranteeing adherence to both regulatory requirements and industry norms. Below is an overview of the relevant codes and standards applied to this project:

1. **ANSI B11.1-2001** (7)
    - This standard ensures the safety of mechanical systems used in industrial environments. For this project, it guides the design of the actuator mechanism and tray to minimize risks during operation, particularly when handling semi-flexible tubes.
2. **ANSI/RIA 15.06-1999** (8)
    - This standard specifies safety requirements for robotic systems, including actuators and vacuum tooling. It informs the integration of safety mechanisms to protect operators during part handling and isolation processes.
3. **NFPA 79 (9)**
    - The electrical components of the vacuum system and actuator are designed to comply with NFPA 79, ensuring safe and reliable electrical connections, proper grounding, and protection against hazards such as short circuits or overloads.
4. **OSHA CFR 1910 (10)**
    - The overall system design adheres to OSHA safety regulations, including ergonomics, hazard identification, and operator safety features. This ensures a safe working environment for all personnel interacting with the machine.
5. **GAMP 5 (11)**

- GAMP 5 is applied to ensure a risk-based approach in designing and validating the system. This standard emphasizes documentation, testing, and validation of the equipment to meet quality assurance and operational consistency requirements.

Each of these codes and standards has been considered throughout the design process to create a system that meets regulatory compliance and industry expectations. For example, the actuator stroke length and tray geometry were evaluated against safety and operational standards, ensuring minimized operator risk and enhanced reliability. Similarly, the vacuum tooling design and its electrical components are guided by NFPA 79 and OSHA requirements, promoting both functional safety and durability. By incorporating these standards into the design, the final system is not only optimized for performance but also meets the demands of operation ensuring long-term reliability in the manufacturing environments.

Component & Material Selection

The semi-flexible tube pick system incorporates carefully selected materials and components to ensure durability, performance, and efficiency. Each material was chosen for its specific properties to meet the system's functional and operational requirements. One key component, the vacuum generator, will be included but has not yet been selected.

1. **Base Weldment**
   - **Material**: 80/20 Aluminum Extrusion
   - **Key Properties**:
     - **Lightweight**: Facilitates ease of handling and assembly.
     - **Modularity**: Allows for easy customization and adjustments.
     - **Corrosion Resistance**: Suitable for long-term use in various environments.
   - **Reason for Selection**: The 80/20 aluminum extrusion system offers a combination of strength and versatility, making it an ideal foundation for a lightweight yet robust system.
2. **Tray (12)**
   - **Material**: 300 Series Stainless Steel
   - **Key Properties**:
     - **Density**: 8.0 g/cm^3
     - **Corrosion Resistance**: Protects against rust and chemical exposure.
     - **Strength**: Yield Strength: ~205 MPa (varies slightly by specific grade).
     - **Durability**: Resists wear, dents, and deformation.
     - **Non-Reactive Surface**: Ideal for contact with semi-flexible tubes.

  - **Reason for Selection**: Stainless steel ensures the tray is robust and resistant to mechanical and environmental stress, supporting consistent tube alignment and handling.

3. **Part Pusher (13)**
   - **Material**: 6061-T6 Aluminum with Teflon-Impregnated Hard Anodizing
   - **Key Properties**:
     - **Density**: 2.7 g/cm³
     - **High Strength-to-Weight Ratio**: Yield Strength: 276 MPa
     - **Wear Resistance**: Hard anodized layer protects against abrasion.
     - **Low Friction Surface**: Teflon impregnation minimizes friction for smooth operation.
     - **Corrosion Resistance**: Extends operational lifespan under demanding conditions.
   - **Reason for Selection**: This material delivers high durability and smooth performance, making it ideal for precision, high-frequency applications like the part pusher.
4. **Actuator Slide**
   - **Function**: Actuator for linear motion control.
   - **Key Properties**:
     - **Compact Design**: Fits seamlessly into limited spaces.
     - **Smooth Linear Movement**: Ensures consistent and accurate positioning.
     - **Durability**: Engineered for extended operational life.
     - **Load Capacity**: Handles system weight requirements efficiently.
   - **Reason for Selection**: The SMC slide table provides precision and reliability, aligning with the need for consistent linear motion in the tube pick system.
5. **O-Ring (14)**
   - **Material**: Buna-N (McMaster-Carr Part No. 9452K14)
   - **Key Properties**:
     - **Density**: ~1.25 g/cm³
     - **Chemical Resistance**: Withstands oils, fuels, and other industrial fluids.
     - **Elasticity**: Adapts to surfaces for reliable performance.
     - **Temperature Range**: Performs effectively between 40°C to 121°C.
   - **Reason for Selection**: The Buna-N O-ring provides a tight and reliable seal, critical for maintaining consistent vacuum performance during tube isolation.
6. **Vacuum Tip Tools (15)**
   - **Material**: Polycarbonate
   - **Key Properties**:

        - **Density**: 1.2 g/cm³
        - **High Impact Resistance**: Withstands repeated use without cracking or deformation.
        - **Durability**: Maintains structural integrity under vacuum forces.
        - **Transparency**: Allows visual inspection of sealing surfaces.
        - **Machinability**: Provides effective suction for consistent tube isolation.
    - **Reason for Selection**: Polycarbonate ensures durable and reliable vacuum tips. The design includes three profiles tailored for testing compatibility.

7. **Description**: A vacuum generator will be used to create the necessary vacuum pressure for the system. The specific model and specifications are yet to be determined and will be finalized based on system testing requirements and compatibility with other components.

Fabrication and Assembly

Fabrication of the semi-flexible tube pick system was completed at HAHN Automation using a combination of milling and 3D printing processes. Was outsources to another company due to the complexity and inability to complete the bending process in house. Custom components such as the actuator mounting blocks and vacuum tip housing were machined from aluminum and polycarbonate materials. 3D printing was used early in the fabrication phase to prototype initial tip designs, which were evaluated and then replaced with final machined versions. Throughout fabrication, tolerances were monitored to ensure correct fits between subassemblies.

Assembly was completed in a modular fashion to streamline integration and simplify troubleshooting. The tray was mounted onto two machined aluminum support blocks attached securely to the 80/20 frame, ensuring level and consistent alignment. The vacuum system, including the Venturi generators, tubing, and pick tip, was installed with careful attention to minimizing potential leak paths. The actuator assembly was tuned separately, with stroke and cycle timing optimized prior to being integrated with the rest of the test cell and then continuously tested for better optimization. System fit-up checks and manual motion tests were performed during integration to ensure proper clearances and functionality across the assembled platform.

Quality control was maintained throughout fabrication and assembly using calipers, gauges, and visual inspection techniques. Critical dimensions were verified, including the tray support alignment and actuator mounting tolerances. Minor adjustments were made during final assembly to optimize system performance, including refinements to stroke positioning and vacuum line routing. The modular assembly approach proved valuable by allowing individual subsystem testing before full integration, improving system reliability, and reducing rework during the final testing phase.

Testing and Evaluation

Testing of the semi-flexible tube pick system was conducted following full assembly to validate performance and identify areas for refinement. Initial testing focused on individual component functionality, including verifying vacuum tip suction, actuator stroke consistency, and tray alignment. Component-level checks confirmed that the actuator operated smoothly after tuning, and the vacuum system achieved baseline suction levels without major leak paths. Manual pick trials were used early on to evaluate part isolation and identify any immediate mechanical interferences or misalignments.

System-level testing was then performed to evaluate complete pick cycles under simulated operational conditions. Cycle times were recorded across different phases of motion, including vacuum pickup, tube isolation, and actuator retraction. Adjustments to actuator timing and tray positioning were made based on early trial results to improve consistency and reduce skipped picks. Special attention was given to assessing the effectiveness of the O-ring sealing strategy at the vacuum tip. Data presented in Table 3 shows the improvements observed in cycle time across different testing phases, while Table 4 outlines the measured changes in pick accuracy when O-rings were implemented.

Extended testing was carried out to evaluate the durability and repeatability of the system. The platform was run through multiple consecutive pick cycles to observe for wear, vacuum degradation, or mechanical failures. Cycle time improvements were achieved through tuning and mechanical refinement, although isolation reliability showed only minor gains. Results confirmed that mechanical layout and actuator optimization were the primary drivers of system performance, while vacuum tip sealing remained a secondary challenge for future development. Overall, the system demonstrated acceptable consistency for a prototype-level test cell and established a solid foundation for future refinement work.

Test Phase	Expected Cycle Time (sec)	Measured Avg. Cycle Time (sec)	Variance (sec)	% Difference
Initial Estimation (Sum)	11.5	10.10	-1.40	-12.2%
Phase 1 – Initial System Start	2.00	4.35	+2.35	+117.5%
Phase 2 – System Picking	8.00	4.50	-3.50	-43.8%
Phase 3 – Actuator Timing	1.50	1.25	-0.25	-16.7%

Table 3 Comparison of expected and measured cycle times across different testing phases, showing improvements achieved through actuator tuning and system refinement.

Test ID	Pick Attempts	Successful Pick 1st Try	Successful Pick 2nd Try	Successful Pick 3rd Try	Fail	Overall %
A	74	36	14	0	24	67.57%
B	59	43	3	4	9	84.75%
C	52	35	11	1	5	90.38%
C1	55	41	8	1	5	90.91%
C2	55	39	11	2	3	94.55%
C3	50	34	7	4	5	90.00%

Table 4 - Pick accuracy results with and without O-ring implementation, highlighting the limited impact of O-rings on vacuum sealing performance.

Project Management

The semi-flexible tube pick project followed a structured schedule from the initial design phase through final testing and reporting. Initial concept development and CAD modeling were completed over a four-week period between December and January. Fabrication and assembly occurred over approximately three weeks in late January and early February, followed by three to four weeks of testing and refinement through March. April was dedicated to final evaluation, system demonstration, and preparation of deliverables. Milestones were tracked internally to ensure consistent progress and to allow time for potential troubleshooting or redesigns.

Tasks	Start Date	End Date	Est Weeks
Professional Proposal	8/26/2024	10/22/2024	8
Concept Design Selection	10/22/2024	11/19/2024	4
Modeling	11/19/2024	12/20/2024	4
Winter Design Presentation	10/22/2024	12/10/2024	8
Release to Manufacturing	12/20/2024	1/1/2025	1
Outsource Components	12/20/2024	1/1/2025	1
Manufacturing Parts Received	1/24/2025	1/31/2025	1
Purchasing Parts Received	1/24/2024	1/31/2025	1
System Assembly	1/27/2025	3/19/2025	7
System Testing	1/27/2025	4/4/2025	9
Tech Expo	1/1/2025	4/8/2025	13
Final Presentation	1/1/2025	5/1/2025	17

Table 5- This table outlines the key tasks, start and end dates for the semi-flexible tube pick system project, providing a structured timeline for design, fabrication, assembly, and testing milestones.

The project budget was initially set at $10,000, with funding provided through HAHN Automation and personal contribution. Actual expenses totaled approximately $5,500, with the majority of costs attributed to in-house labor and machining time for custom components. Material costs for aluminum, stainless steel, and polycarbonate parts were minor. The remaining funds were unused due to efficient resource management and effective use of available fabrication equipment. No major budget overruns or emergency purchases were required, and the project remained financially on track throughout all phases.

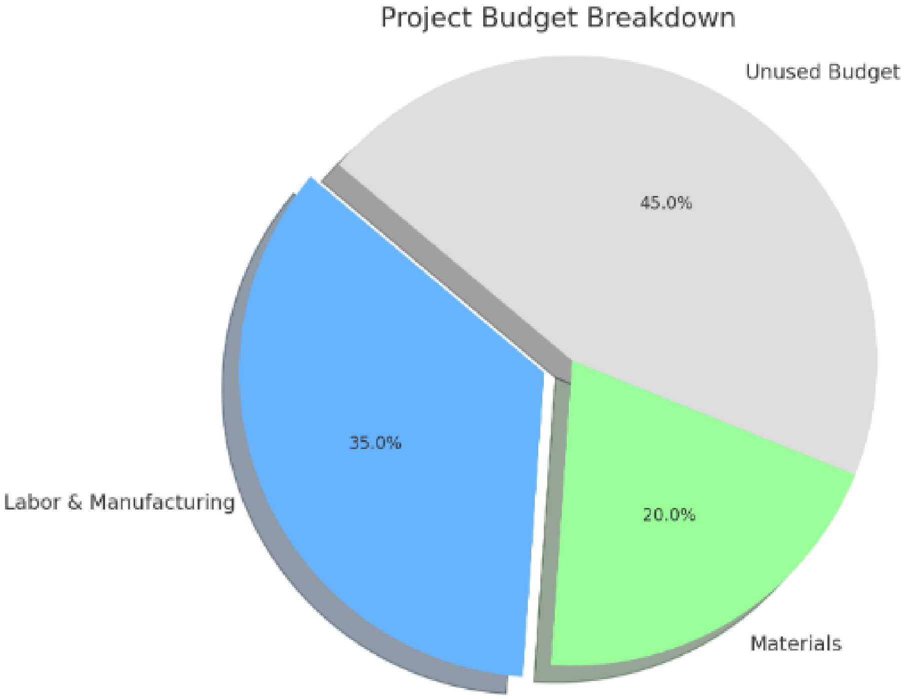

Figure 6 - Project budget allocation, showing distribution of total costs between labor, material expenses, and remaining unused funds.

Project management tools included SolidWorks for design tracking, Excel for budgeting and timeline monitoring, and Outlook for scheduling reviews and assembly/testing deadlines. Regular informal reviews were conducted with mentors and colleagues to validate system design choices and ensure feasibility. The modular build approach allowed flexible scheduling, as individual subassemblies could be completed and validated independently. Overall, project management practices contributed to the successful and timely completion of the prototype system within the original scope and financial targets.

Challenges Encountered, Opportunities for Improvement, and Project Conclusion

Throughout the development of the semi-flexible tube pick system, several challenges were encountered that influenced design iterations and testing strategies. The primary technical challenge involved achieving reliable tube isolation during vacuum pickup cycles. While mechanical adjustments to the tray geometry and actuator tuning resulted in improved consistency, attempts to further enhance vacuum sealing through the addition of O-rings proved ineffective. Vacuum losses due to tubing friction were calculated and determined to be negligible, confirming that seal design at the part interface was the limiting factor. Minor mechanical alignment issues during initial assembly were quickly resolved through modular subsystem adjustments, validating the effectiveness of the modular design approach.

Future development efforts should focus on refining the vacuum pick interface to achieve more reliable tube retention. Potential improvements include investigating alternative sealing materials, custom gasket profiles, or rigid mechanical capture designs at the pick tip. Additional opportunities exist in automating the actuator cycling and vacuum confirmation through simple sensors and a basic PLC or microcontroller system. Enhanced data logging during future testing phases could provide more detailed cycle-by-cycle analysis and drive further optimization of timing and mechanical performance.

The final semi-flexible tube pick test cell successfully met the core project goals of building a functioning platform capable of isolating tubes and validating design concepts. Mechanical improvements to the tray and actuator significantly enhanced operational consistency, while modular fabrication strategies allowed efficient troubleshooting and assembly. Although some experimental design features, such as the O-ring seals, did not yield the desired results, the project demonstrated strong engineering process discipline and delivered a working system suitable for continued development. The final assembled system is shown in Figure 7.

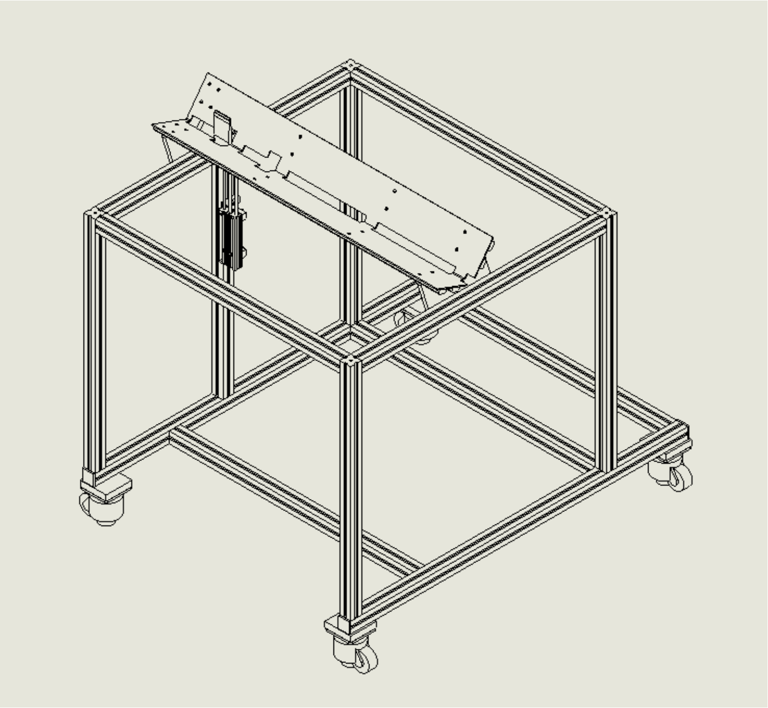

Figure 7 - Isometric view of the completed semi-flexible tube pick system, showing final assembly of the tray, actuator, vacuum components, and supporting frame.

References

1. Smt Preventive Maintenance: Stop 5 major problems with pick-and-place nozzles. IConnect007 Good for the Industry [online]. [Accessed 13 September 2024]. Available from: https://iconnect007.com/index.php/article/52613/smt-preventive-maintenance-stop-5-major problems-with-pick-and-place-nozzles/52616
2. Parts positioning: Fine-tuning parts placement. ASSEMBLY RSS [online]. 28 December 2011. [Accessed 13 September 2024]. Available from: https://www.assemblymag.com/articles/82738 parts-positioning-fine-tuning-parts-placement
3. ADAMS, Paul. Manufacturing cycle time (part 1): Machining Optimization. Agilian [online]. 3 June 2024. [Accessed 13 September 2024]. Available from: https://www.agiliantech.com/blog/manufacturing-cycle-time-part-1-machining-optimization/
4. KORANE, Ken, NADAR, Vgneshwaran, SAYS, Franz and PATRO, Roopjeet. Vacuum cups: How are they used? Pneumatic Tips [online]. [Accessed 30 September 2024]. Available from: https://www.pneumatictips.com/how-are-vacuum-cups-used/
5. DAVIS, Lakisha. 4 types of robotic grippers and their pros and cons. Metapress [online]. 12 May 2021. [Accessed 30 September 2024]. Available from: https://metapress.com/4-types-of-robotic grippers-and-their-pros-and-cons/
6. Vision-guided robotic systems. Acieta [online]. [Accessed 30 September 2024]. Available from: https://www.acieta.com/automation-application/vision-systems/
7. American National Standards Institute. Safety Requirements for Mechanical Power Presses. New York: ANSI, 2001.
8. American National Standards Institute and Robotic Industries Association. American National Standard for Industrial Robots and Robot Systems – Safety Requirements. New York: ANSI/RIA, 1999.
9. National Fire Protection Association. Electrical Standard for Industrial Machinery (NFPA 79). Quincy, MA: NFPA, 2021.
10. Occupational Safety and Health Administration. General Industry Safety Standards (29 CFR 1910). Washington, DC: OSHA, 2021.
11. International Society for Pharmaceutical Engineering (ISPE). GAMP 5: A Risk-Based Approach to Compliant GxP Computerized Systems. Tampa, FL: ISPE, 2008.

12. PENFLEX and BARKER, Alexandra. Differences between the 300 series Stainless Steels. *Penflex* [online]. 23 August 2023. [Accessed 8 December 2024]. Available from: https://www.penflex.com/differences-between-300-series-stainless-steels/
13. ASM Aerospace Specification Metals Inc. *ASM material data sheet* [online]. [Accessed 8 December 2024]. Available from: https://asm.matweb.com/search/specificmaterial.asp?bassnum=ma6061t6
14. Product Detail. *McMaster* [online]. [Accessed 8 December 2024]. Available from: https://www.mcmaster.com/catalog/130/4000/9452K14
15. Accura 60: A clear polycarbonate 3D printing material. *Protolabs* [online]. [Accessed 8 December 2024]. Available from: https://www.protolabs.com/services/3d-printing/plastic/polycarbonate/accura-60/

ABSTRACT

The goal of this project was to design, fabricate, and validate a modular semi-flexible tube pick system capable of isolating individual tubes for future automation applications. The system incorporated a redesigned stainless-steel tray, a vacuum pick mechanism, and an actuator-driven support structure. Fabrication was completed using in-house CNC machining, manual processes, and 3D printing, with modular design allowing independent testing of key subsystems. Testing demonstrated improvements in cycle time consistency and system reliability, though efforts to enhance vacuum sealing using O-rings proved largely ineffective. Overall, the system successfully validated mechanical improvements to the part handling process and provides a platform for future development focused on vacuum optimization and automation integration.