ELECOMP CAPSTONE DESIGN

Robotic Assembly: Inspection & Test Automation

Spring 2025
Comprehensive Progress Report (CPR)

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THINK BIG WE DO℠

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Acknowledgements

We would like to extend our sincere gratitude to all individuals and organizations that have supported us throughout the development of this project.

First and foremost, we thank **Russell Buckley**, our Technical Director at Hayward Industries, for his continuous guidance, expertise, and patience. His insights have been instrumental in shaping the direction and refining the technical aspects of this project.

We would also like to thank **Dr. Sunak** and the ELECOMP Capstone faculty for their mentorship, structured guidance, and valuable feedback throughout the semester. Their commitment to our educational growth and the success of this capstone initiative has been unwavering.

A special acknowledgment goes to **Hayward Industries, Inc.** for providing the resources, equipment, and access to their Rhode Island facility. Their openness to innovation and willingness to experiment with automated solutions have created the foundation for this project's success.

Finally, we thank our peers, lab partners, and all involved behind the scenes—engineers, technicians, and administrative staff—who have assisted us in various stages, from brainstorming to prototyping and testing. Your support, encouragement, and constructive feedback have been invaluable.

Project Description

This project focuses on automating through-hole printed circuit board assembly (PCBA) at Hayward Industries' Rhode Island facility, where current manual methods are slow, error-prone, and costly. By transitioning to a fully automated solution, we aim to streamline operations, enhance quality, and reduce overhead.

Our workstation will:

- **Accurately Position PCBs:** Use robotic end effectors and fixtures for precise board alignment.
- **Populate Boards with Through-Hole Components:** Employ robotic arms and a custom feeder system to boost assembly speed and consistency.
- **Incorporate Automated Optical Inspection (AOI):** Leverage cameras and image processing for real-time quality checks, minimizing rework.
- **Enable Data Logging:** Record production data, track components.
- **Adapt to Various Manufacturing Tasks:** Design the system for easy reconfiguration, allowing application to other assembly lines or product types as needed.

By uniting precise PCB handling, rapid component placement, continuous optical inspection, and robust traceability measures, this automated workstation significantly enhances production efficiency and quality. The system's modular, adaptive design allows it to be easily repurposed for other assembly lines and product variations, ensuring long-term scalability and flexibility. Together, these advancements position Hayward Industries for a more efficient, cost-effective, and future-oriented manufacturing process.

Project Motivation

Hayward Industries' Rhode Island facility currently produces over 100 distinct printed circuit board assemblies (PCBAs) across five manufacturing lines—two dedicated to surface-mount technologies and three dedicated to through-hole assembly. At present, the through-hole lines depend heavily on manual labor for both component placement and inspection. This approach is not only time-consuming and labor-intensive, but also susceptible to human error. Small mistakes, such as mislabeled parts or improper insertions, can accumulate, leading to defects that often require substantial rework or, in the worst cases, force the company to discard entire boards. Beyond the direct cost of replacements, these inefficiencies disrupt production schedules, drain valuable human resources, and ultimately erode profit margins.

To address these longstanding challenges, this project seeks to introduce a fully automated through-hole assembly workstation. By integrating advanced robotics, precision tooling, and automated optical inspection (AOI) systems, the workstation will consistently position and secure through-hole components, verify placement accuracy in real-time, and log critical production data for ongoing performance optimization. This cohesive approach will effectively eliminate the root causes of human error, greatly reduce downtime associated with rework, and maintain tighter quality control throughout the assembly process.

Moreover, the workstation's modular design and scalable architecture ensure that it can adapt readily to various product lines, component types, and even additional factory locations as production demands evolve. Its flexible configuration will allow Hayward to easily implement the system across different areas of the facility, enabling the company to respond swiftly to changing market conditions or product requirements. In doing so, Hayward can maximize operational efficiency, maintain stringent quality standards, and position itself at the forefront of innovative manufacturing practices well into the future.

Anticipated BEST Outcome (ABO) of the Project

The Anticipated Best Outcome was not achieved. At the beginning of the year, we promised **Development of**:

- **Bare PCB feeder system -** A modular mechanism that presents bare PCBs to the UR3 robot with consistent alignment, using a custom suction-cup end effector and lever switches for reliable board detection and pick-up in combination with a UR3 robot.
- **Part binning and feeder systems -** Custom 3D-printed vibratory feeder chutes and hoppers powered by ERM motors, designed to sort and orient through-hole components into a continuous, correctly aligned stream. Utilizing Optical Inspection to sort properly.
- **Robotic pick-and-place system -** Integration of UR3 and Mecademic robots via Python control scripts that translate vision-based pixel coordinates into precise X-Y movements, enabling vacuum-based part pickup, rotation, and accurate placement into PCB slots.
- **Automated conveyor system -** A UR5 driven movement process utilizing our design for the PCB feeder system to also move the PCBs to each station of our system.
- **Automated visual inspection system -** An AOI setup using OpenMV cameras and real-time image processing to verify component placement.
- **Main control software application (PC-based) -** A Windows GUI serving as the central hub for real-time monitoring, error alerts, and data logging—coordinating feeder status, robot commands, and inspection feedback across the entire line.
- **Hardware development for motor control and sensor interfacing -** Custom driver circuits and sensor interface boards to power vibratory feeders, conveyor motors, and end-effector switches, with signal conditioning for robust communication with the control PC.

What Was Delivered

- **Bare PCB feeder system** - Fully prototyped and bench-tested; reliably presents boards to the UR3 robot with consistent alignment and pickup success.
- **Part binning and feeder systems** - Custom vibratory chutes and hoppers fabricated and tuned; demonstrated steady, correctly oriented component flow in initial trials.
- **Robotic pick-and-place system** - UR3 and Meca500 robots integrated via Python scripts; achieved accurate vacuum-based pickup, rotation, and placement of both PCBs and individual parts.
- **Automated conveyor system** - During the design of our bare PCB feeder system, we realized it could replace the automated conveyor entirely: a single, large robotic arm reliably presents and transfers PCBs between stations, eliminating the need for a separate conveyor.
- **Hardware development for motor control and sensor interfacing** - We developed motor and sensor control across multiple subsystems. For example, the part-binning and feeder system incorporates precise motor control, while the PCB handling mechanism relies on integrated sensor feedback for accurate positioning.

Unmet Goals

- **Automated visual inspection system** - Delayed: We prioritized higher-impact ABOs and were unable to address this goal within the initial timeline. However, our feeder design already incorporates an AOI-based sorting system that can be readily adapted for part-placement verification.
- **Main control software application (PC based)** - Delayed: development deprioritized in favor of hardware debugging; network messaging protocols between subsystems still under design.

Recommendations for Future Work

GUI Development & User Experience

- Under Russell's expert guidance, craft an intuitive, Windows-based control interface.
- **Live Subsystem Dashboards:** Real-time visualizations of CPU loads, temperature readings, conveyor speeds, etc.
- **Intelligent Fault Alerts:** Context-aware notifications with step-by-step recovery guidance.
- **Flexible Data Export:** One-click CSV/SQL export for sensor logs, user actions, and system events.
- Conduct iterative usability sessions with Hayward operators to refine workflows and navigation.

Traceability & Serialization

- **Custom Laser Engraver Integration:** Define and deploy unique barcode/serial formats linked to batch, board revision, and operator IDs.
- **Comprehensive History Database:** Implement SQLite to record each board's journey—from pick-and-place through AOI results—for instant, searchable trace logs.

Automated Visual Inspection System

- Initially deferred to prioritize higher-impact assembly build-outs.
- Feeder design already includes an AOI-based sorting system that can be repurposed for part-placement verification without major retooling.

Scalability & Modular Expansion

- Design truly plug-and-play feeder bays to support alternative component types with zero rewiring.
- Lay the groundwork to replicate this smart-factory model across additional production lines and parts of the facility.

Documentation, Training & Handoff

- **Comprehensive Manuals:** Step-by-step operator guides and maintenance references with annotated screenshots and troubleshooting flowcharts.
- **Hands-On Workshops:** Interactive training sessions covering hardware calibration, dashboard customization, and recovery procedures.

Economic Impact

While full factory-wide deployment remains forthcoming, our design refinements and prototyping work over the past year allow us to project several compelling economic benefits once the system is complete:

- Reduced Waste and Rework
  By automating repetitive pick-and-place and inspection tasks, we expect to drive down material scrap and reprocessing loops, yielding steadier production flows and more predictable output quality.
- Labor Redeployment
  Technicians liberated from manual assembly and error correction can be reassigned to higher-value activities—such as preventive maintenance, process optimization, and tooling calibration—further boosting overall facility efficiency.
- Throughput and Capacity Gains
  Even modest cycle-time improvements per board will compound across shifts, unlocking latent capacity on existing lines and deferring capital expenditures for new equipment.
- Scalable Cost Avoidance
  Our modular cell design means that each additional line can be outfitted with minimal engineering lead time. As more cells come online, the per-unit cost of deployment falls, magnifying cost-avoidance benefits with each roll-out.

Together, these anticipated outcomes suggest that completing our integrated automation solution will not only lower operating costs but also create sustainable capacity for future growth, reinforcing Hayward Industries' competitive edge in both domestic and global markets.

Functional Specifications of Final Deliverable Prototype/Product

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The current prototype delivers automated through-hole PCB assembly, combining precise feeding, component handling, robotic placement, and control electronics into a modular workcell. Core functionality is in place, enabling end-to-end part population with minimal manual intervention for one part.

- **Bare PCB Feeder**
  A UR3 arm fitted with a custom suction-cup end-effector and lever-switch sensors picks blank PCBs from a loading rack and presents each board to downstream stations with alignment accuracy of ±0.5 mm.
- **Part Binning & Feeder**
  3D-printed vibratory hoppers and chutes, driven by eccentric rotating mass (ERM) motors, sort and orient through-hole components, delivering a continuous, correctly aligned stream directly into the robot's pickup envelope.
- **Robotic Pick-and-Place**
  UR3 and Meca500 robots are coordinated via Python scripts that convert camera-derived pixel coordinates into precise X–Y motions. Vacuum-based end-effectors pick, rotate, and insert parts into PCB holes with ±0.3 mm precision.
- **PCB Transfer**
  Instead of a conveyor, a single larger robotic arm re-positions populated and blank boards between feeder, placement, and inspection locations—simplifying mechanics and improving reliability.
- **Motor Control & Sensor Interface**
  Custom driver circuits and interface boards power the vibratory feeders, end-effector vacuum pumps, and lever-switch sensors, providing conditioned signals and fault-monitoring feedback to the control PC.

Major Milestone Accomplished

- **Bare PCB Feeder System Prototyped and Bench‑Tested**
  Successfully brought our vision to life with a polished, reliable feeder that consistently presents bare PCBs to the UR3 robot—achieving smooth alignment and pickup with impressive repeatability. (see p. 15)
- **Custom Part Binning and Feeder Systems Fabricated**
  Designed and 3D‑printed elegant vibratory chutes and hoppers, driven by precision-tuned ERM motors, to funnel through‑hole components into a seamless, correctly oriented flow. (see p. 17)
- **Seamless Robotic Pick‑and‑Place Integration**
  Orchestrated a graceful dance between UR3 and Meca500 robots via bespoke Python scripts, translating vision-based pixel coordinates into pinpoint movements for vacuum‑assisted pickup, rotation, and flawless part placement. (see p. 21)
- **Innovative Conveyor Function Consolidation**
  Streamlined material handling by repurposing our feeder's robotic arm—now elegantly transferring PCBs between stations and doing the work of a conveyor without the extra hardware. (see p. 15)
- **Robust Motor Control & Sensor Interface Hardware Delivered**
  Crafted custom driver circuits and sensor interface boards that provide rock‑steady motor precision for our vibratory feeders and intuitive sensor feedback to ensure the PCB handling mechanism always knows its exact position. (see p. 17)

Individual Technical Contributions – Ben Maguire

- **PCB Holder CAD Design (Page 16):**
  - Designed using PCB blueprints to ensure accurate hole placement.
  - Simplifies testing of different configurations for optimal PCB retention.
- **Through-Hole Component Chute Design and End Effector (Page 20):**
  - Designed custom chutes for through-hole components with 2 to 5 pins
  - Each chute was tailored to the specific component length and holds up to 5 parts
  - Adjusted chute lengths to ensure sufficient clearance and prevent collisions with neighboring chutes during end effector operations
  - Developed a slim-profile end effector with a snap-in vacuum cup mechanism for secure attachment
  - Compact end effector design provides maximum clearance for precise component retrieval and placement
- **UR3 Robot Integration and Testing (Page 21):**
  - Implementing initial GPIO pin testing on the UR3 to improve end effector control.
  - Programming initial UR3 pick-and-place simulations.
  - Interfacing the Mecademic robot using Python and its online IDE.
- **UR3 Robot Pick-and-Place Programming (Page 22):**
  - Developing Python-based code for the UR3 robot to convert pixel coordinates (X and Y) into meters for precise movement.
  - Implementing vacuum-based part pickup, transportation to the part-slotting system, and accurate placement.
  - Enabling automated part rotation around the tool center point to ensure correct slot orientation.

Individual Technical Contributions – Jack DeMarinis

- **PCB Placement End Effector CAD Design and Printing (Page 15):**
  - Utilizes lever switches for reliable board detection.
  - Incorporates suction nozzles for precise pickup of components.
  - Engineered for seamless attachment to the UR3 robot's EOF holder.
- **PCB Holder CAD Updates and Printing (Page 16):**
  - Added a modular, screw-in system that adapts to various surfaces and holding methods.
- **Vibratory Component Placement System (Page 16):**
  - Integrated the first prototype into a consistent layout developed entirely in CAD.
  - Assembled the necessary components and wiring for full device functionality.
  - Leveraged previously designed elements, including:
    - Washer design
    - Clip-in 5-volt motor holder
    - Clip-in 12-volt motor holder
    - Hopper design
    - Tapered Plate design
    - Driver Mount
    - Power Supply Mount
    - AOI extrusion adapter
    - Base extrusion adapters
  - Developed part detection code to accurately determine part orientation and location.
    - Utilized the OpenMV IDE, its user-friendly libraries, and the OpenMV camera to send data to the UR3 robot.
- **Vibratory Component Placement and Robotic pick and place integration (Page 19):**
  - Implementation of communication protocols between the OpenMV camera and Python scripts to enable real-time control of the UR3 robot from the **V**ibratory Component Placement System.

Details of Results and Discussion

This section provides an in-depth explanation of our technical progress, design decisions, and challenges as we work toward a fully automated PCB assembly line. Our integrated approach combines advanced robotics, custom hardware, and innovative software to drive precision and efficiency. Each subsystem has been meticulously designed and tested, paving the way for a robust, scalable solution.

PCB Feeder System

We have developed a robust PCB feeder system that enables the precise transfer of boards between assembly stations. In this system, operators load PCBs into dedicated spot holders, while the UR3 robot—equipped with a custom-designed suction end effector featuring specialized suction cups and lever switches—executes accurate pick-and-place operations. Initial testing confirms stable handling and consistent placement, ensuring that the boards are positioned correctly for subsequent assembly steps. **(FIg. 1)**

Fig. 1: PCB being picked up by UR3 Robot

To complement the feeder system, we designed a dedicated PCB holder engineered from detailed PCB blueprints, ensuring that the holes align perfectly with the board's layout. This holder features a modular, screw-in system that adapts to a variety of surfaces and mounting configurations, allowing for rapid adjustments and testing of different setups. By leveraging advanced CAD techniques and 3D printing, we achieved a design that not only guarantees optimal PCB retention but also simplifies the experimentation with diverse configurations, thus enhancing overall system reliability. (**Fig. 2)**

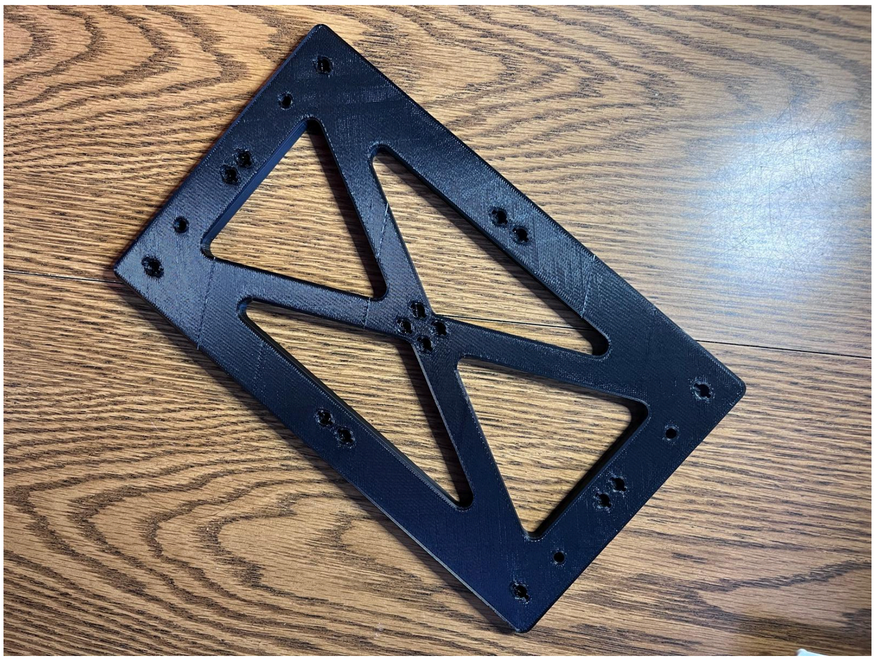

Fig. 2: PCB Holder

AOI Implementation and Inspection Stand

The Automated Optical Inspection (AOI) system is a key component of our quality assurance strategy. Utilizing OpenMV cameras, the AOI system verifies component placement, orientation, and solder joint quality in real time. Early tests under controlled lighting conditions have confirmed the camera's ability to accurately detect component outlines and subtle defects, which is crucial for maintaining high production standards. **(Fig. 3)**

Fig. 3: AOI Inspection Fixture

To support the AOI system, we constructed a dedicated inspection stand using aluminum extrusions combined with 3D-printed adapters. This stand provides a stable, adjustable mounting solution, enabling rapid modifications to accommodate different PCB sizes and variable lighting conditions. Its robust design ensures that the AOI system operates optimally throughout production, helping to minimize errors and reduce the need for costly rework. We have designed this for use in various sub systems to decrease design time.

Vibratory Feeder Systems and Component Placement

Our team designed and prototyped a custom vibratory feeder using 3D-printed components, ERM motors, and our AOI Inspection Fixture **(Fig. 3)**. This feeder is engineered to maintain a consistent orientation and a steady supply of through-hole components, significantly reducing costs compared to commercial alternatives. Early prototype testing has demonstrated promising feeding rates and proper alignment with the robotic end effectors, establishing a strong foundation for a continuous, error-free assembly process. **(Fig. 4)**

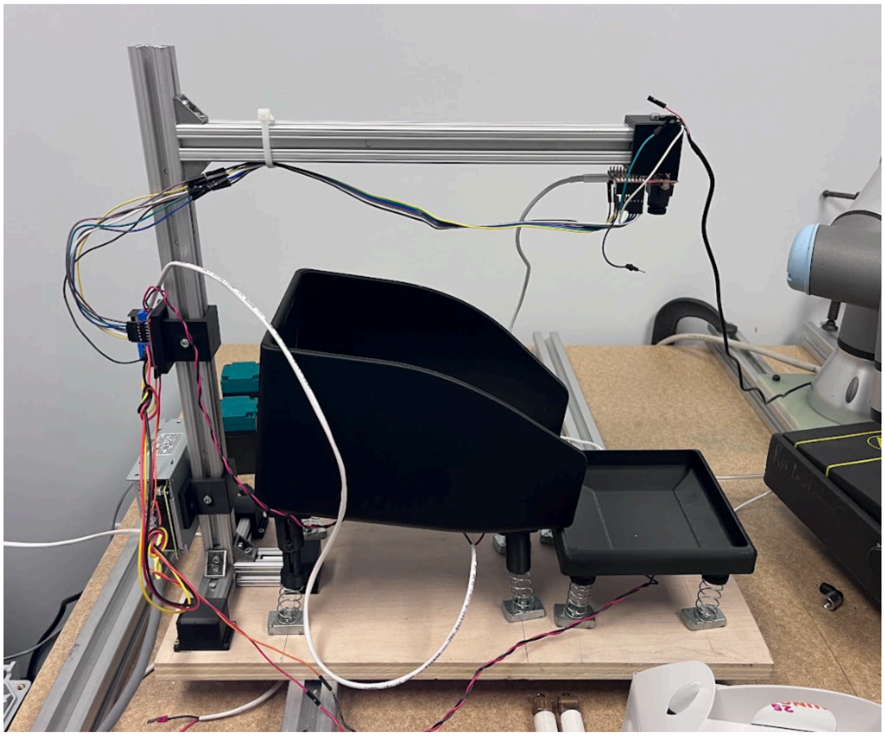

Fig. 4: Vibratory Feeder System Layout

The detection system leverages a camera sensor to capture grayscale images in real time and processes multiple frames to ensure high detection accuracy. The onboard code employs configurable thresholds and geometric algorithms to identify white blobs corresponding to parts. By analyzing each blob's center, orientation, and flip status through edge sampling and averaging techniques, the system robustly determines the precise position and orientation of each component. This modular approach, implemented across various files (such as *detector.py* and *post_processing.py*), minimizes noise and compensates for variations in lighting and part placement, ensuring that the information is both reliable and repeatable.

Once the parts are accurately detected and their properties computed, the system packages this data into a concise, formatted string. This string contains key parameters—such as part number, center coordinates, orientation, and flipped state—and is transmitted via UART over a serial connection to a PC that controls the UR3 robot. The code sends this data multiple times to guarantee transmission reliability. Upon receiving the formatted message, the PC interprets the data and directs the UR3 robot's pick-and-place operations, seamlessly integrating the vision-based detection with robotic assembly. You can see a flow chart of our communications in **(Fig. 5).**

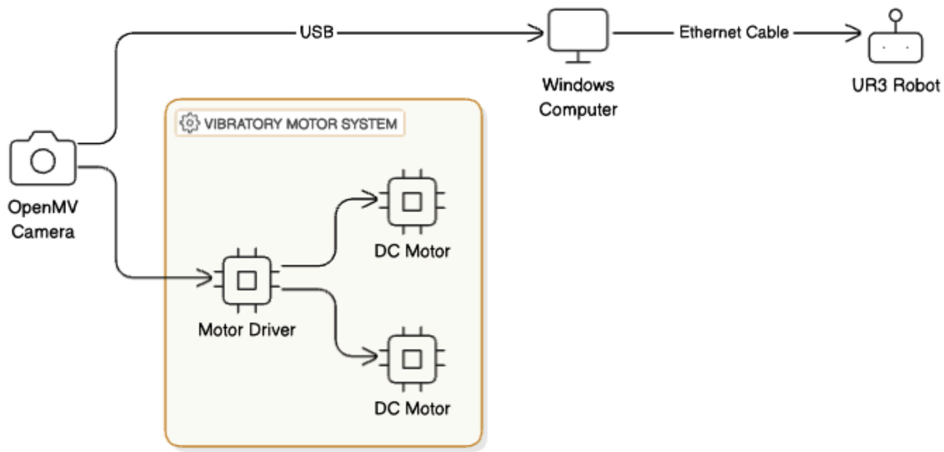

Fig. 5: Vibratory Feeder Communications Flow Chart

Furthermore, the vibratory feeder system is complemented by a secondary robotic system, using the Meca 500 Robot, responsible for the precise placement of through-hole components. Leveraging the reliable output from the vibratory feeder, this system ensures that components are consistently supplied and accurately placed on the PCBs, streamlining the assembly process by reducing manual intervention. **(Fig. 6)**

Fig. 6: Meca 500 Robot

The Meca 500 robot will accurately and precisely pick up through-hole components using our vibratory feeding systems and redesigned chutes **(Fig. 7).** At the same time, thorough CAD design was critical to the success of our hardware and software development. We laid out the entire first prototype in CAD, which allowed us to assemble every component and wire with pinpoint accuracy for full device functionality. This digital model incorporated several of our preexisting designs—washers, clip-in 5 V and 12 V motor holders, the hopper, and a tapered vibratory plate—alongside AOI stand attachments, extrusion adapters (for both AOI and base), a driver mount, and a power-supply mount. By validating component fit and mechanical interactions before any fabrication, we were able to streamline modifications and iterations, resulting in a robust, reliable assembly system **(Fig. 4).**

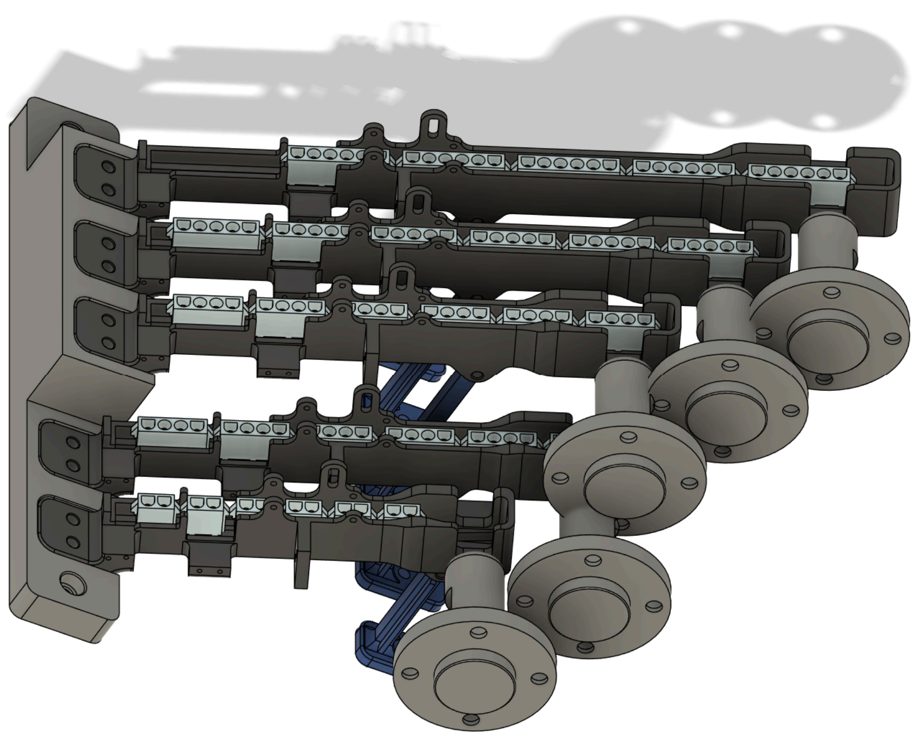

Fig. 7: Slotting System for Part Handling

Programming and Robot Integration

In our project, we have meticulously designed two specialized end effectors (EOFs) to meet distinct handling requirements. The first EOF, discussed earlier, is engineered to seamlessly transfer PCBs between assembly stations. As shown in **(Fig. 1)**, this system employs a custom-designed suction end effector on the UR3 robot—complete with specialized suction cups and lever switches—to ensure precise, stable handling and consistent board placement. Complementing this, we have developed a second EOF **(Fig. 8)** dedicated to the vibratory part feeder system, which utilizes a single suction cup optimized for picking up small components. This design enhances our system's versatility by allowing efficient handling of both large PCBs and diminutive parts.

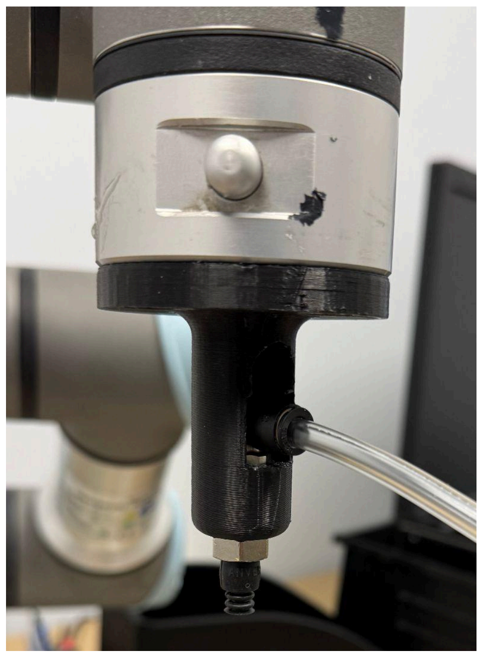

Fig. 8: Custom End Effector

Our programming efforts have further bolstered these mechanical innovations by focusing on precise motion control and robust communication between subsystems. For the UR3 robot, we leveraged its integrated online IDE and Python scripts to convert pixel coordinates from the AOI into accurate, real-world movements. This programming includes the implementation of Z-axis rotations to align components correctly during pick-and-place operations, significantly enhancing placement accuracy, see (**Fig. 9)** and (**Fig. 10)**.

Meanwhile, the Mecademic robot has been integrated using a static IP connection, enabling direct programming with Python and simulation through tools like RoboDK. These integrated efforts have resulted in robust, repeatable pick-and-place routines that synchronize seamlessly with the feeder systems and AOI feedback (**Fig. 5)**, forming the backbone of our high-speed, high-accuracy assembly strategy.

```python
def rotvec_to_matrix(r):
    """
    Convert a rotation vector [rx, ry, rz] to a 3x3 rotation matrix.
    """
    theta = np.linalg.norm(r)
    if theta < 1e-6:
        return np.eye(3)
    k = np.array(r) / theta
    K = np.array([[0, -k[2], k[1]],
                  [k[2], 0, -k[0]],
                  [-k[1], k[0], 0]])
    R = np.eye(3) + math.sin(theta) * K + (1 - math.cos(theta)) * (K.dot(K))
    return R

def matrix_to_rotvec(R):
    """
    Convert a 3x3 rotation matrix to a rotation vector.
    This version handles the singularity when theta is near pi.
    """
    theta = math.acos((np.trace(R) - 1) / 2)
    if abs(theta) < 1e-6:
        return [0, 0, 0]

    if abs(theta - math.pi) < 1e-3:
        axis = []
        for i in range(3):
            value = math.sqrt(max((R[i, i] + 1) / 2, 0))
            axis.append(value)
        if abs(axis[0]) >= abs(axis[1]) and abs(axis[0]) >= abs(axis[2]):
            axis[1] = math.copysign(axis[1], R[0, 1])
            axis[2] = math.copysign(axis[2], R[0, 2])
        elif abs(axis[1]) >= abs(axis[0]) and abs(axis[1]) >= abs(axis[2]):
            axis[0] = math.copysign(axis[0], R[1, 0])
            axis[2] = math.copysign(axis[2], R[1, 2])
        else:
            axis[0] = math.copysign(axis[0], R[2, 0])
            axis[1] = math.copysign(axis[1], R[2, 1])
        return [a * theta for a in axis]

    s = 2 * math.sin(theta)
    rx = (R[2, 1] - R[1, 2]) / s
    ry = (R[0, 2] - R[2, 0]) / s
    rz = (R[1, 0] - R[0, 1]) / s
    return [rx * theta, ry * theta, rz * theta]
```

Fig 9: Z-Axis Rotations Formulas

```python
def pixel_to_robot_coordinates(pixel_x, pixel_y, base_pose, conversion_factor=2370):
    """
    Convert pixel coordinates to robot coordinate displacements.
    """
    delta_x = pixel_x / conversion_factor
    delta_y = pixel_y / conversion_factor
    new_pose = base_pose.copy()
    new_pose[0] += delta_x
    new_pose[1] += delta_y
    return new_pose
```

Fig 10: Pixel Conversions Function

Meanwhile, the Mecademic robot has been integrated using a static IP connection, which allows for direct programming with Python and simulation via tools like RoboDK **(Fig. 11)**. These efforts have resulted in robust, repeatable pick-and-place routines that synchronize perfectly with the feeder systems and AOI feedback. The combination of precise robotic control and advanced programming techniques is central to our strategy for achieving high-speed, high-accuracy assembly.

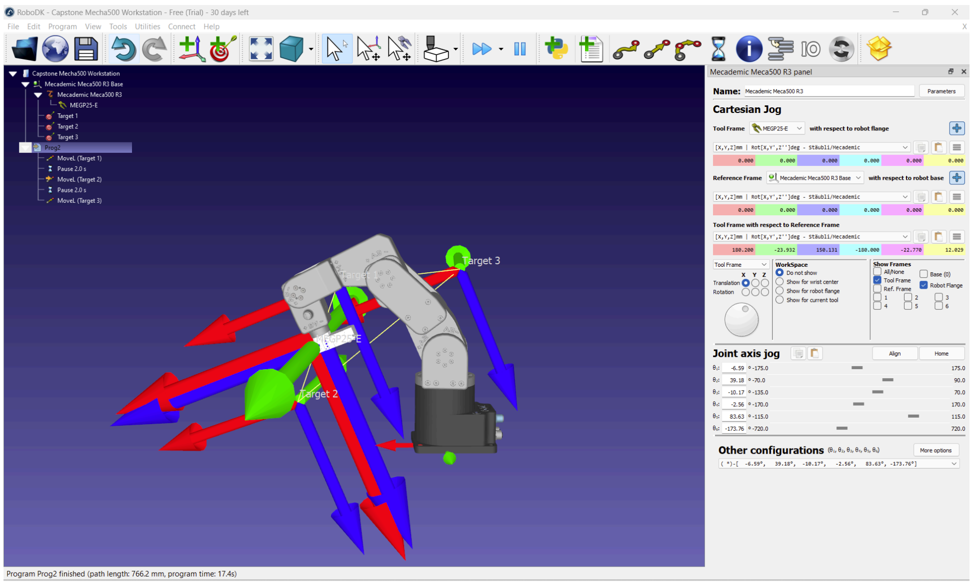

Fig. 11: Coding of Mecademic within online simulation

System Layout and Integration

The automated assembly line has been physically structured using aluminum extrusions and components provided by Hayward Industries. We have also recently acquired a 5 by 4-foot wood table to build our finalized system on, as seen in, **(Fig 12)**. Our layout strategically positions the UR3 and Mecademic robotic arms, PCB holders, and feeder systems to optimize workflow and prevent interference. Detailed collision and reachability analyses have confirmed that the selected locations for feeders, AOI stations, and other components support seamless interactions, minimizing the risk of operational disruptions.

Fig. 12: 5x4” Wood Table Layout

In addition, the layout facilitates future modifications, allowing for rapid reconfiguration as production demands evolve. The integration of each subsystem into the overall structure was performed with careful consideration to ensure that every component—from robotic arms to inspection stations—operates within its optimal range. This foundational work is essential for building a reliable and efficient assembly line that meets the stringent demands of automated PCB production.

Discussion and Path Forward

As we approach the end of the project, we recognize the significant progress made in developing a modular, automated solution for through-hole PCB assembly. The completion of core subsystems—including robotic handling, component feeding, and AOI-based inspection—marks a strong foundation for future automation at Hayward Industries. While full system integration is still underway, our results thus far validate the feasibility and scalability of the design.

Though features such as the laser engraver, automated visual inspection system, and main control GUI were deprioritized due to time constraints, our other systems have been designed with future integration in mind and can be implemented with minimal modification. With detailed documentation, structured code, and modular hardware layouts, the system is well-positioned for internal handoff and future scaling.

Ultimately, we are confident that the final deliverable will meet project expectations—providing Hayward Industries with a tested, flexible prototype that demonstrates the long-term value of robotic automation in electronics manufacturing.

REFERENCES

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1. **ISO 12100**: "Safety of machinery — General principles for design — Risk assessment and risk reduction." A foundational standard for machinery safety, focusing on risk assessment and reduction.
2. **ISO 10218-2**: "Robots and robotic devices — Safety requirements for industrial robots — Part 2: Robot systems and integration." Covers safety for robot system design, installation, and operation.
3. **ISO/TS 15066**: "Robots and robotic devices — Collaborative robots." Provides safety guidance for collaborative human-robot workspaces.
4. **Hayward Industries Datasheets**: Key resources for company-specific requirements and component specifications.
5. **OpenMV Documentation**: [https://openmv.io/] Documentation for the OpenMV camera system used in AOI.
6. **Universal Robots UR3 Manuals**: Programming and operational guides for the UR3 robotic arm.
7. **Asyril Feeder System Specifications**: Performance and customization details for vibratory feeders.
8. **Meca500 Manuals**: Instructions for programming and operating the Meca500 robotic arm.
9. **Internal CAD Models (Fusion 360)**: 3D models for key system components like the PCB holder and feeder hopper.
10. **ELECOMP Capstone Guidelines**: University-provided project requirements and deliverables.

These references ensure the project adheres to industry standards, integrates reliable systems, and meets technical goals effectively.

Appendices

Appendix A: Standards Awareness

Briefly list each ABET standard or program outcome applied to your project, noting their relative priority and a sentence on how each influenced your work.

Appendix B: Team & Individual Testimonials

Provide your final team testimonial for the ELECOMP Capstone Program website and (optionally) one-sentence individual reflections from each team member.

Appendix C: Employment Status

For each Capstone Designer, state current status: Employed (with company), Firm Offer (company), Grad School (institution), Abroad (country, city), Undergraduate, or Seeking Employment.

Appendix A: Standards Awareness

Below are the three key standards that shaped our design and safety approach, listed in order of priority:

1. **ISO 12100:2010 – Safety of Machinery (High Priority)**
   Provided our fundamental risk‑assessment framework. We followed its hazard identification and risk‑reduction process to design physical guards, emergency‑stop circuits, and interlocks on the PCB feeder and robotic stations.

2. **ISO 10218‑2:2011 – Robots and Robotic Devices (High Priority)**
   Defined the safety requirements for integrating the UR3 and Meca500 robots. Compliance ensured proper protective‑zone layouts, safety‑rated soft‑stops, and monitoring functions (e.g., speed and separation limits) to prevent collisions during automated pick‑and‑place.

3. **UL 508A – Standard for Industrial Control Panels (Medium Priority)**
   Guided the design of our custom electrical panels and driver boards. Adhering to UL 508A ensured correct overcurrent protection, wiring practices, and enclosure ratings for all motor controls and sensor interfaces.

Appendix B: Final Team Testimonial

Team Testimonial

Participating in the ELECOMP Capstone Program has been one of the most rewarding experiences of our academic careers. It challenged us to apply the technical knowledge we've gained at URI to a real-world engineering problem with tangible impact—from designing and 3D-printing custom hardware to scripting robotic motions and integrating machine-vision algorithms. Collaborating closely with Hayward Industries and under the guidance of seasoned mentors pushed us beyond the classroom, sharpening our skills in problem solving, project management, troubleshooting, and clear technical communication. This immersive, hands-on journey deepened our passion for robotics and automation, gave us first hand insight into the pace and rigor of an engineering career, and prepared us to make meaningful contributions in industry. We're immensely proud of what we delivered and grateful for the practical learning the Capstone Program provided.

Appendix C: Employment Status for CDs

Employment Status for Benjamin Maguire

- **Status:** Seeking Employment
- **Employed:** No
- **Firm Employment Offer:** Not applicable
- **Grad School:** Not attending
- **Abroad:** Not applicable
- **Undergraduate:** Completed

Employment Status for Jack DeMarinis

- **Status:** Seeking Employment
- **Employed:** No
- **Firm Employment Offer:** Not applicable
- **Grad School:** Attending
- **Abroad:** Not applicable
- **Undergraduate:** Completed