# Automatic Tool Changer – CNC Fiber Laser

A Baccalaureate thesis submitted to the
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Bachelor of Science

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by

Jacob Carver

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Thesis Advisor:

**Moise Cummings**

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## ABSTRACT

This project aims to develop an in-house Automatic Tool Changer (ATC) that enhances cost-effectiveness, reliability, and seamless integration with Cincinnati Incorporated's CNC fiber laser systems.

Currently, Cincinnati Incorporated relies on third-party ATCs, which has resulted in high costs and inconsistent performance. By designing a custom ATC, the company can achieve tighter control over quality, reduce expenses, and boost operational efficiency. The proposed in-house solution uses durable materials, detailed design analysis, and finite element modeling to ensure performance and safety. The final design enables precise tool changes, minimizes downtime, and integrates easily with existing systems. Successful implementation of this ATC is expected to yield long-term savings and improved production outcomes for CI.

## ACKNOWLEDGMENTS

This project is made possible through the guidance of Prof. Moise Cummings and the support of Cincinnati Incorporated engineers, applications, service, training, and shop teams. Special thanks to colleagues who provided valuable insights and feedback during the research, design, manufacturing, assembly, and testing phases.

# PROBLEM DEFINITION AND RESEARCH

### *PROBLEM STATEMENT*

Cincinnati Incorporated currently sources Automatic Nozzle Changers (ATCs) from a third-party supplier for their CLX fiber laser systems. These ATCs have become a significant cost burden and do not meet the company's performance expectations. This inadequacy has led to increased operational costs and concerns among engineering, training, service, and application teams. To address these issues, this project will develop an in-house ATC specifically designed to meet the needs of Cincinnati's CLX fiber lasers. The goal of this project is to: reduce expenses, enhance the efficiency of laser cutting operations, and ensure the ANC meets or exceeds current performance standards.

### *BACKGROUND*

Automatic Tool Changers are essential in modern CNC fiber laser manufacturing; They allow quick nozzle changes that are critical for cut quality and efficiency. A nozzle exchange is required anytime a customer is changing their material thickness or material type. In a high production environment this can happen multiple times an hour.

For reference, consider a standard CNC, 3-axis milling machine without an automatic tool changer: the operator would need to manually stop the machine, open the enclosure, and change the tool for each operation such as switching from a roughing end mill to a finishing tool or a drill. This manual interruption is time-consuming, increases the chance of tool misalignment, and significantly reduces throughput as the machine must be shut down for safety between each change. The same situation applies to fiber laser machines when operators must manually switch cutting nozzles between operations involving different materials and thicknesses. Each change introduces downtime, potential safety risks, and variability in cut quality.

Automatic Tool Changers (ATCs) eliminate these inefficiencies by automating the switch between nozzles, ensuring precision, repeatability, and faster transitions. In modern CNC production environments, automation is essential not only for maintaining competitive production speeds but also for achieving the high precision and consistency demanded by customers. Fiber lasers are sensitive to nozzle condition; a damaged or incorrect nozzle can degrade cut quality or cause failed cuts. As such, routine changes must be efficient and reliable.

Tool changers have evolved in parallel with broader CNC and manufacturing automation systems, improving production speed and operator safety. In-house development of such systems allows for better integration, cost savings, and engineering flexibility. Cincinnati Incorporated's goal is to match or exceed the performance of third-party ATCs while tailoring the system specifically to the constraints of their fiber laser platform.

## RESEARCH

### *SCOPE OF THE PROBLEM*

This project originated from Cincinnati Incorporated's Strategic Global Deployment (SGD) initiatives, which are to always delight customers, produce high-quality products, and drive continuous improvement. One of the key engineering initiatives within SGD was identifying areas where cost could be removed from CI's current CNC flagship platform, the CLX. The ATC project was selected as an engineering priority that had not yet been assigned to a full-time internal resource.

The goal of this project is to deliver value in three core ways: reduce cost, increase system reliability, and integrate a tailored solution into the fiber laser platform. Initial contact was made to CI's engineering teams where interviews where conducted to get up to speed quickly on the history of problems facing the current ATC and to being identifying areas to strategically improve the design.

Key issues revealed by these interviews included high per-unit cost, frequent misalignment and reliability issues, difficult maintenance procedures, and limited design flexibility. These insights pointed to the opportunity not only to save money but to substantially improve the end-user experience and system performance through an internally developed tool-changing system.

### *CURRENT STATE OF THE ART*

During the research phase of this project, three leading CNC Fiber Laser producers CI compete for market share with were analyzed based on each of their offerings on ATC's. Systems were analyzed to establish the baseline for performance, integration, and cost feasibility. Each represents a different approach to solving the problem of reliable and efficient nozzle changes in fiber laser systems.

**Glorious Laser** (3) integrates a standoff pad, nozzle cleaning system, and nozzle storage into a compact, front-access footprint. This promotes user convenience and maintenance efficiency. However, its integration into the main frame of the laser system renders it incompatible with CI's current CLX platform, which cannot support modifications to the core frame structure.

**HGTECH** (2) features a threading mechanism within the ANC itself, offering precise control of nozzle engagement. While innovative, this method may require redesign of CI's existing nozzle and collet interface, and its complexity would likely increase manufacturing costs and maintenance difficulty, key factors that go against the project's cost and reliability goals. This type of nozzle exchange is also seen as a regression of current technology, Ci has used this technology on its older system but through comminuted innovation, currently used the ring detent system on current laser cutting heads.

**Bystronic** (1) offers a sophisticated magnetic nozzle attachment system. The nozzles are magnetically held, and the system includes automatic cleaning and storage for up to 64 nozzles. The ANC unit also folds into the main frame for protection. While impressive, this solution's size, complexity, and reliance on a separated nozzle/collet architecture makes it impractical for integration into CI's system. Additionally, the high part count and automation complexity introduce cost barriers inconsistent with the goals of this project. These nozzles are also single use, this solution is great for high production, rapid cutting environments, not something the CLX is branded for.

All current solutions prioritize automation and precision while reducing operator interaction. They feature integrated cleaning mechanisms, consistent alignment tools, and multi-position storage systems. These innovations clearly indicate that automation in nozzle changing is the expected standard in high-throughput, high-precision laser environments.

None of the systems reviewed strikes a balance between high performance and low cost. Additionally, most are designed around a fixed architecture that assumes full control over each machine's physical envelope, something CI would consider a major design change to the machine's mainframe and outside the scope of this project. The inability to customize these third-party systems to CI's hardware, combined with their cost and complexity, highlights the need for an in-house system that retains the key benefits of automation while being cost-efficient and fully compatible with existing laser infrastructure.

***END USER***

Cincinnati Incorporated's Automatic Tool Changer project is ultimately built for the people who use and rely on the system daily. This includes laser operators, CI engineers, mechanical assembly teams, and service technicians, but the most important audience remains our customers. The goal of CI's Strategic Global Deployment (SGD) initiative is simple: delight the customer. Every design decision made during this project has been grounded in that principle. Our customers expect reliability, easy maintenance, and precision performance in every product, and they will not tolerate downtime or complicated troubleshooting caused by misaligned tooling. Operators require intuitive systems that streamline workflow, service teams require durable designs that can be accessed and repaired quickly, and application and training teams need a solution they can confidently support across all use cases. Above all, the ATC system must function flawlessly for CI customers on the shop floor. This in-house ATC doesn't simply reduce costs—it creates a better experience, built specifically around how CI's systems are actually used, reinforcing the trust and confidence our customers place in CI technology every day.

## *Conclusions and Summary of Research*

The culmination of survey insights, internal interviews, and competitive product analysis strongly supports the pursuit of an internally developed Automatic Tool Changer for CI's fiber laser platform. Existing commercial systems while technologically advanced consistently fell short in critical areas such as integration feasibility, fundamental design principles, and long-term cost control. Most required significant changes to CI's CLX machine frame or tool interface, making them incompatible.

Internal survey responses highlighted recurring challenges with third-party systems, including frequent tool misalignment, complex maintenance procedures, and excessive cost per unit. The survey also revealed strong cross-departmental support for a solution that would simplify operation, enhance serviceability, and align with CI's existing pneumatic collet and tooling infrastructure.

As a result, this project has identified a clear gap between market offerings and CI's operational needs. The proposed ATC design, built in-house and tailored specifically to CI's existing systems, fills that gap by optimizing reliability, cost-efficiency, and seamless integration. The scope of work now advances toward physical prototyping and system testing to validate the concepts established through this research.

The primary design driver is the need for an in-house ATC that delivers the same or better performance than outsourced options at a reduced cost. Survey results, cost analysis, and industry research confirmed the opportunity to simplify CI's tool change process while improving long-term maintainability and performance.

## CUSTOMER FEATURES

A structured approach to our design started with a cross-functional survey. This was created and distributed to key CI departments, including mechanical and electrical engineering, service, training, applications, and assembly teams. The survey asked respondents to rate various features based on importance and rank common issues experienced with third-party ATCs. This provided a foundation for customer-driven design criteria. The results of this survey are consistent with a high quality of response, instead of a high quantity.

Table 1 below summarizes the average importance rankings assigned to each feature. The values are presented on a 10-point scale.

| Feature | Importance (1–10) |
|---|---|
| Reliable nozzle engagement | 9 |
| Fast and repeatable changeover | 8 |
| Ease of maintenance | 6 |
| Compatibility with CI fiber laser | 10 |
| Durability under production conditions | 7 |
| Low system cost | 10 |

**Table 1: Feature importance Survey Results**

Using this feedback, customer features were ranked by criticality in Table 2. These rankings helped inform the Quality Function Deployment matrix and ultimately shaped the final design parameters.

| Rank | Customer Feature | Description |
|---|---|---|
| 1 | Compatibility with laser | Must fit directly into CLX platform hardware |
| 2 | Low system cost | Must be more affordable than third-party ATCs |
| 3 | Reliable nozzle engagement | Ensure secure and repeatable fitment |
| 4 | Fast and repeatable exchange | Minimize operator wait time and errors |
| 5 | Durability | Reliable under constant industrial use |
| 6 | Ease of maintenance | Simplified service routines and adjustments |

**Table 2: Ranked Customer Features for Design Guidance**

## PRODUCT OBJECTIVES

Based on survey input and engineering analysis, the primary objectives for the ATC are:

- Design a system that performs consistently under production-level use
- Keep production cost under $8,000 per unit
- Support at least 8 nozzle positions within the changer
- Integrate seamlessly into CI's automated fiber laser cell
- Utilize push-connect actuation for secure and repeatable tool changes
- Achieve repeatable tool placement with less than 0.22 mm displacement under load
- Design for maintainability using CI's internal manufacturing capabilities

Integrating pneumatic actuation maintains compatibility with existing fiber laser platforms while reducing design complexity. Setting a manufacturing cost target of less than $8,000 per unit protects machine margins and offers a compelling financial advantage over outsourced solutions. Other considerations included: using DFMA principles consistent with Cincinnati Incorporated's design engineering standards. These objectives serve as the foundation for delivering a highly functional, reliable, and customer-driven product that meets Cincinnati Incorporated's standards of excellence.

## QUALITY FUNCTION DEPLOYMENT

House of Quality analysis was performed to align customer requirements with engineering characteristics. In this QFD, key customer needs were mapped against measurable design responses such as tool retention force, change time, component material strength, and compatibility with CI's systems. This structured evaluation helped identify the most critical areas for design optimization and clarified trade-offs between cost, speed, and structural integrity. The QFD served as a foundation for engineering decision-making throughout the development process.

Analyzing the House of Quality allows us to compare our customer features to our engineering characteristics, in doing so we can draw comparisons such as; Cost Effectiveness has strong relationships with both Cost of Production and Footprint, emphasizing the need for a design that minimizes space and expenses. The feature of Customization is critically related to Tool Capacity and Autonomy Level, suggesting that providing flexibility in tool configurations and increasing automation will be highly valued by users. Speed of Tool Changes correlates strongly with both Autonomy Level and Tool Placement Precision, emphasizing that improvements in automation and precision will enhance operational efficiency. Overall, these relationships guide the design decisions for the ATC, ensuring that user needs and operational requirements are effectively met.

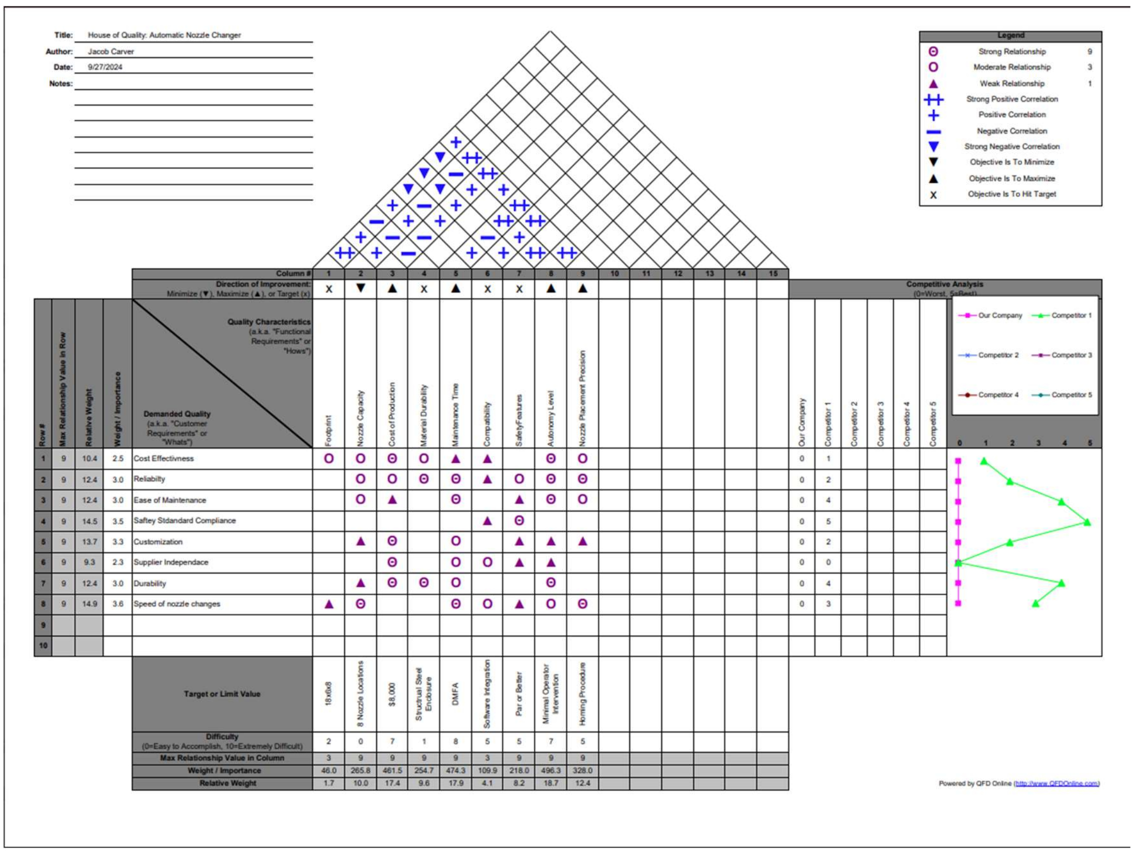


**Figure 1: House of Quality**

# DESIGN

## *CONCEPT 1 – AUTO THREAD*

This concept introduces an automatic threading mechanism for tool changes. The system automatically aligns and threads the tools onto the laser head, reducing manual intervention and increasing precision in tool placement. The auto-threading feature ensures secure attachment and can be integrated with existing laser systems. Preliminary concept reviews trended to infer that this option is the most cost effective as a single motor and belt assembly can drive all nozzle locations.

**Figure 2: Render, Auto Thread**

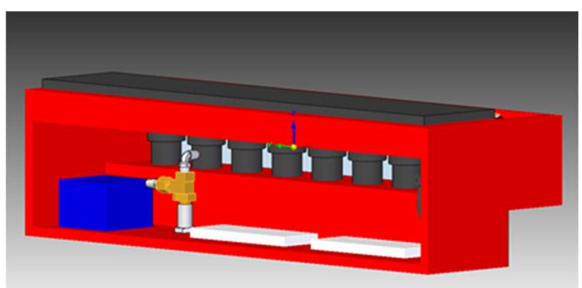

**Figure 3: CAD, Auto Thread Mechanism Example**

### *Concept 2 – Pneumatic Ball detent mechanism*

This concept utilizes a pneumatic ball detent system for tool exchange. The ball detent mechanism allows for quick release and secure reattachment of the tool. This design prioritizes fast, efficient tool changes by using compressed air to control the locking and unlocking mechanism, minimizing downtime during tool replacement. This design is having the best compatibility as it uses current technology on the laser head to create the nozzle exchange and compressed air is already plumbed throughout the machine.

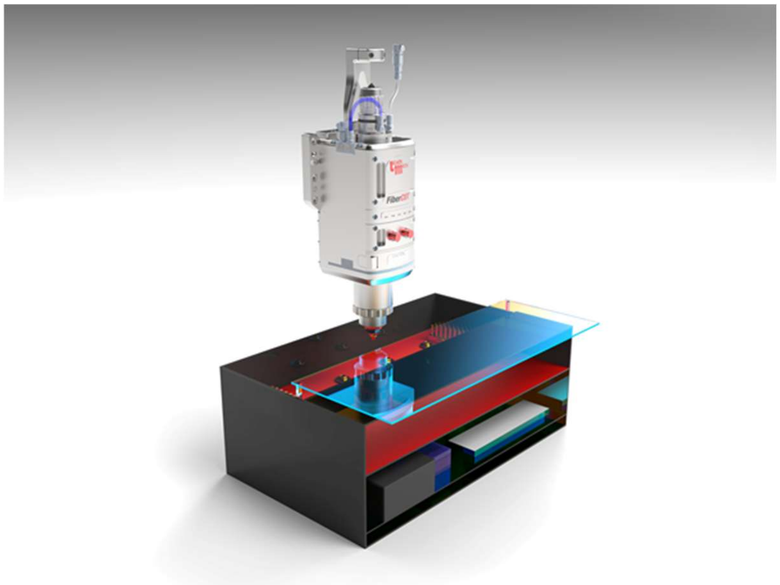

**Figure 4: Render, Pneumatic Ball Detent**

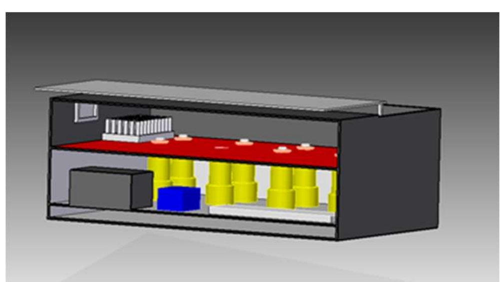

**Figure 5: CAD, Pneumatic Ball Detent Mechanism Example**

### *CONCEPT 3 – HIGH-CAPACITY REVOLVING STORAGE SYSTEM*

This concept features a high-capacity revolving changer that can store multiple tools. The revolving mechanism allows for quick switching between different tools during operation, improving efficiency in high-volume production environments. The high-capacity design can accommodate more than 10 tools, reducing the need for frequent restocking during high production.

**Figure 6: Render, Revolving Storage**

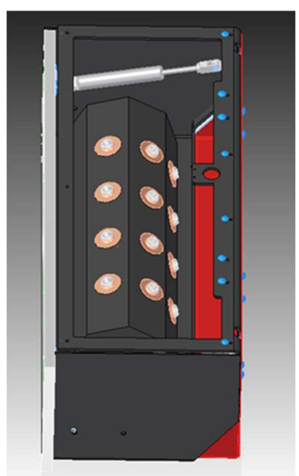

**Figure 7: CAD, High-Capacity Mechanism Example**

These concepts where presented in a design review with mechanical, electrical, and software engineering teams. Ultimate the decision was made to pursue the pneumatic ball detent design as it is consistent with current technology used on the CLX laser head and air is plumbed to the laser, favoring pneumatic cylinder activation.

## *FINAL DESIGN CHOICE:*

Ultimately, Concept 2 was chosen to begin final design on the ATC. This concept paired the most up-to-date technology in our current laser head with the cost-effective option of using pneumatic cylinders powered by compressed air already supplied to the machine. In addition to reducing component costs, this approach simplified both electrical and mechanical integration by eliminating the need for more complex motorized actuation systems. Concept 2 also offered the greatest modularity, which aligned well with DFMA principles and allowed for straightforward maintenance and future scalability. Most importantly, this design met key customer features identified through the House of Quality process, including reliability, ease of maintenance, and safety compliance.

## *Loading Conditions*

To ensure structural integrity under both repeated and accidental load scenarios, conservative stress design limits were applied to critical components. For repeated loading caused by consistent nozzle exchanges, medium carbon steel was used with an assumed ultimate strength ($S_u$) of 457 MPa and a safety factor of 8, resulting in a design stress ($\sigma_d$) of 57.13 MPa. This value ensures the system can handle thousands of cycles without fatigue failure.

For the accidental strike condition, affecting the structural enclosure fabricated from A500 Grade A steel, a more conservative safety factor of 12 was used. This yielded a design stress limit of 38.03 MPa, again based on a 457 MPa ultimate strength. These safety margins help ensure the ATC remains robust and reliable in both expected use and worst-case impact scenarios.

For the laser head accidental impact, FEA was run simulating a corner strike at 225N.

$$F = M\ x\ A$$
$$M = 11.34kg$$
$$A = 19.613m/s^2$$
$$F = 225N$$

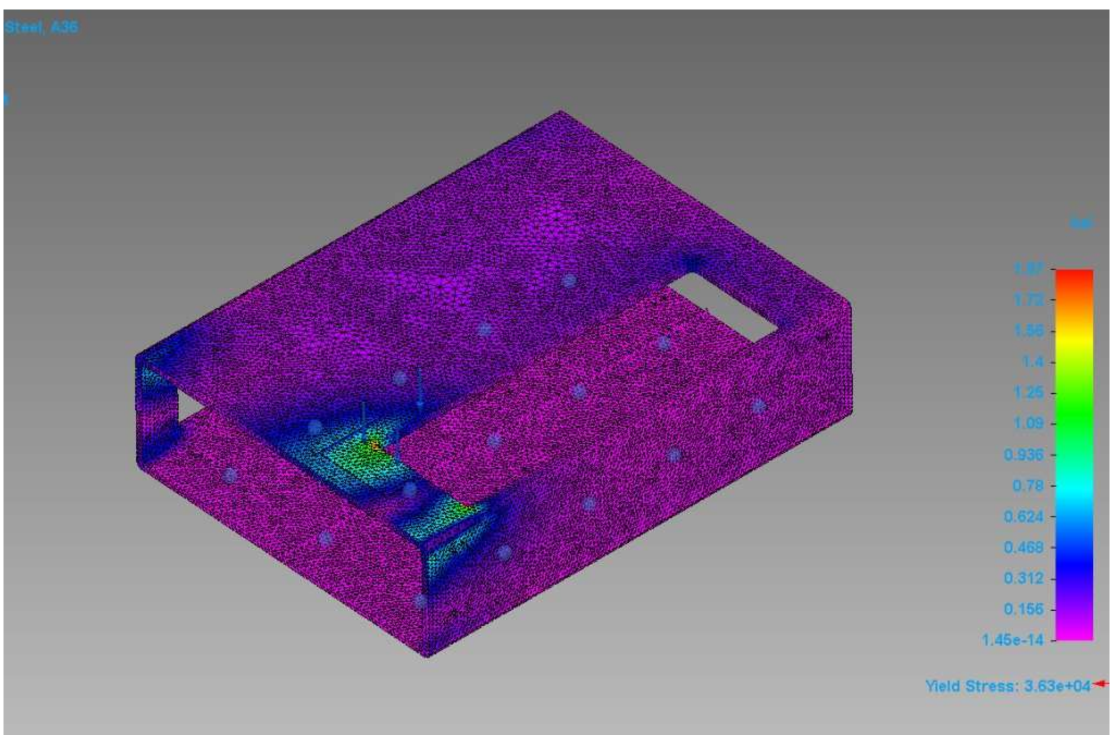


**Figure 8: FEA, Impact Loading 3/8"**

This resulted in:
12.89 $Mpa$ Peak Stress
$SF = 35.45$ or a 295% from required 12

With a safety factor so high we made the decision to scale down the enclosure material thickness to 1/4". This is a stock size, aligning with our cost cutting goal.

Next, I ran the same 225N strike simulation on our new enclosure size:

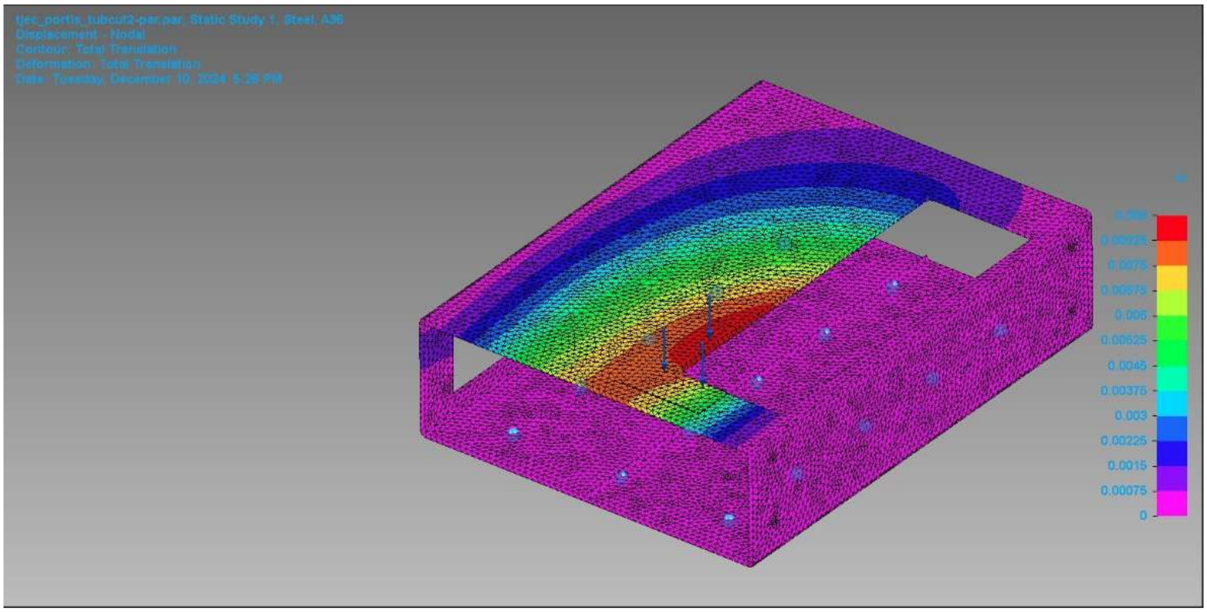


**Figure 9: FEA 1.2 Impact Loading 1/4"**

This resulted in:
26.95$Mpa$ Peak Stress
$SF = 16.95$

The safely factor is still considerably higher than the required 12, but with concerns about thread engagement when fastening critical components, the deign choice was made to remain at this stock size instead of further decreasing material thickness.

The second case evaluated repeated load conditions on the nozzle exchange top plate—specifically the region most likely to receive consistent, localized impacts from the laser head during automatic nozzle changes. A simulated impact load was applied using FEA to determine peak stress values and displacement at the top plate. This analysis confirmed that the design could support repeated contact without risk of permanent deformation or performance degradation. As this is the only area expected to receive frequent impact, the top plate was specifically reinforced and analyzed in greater detail to ensure long-term reliability.

Again, this test was run at 225N to simulate a maximum acceleration strike despite the laser head having coded slow down features.

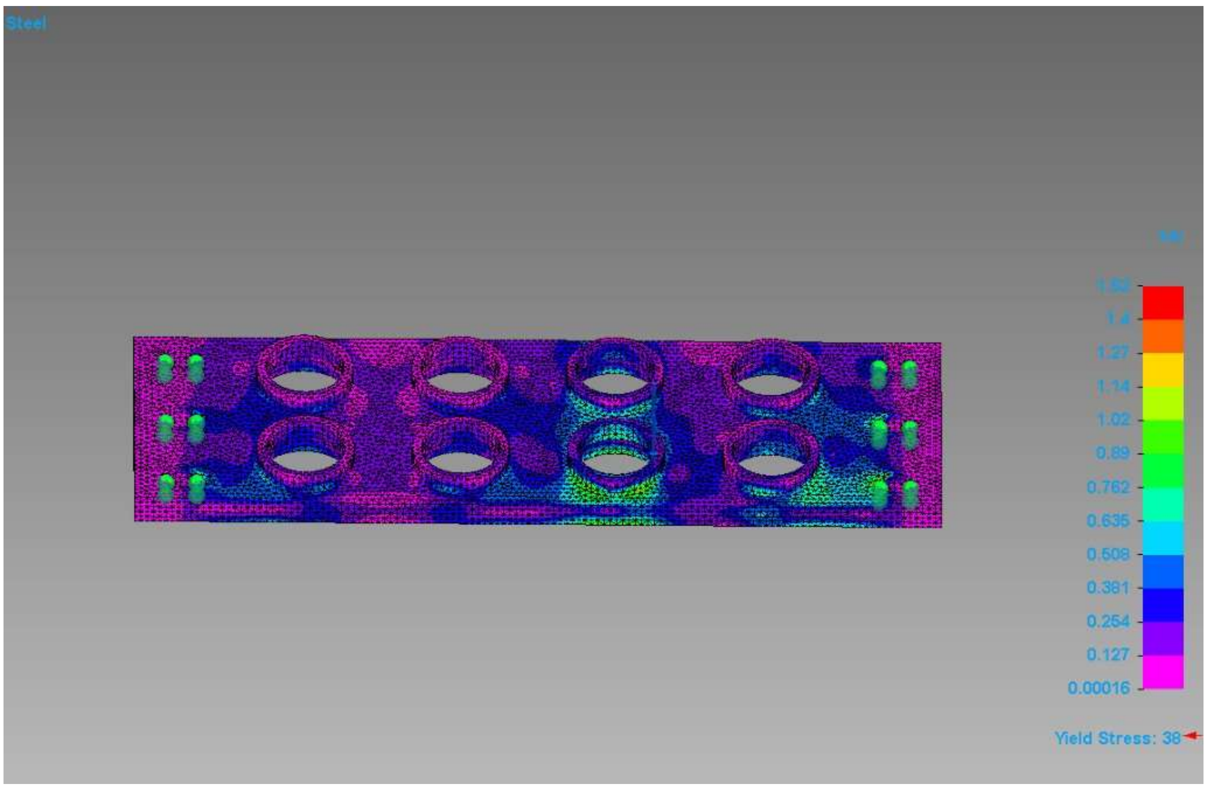


**Figure 10: FEA 1.3 Repeated Loading 1/4"**

This resulted in:
10.48 $Mpa$ Peak Stress
$SF = 25$

**Pneumatic Cylinder Calculations:**

For the lid actuation cylinder bore size needed to be calculated based on stock cylinder offering as well as stock sheet metal offerings.

$$F = P\left(\frac{N}{M^2}, Pa\right) x\ A(m)$$
$$F = P\ x\ \left(\frac{\pi\ x\ D^2}{4}\right)$$
$$75 = (551{,}580) x\ A(m)$$
$$D = 0.0135m\ or\ 13.5mm$$

## *FACTORS OF SAFETY OF CONCERN*

Safety factors exceeded required limits in all cases. The original design used 3/8" A500 steel tubing, which showed an extremely high safety factor of 35.45. To reduce cost and weight, the wall thickness was reduced to 1/4", which still exceeded safety requirements despite introducing some thread engagement concerns.

Due to stock limitations and manufacturability constraints, 1/4" remained the most viable option for the enclosure and top plate.

## *DRAWINGS*

Detailed CAD drawings were produced using Solid Edge. These ranged from individual parts, laser cut and bent, machined pieces requiring GD&D detailing, as well as assembly drawings for individual sub systems and the final assembly drawing.

To protect Cincinnati Incorporated’s IP, no drawings will be shown in this thesis.

## *COMPONENT SELECTION*

The ATC system was composed of both in-house manufactured and externally sourced parts to maximize performance while aligning with CI's production capabilities. The enclosure housing was fabricated from A500 Grade A square tubing using a third-party tube cutting vendor to ensure consistent dimensions and clean edge preparation. All machined components, including the top and bottom plates, guide hardware, and actuation interfaces, were produced internally on Cincinnati Incorporated's 3-axis machining centers. Custom fixturing and brackets were manufactured in-house using CI's laser-cutting and press brake capabilities, allowing for precise bends and assembly alignment. Purchased components, including pneumatic cylinders, bushings, and hardware, were sourced from CI's approved vendor list to maintain quality standards and simplify procurement. This mixed sourcing strategy allowed for streamlined assembly while ensuring quality and performance at every level of the design.

**Table 3: Bill of Material**

| Description | CI Part Number | Unit Cost |
|---|---|---|
| CVR ANC LID | 919059 | $39.23 |
| BRKT ANC LID | 919051 | $8.59 |
| BRKT MTG ANC CVR SIDE | 919039 | $4.29 |
| CVR ANC FRONT BACK | 919047 | $5.36 |
| CVR ANC SIDE | 919058 | $8.38 |
| CVR ANC BOTTOM | 919043 | $8.38 |
| PNUE CLY ANC LID | 919050 | $498.43 |
| PNUE CLY ANC NZZL | 919048 | $227.42 |
| 0.375X0.25 BUSHING | 919045 | $1.11 |
| FELT ANC | 919061 | $4.90 |
| 0.75X0.25 STANDOFF | 919042 | $2.53 |
| SWTCH PROX36MM PNP 10-30V | 848620 | $39.23 |
| BOARD ASSY BH ECAT EK1101 | 850314 | $175.13 |
| BOARD ASSY BH ENCP EL9011 | 847320 | $3.34 |
| BOARD ASSY BH INP8 EL1808 | 847316 | $49.69 |
| BOARD ASSY BH OUT8 EL2808 | 847317 | $56.57 |
| CONN BASE TO WIRE STR | 848625 | $16.44 |
| ENCL ANC | 919060 | $651.68 |
| VALV FLOW METER OUT | 929857 | $8.59 |
| VALVE FLOW CNTRL M5 | 919077 | $5.78 |
| SOLENOID ANC | 919076 | $224.64 |
| FTNG TUBE 1/8 NPT X 1/4 PC | 919075 | $1.11 |
| MUFFLER 1/8 NPT | 919078 | $2.03 |
| SCR CAP SK .37-16X .87 | 207899 | $0.36 |
| WSHR PLAIN .31X .75X.062 | 027308 | $0.01 |
| SCR CAP HX .25-20X .75 | 027201 | $0.04 |
| SCR CAP MS M 3.0- .50X 16 | 441206 | $0.08 |
| SCR CAP HX .37-24X .75 | 243049 | $0.12 |
| NUT HV HEX .250-20 .23 | 026140 | $0.09 |

| | | |
|---|---|---|
| SCR CAP SK # 8-32X 1.00 | 220914 | $0.02 |
| SCR CAP HX .25-20X .50 | 073766 | $0.33 |
| WSHR PLAIN .43X1.00X.078 | 041086 | $2.70 |
| SCR CAP HX .37-16X 1.00 | 041175 | $0.09 |
| WSHR LOCK .38X .56X.125 | 071011 | $0.08 |
| SCR CAP MS M 6.0-1.00X 18 | 422433 | $0.09 |
| SCR MACH #10-32X.5 SLFTAP | 833624 | $0.31 |
| BOARD ACC DIN MTG RAIL | 829295 | $4.03 |
| PLATE MTG ANC | 919044 | $70.30 |
| STANDOFF ANC | 919054 | $54.82 |
| STANDOFF MIDDLE ANC | 919046 | $353.94 |
| CUP NOZZLE ANC | 919073 | $22.38 |
| MTG BRKT ANC CYL | 919101 | $34.36 |
| PLATE ANC TOP PARTIAL | 919105 | $1,649.39 |
| PLATE ANC MIDDLE PARTIAL | 919104 | $316.02 |
| PLATE ANC BOTTOM PARTIAL | 919103 | $232.26 |
| VALV FLOW METER OUT R THREAD | 919106 | $7.73 |
| BRKT ANC BC | 919049 | $30.26 |
| BRKT ANC BC 2 | 919110 | $29.30 |
| BRKT ANC BC 3 | 919109 | $29.30 |
| SCR CAP SK # 8-32X 2.5 | 919150 | $0.51 |
| PLATE MTG ANC SNSR | 919040 | $67.02 |
| NUT HEX M12-1.25 | 919131 | $0.26 |
| INSERT M12-1.75XM8-1.25 | 919132 | $7.41 |
| TAP M12X1.75 | 919133 | $19.39 |
| CONN FRAME 24B A..F M | 850018 | $14.23 |
| CONN BASE PNL MNT 24B | 850017 | $16.52 |
| CONN MOD PNU HOLDER | 851215 | $5.57 |
| CONN MOD PNU 6MM OD M | 851216 | $11.25 |
| CONN MOD BLANK | 850034 | $2.16 |
| CONN MOD 10A 12PIN M S | 850026 | $10.41 |
| CONN MOD RJ45 M | 850028 | $2.74 |
| PLATE MTG ANC CLY | 919038 | $200.34 |

## *FINAL DESIGN OVERVIEW:*

The final design for the ATC features a pneumatic driven nozzle exchange. Using laser distance sensors, we are able to define nozzle positions preventing a nozzle swap into an occupied location. This design also features a smart camera, where the laser head can drive to position to check beam center, preform a debris check, as well as nozzle quality inspection all without the operator moving from the machines HMI. The lid for the ATC prevents laser dust and other debris found during the cutting process from entering the enclosure. This is also pneumatically driven, using the same air that supplies the machines currently. All wiring and pneumatic plumbing is contained within the enclosure which also uses the same mounting hardware as the previous edition. This way the new ATC can be mounted the machine, and one secure connection provides air and power. Once this is completed the calibration program will run and upon completion the ATC is ready to function in a full-scale production environment.

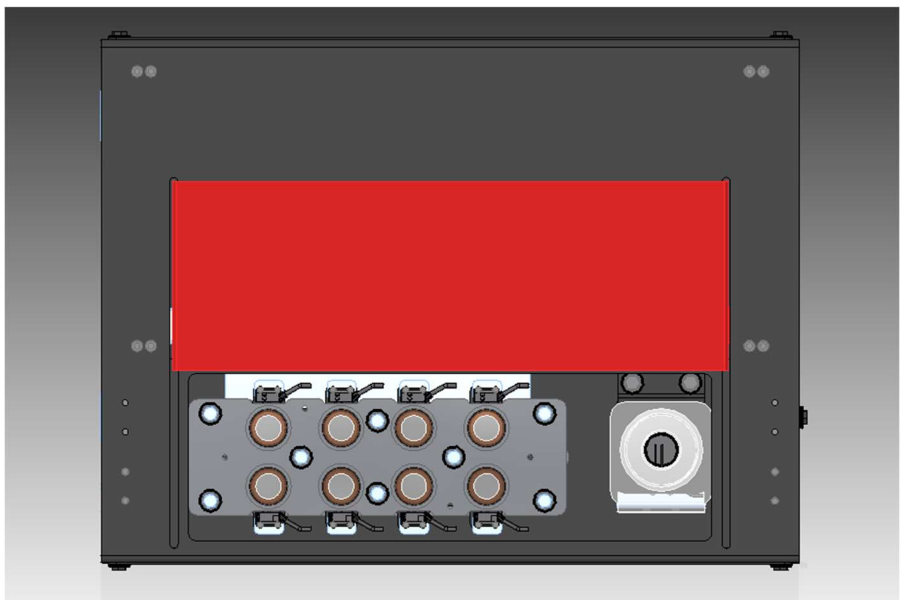

**Figure 11: Final CAD (Top)**

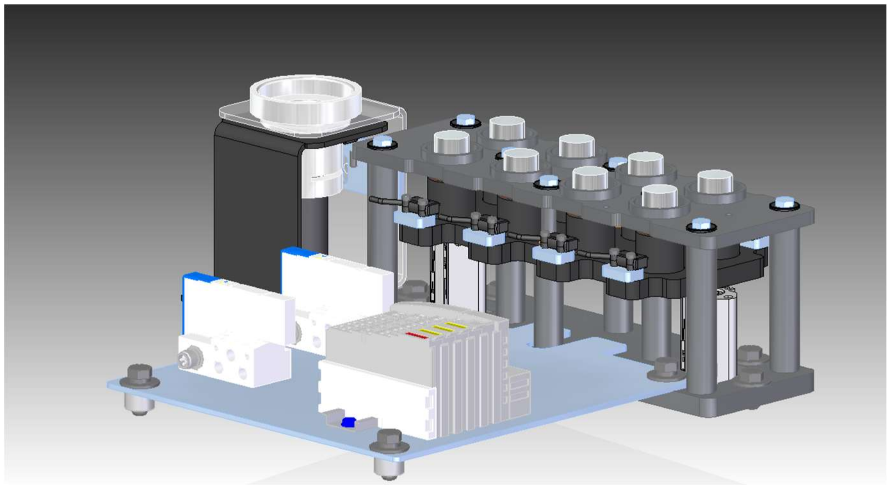

**Figure 12: Final CAD (Exchange and Camera ISO)**

### *DESIGN ANALYSIS*

A key benefit of this ATC design is its strong alignment with DFMA principles, particularly in how the enclosure tube streamlines assembly processes. This design allows one assembly technician to construct the tool exchange mechanism entirely outside the enclosure, while a second technician can simultaneously complete the wiring and pneumatic plumbing. Once the subassembly is fully prepared, it can be easily slid into the enclosure from the side and secured using just four bolts.

This modular, front-loaded approach drastically reduces assembly time and improves accessibility during the build. After the subsystem is installed, the only remaining steps involve attaching the lid actuation pneumatic cylinders, routing the plumbing to the solenoid valve, bolting on the ATC covers, and connecting the unit to the CNC Fiber Laser. This level of pre-assembly and ease of integration supports a more efficient production workflow and enables quick maintenance or replacement in the field. Working though design reviews with the assembly workers that would be building the units was of great value and a large reason to the estimation of 10 total assembly hours to complete a production ready unit.

## *ASSEMBLY:*

The prototype build began with the preparation of the enclosure, a simple but highly effective open-top tub design. This approach was chosen for its manufacturability and accessibility. The enclosure was fabricated to accept the major subsystems as drop-in modules. Key mounting points and pass-throughs for plumbing and wiring were integrated from the start, enabling a smooth assembly sequence with minimal tools. The open design also allowed multiple technicians to work in parallel without spatial interference.

**Figure 13: Enclosure**

The core mechanical system, responsible for executing tool changes was assembled next. This subsystem, built from a sandwich-style stack of machined plates, housed the actuating and guiding components for the tool handling process. It was fully constructed and tested outside of the enclosure, with careful attention paid to alignment and tolerances. Once validated, the complete mechanism was bolted into the enclosure as a single unit, reinforcing the modular DFMA strategy that defined the project.

**Figure 14: Nozzle Exchange Mechanism**

With the core subsystem in place, final integration focused on lid actuation and system controls. Pneumatic cylinders were mounted to the enclosure and connected to the upper lid assembly, allowing for controlled access. Solenoids, plumbing, and wiring were then routed through pre-cut channels and secured for testing. The final step involved attaching the protective ATC covers and mounting the full assembly to the CNC Fiber Laser. This final stage confirmed the system's readiness for testing, while showcasing the value of front-loaded modular construction.

**Figure 15: ATC Final Assembly**

## *TESTING:*

These figures detail a DVP&R and FMEA documents that are used to capture testing done to production ready units. For this prototype a proof-of-concept test plan was written to validate the design before optimizing. This can be found in Appendix D.

CINCINNATI

### Design Verification Plan & Report

| | | | | |
|---|---|---|---|---|
| Part Number: | Part Description: **Automatic Tool Changer** | System / Machine Type: **CLX** | | List of related components / other parts of assembly to be considered: |
| Part / Sub-Assembly Name: | Drawing Number & Revision: | | | |
| Project Engineer: **Jacob Carver** | Reason for Change or New design: **Cost** | Supplier Name (if Purchased Part) | | Related Drawing Number(s): |

| Testing and Design Verification Plan | | | | | | | Test Report & Results | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Functional Criteria** or Critical Dimension to be evaluated | **Purpose: Why is it important?** Customer Satisfaction - Warranty Regulatory - Functional - Safety | **Evaluation Method** How will we test the criteria? | **Acceptance Criteria** What will determine if the test is successful? | **# of Tests / Required Duration** | **Environmental Considerations** Temperature, humidity, moisture, dust, enclosed, open to air, etc. | **Test Date** | **Test Results** | **Observations / Notes** | **Outstanding Concerns** Any Follow-up actions required or unanswered questions? | **Test Completed By** | **Pass / Fail** |
| Lid Actuation | Allows access to nozzles and prevents debris from entering | Cycle test lid actuation | React within 1s and take no longer that 2s to complete move<br>Completely covers or exposes nozzles each cycle | 10 | Environment within laser (visible laser dust, suspended particles 95 degrees) | | | | | | |
| Nozzle Exchange | Initial validation of core functionality | Initialing nozzle swap from HMI | Laser is able to exchange all nozzle positions without fail | 2 (for each position) | Environment within laser (visible laser dust, suspended particles 95 degrees) | | | | | | |
| Lid Actuation | Confirm ATC design is viable enough and ready for increased optimization | Showroom/900 /Fab shop | Successfully complete test without binding errors or excessive dust/debris buildup | 10,000 | Environment within laser (visible laser dust, suspended particles 95 degrees) | | | | | | |
| Nozzle Exchange | Confirm ATC design is viable enough and ready for increased optimization | Showroom/900 /Fab shop | Complete test without any nozzle exchange failures | 10,000 | Environment within laser (visible laser dust, suspended particles 95 degrees) | | | | | | |

**Figure 16: Example DVP&R**

CINCINNATI

### Failure Mode & Effects Analysis

| Function, Feature, Attribute | Operation | Potential Failure Mode | Potential Effects of Failure | Severity | Potential Causes of Failure | Current Prevention Controls | Occurrence | Current Detection Controls | Detection | R.P.N. | Potential Improvement Ideas |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Pneumatic System | Supplies air for dust cover operation | Loss of PSI | Dust cover does not open/close properly | | Regulators malfunction | Regulators have locking adjustment valves and number set-points. Should not be touched after being set | | Magnetic contacts detect position of door - in both open & closed position - Programming doesn't proceed forward until open/close condition has been met | | | |
| | | | | | Drop in Plant Air | Plant air supply PM's and redundancies | | low psi alarm on machine will detect & alert operator | | | |
| | Supplies air that allows release ring to be compressed and a nozzle to be installed | Loss of PSI | collet holding device *does not open* up and ANC is unable to pick-up designated nozzle | | Regulators malfunction | Regulators have locking adjustment valves and number set-points. Should not be touched after being set | | Redundant sensors in holding cavity detect the presence of the nozzle (after a failed pickup) and sends alarm | | | |
| | | | | | Drop in Plant Air | Plant air supply PM's and redundancies | | low psi alarm on machine will detect & alert operator | | | |
| | Purge Air Required to keep positive air pressure inside ANC box | Too much CFM used for purge creates drain on air system | Not enough air to operate other machine functions | | ? | ? | | ? | | | |
| | | Loss of PSI | Lack of positive air pressure could allow for debris and contamination inside the box | | obstructions or blockages keeping air from evacuating | ? | | ? | | | |
| Lock collar mechanism - engage & disengage | Release Ring presses up to release collet holding pins and allow for exchange of nozzles | Holding pins stick and do not slide properly in milled slots | 1) Partial pick-up: nozzle falls out of TRA once arm raises up 2) Nozzle will not pick up 3) nozzle will not release and empty into holding location | | contamination causes obstruction in the pin's path | Sealed design to prevent dirt or contamination into the working are of the pins - PM schedule to clean - material selection of brass provides lubricity - air purge inside TRA | | Redundant sensors in the nozzle holding chamber detect the presence of the nozzle. If it failed to engage or disengage, the system will automatically try X more times. After X attempts - it will send alarm. | | | |
| | | Compression spring failure causes | | | Spring fails under fatigue loading | spring is designed to withstand "X" number of cycles - longer than the expected TRA life. | | | | | Spring Reset Counter that tracks life of the Spring when it is replaced |
| | | Release ring does not compress the spring | | | Dirt & contamination in the TRA causes a bind in the release ring | TRA will need to be services after "X" number of hours | | | | | Currently no way of knowing if nozzle was picked up, but dropped after leaving holding area. |

**Figure 17: Example FMEA**

# PROJECT MANAGEMENT

## *BUDGET, PROPOSED/ACTUAL*

The budget for the project was set at $12,000 for parts and testing. The target cost was $8,000 for a production ready unit broken down to: $6,500 for parts, and an additional $1,500 for final assembly labor hours in CI's shop. This was monitored using an Excel spreadsheet. Data was pulled from outside vendor quotes and ERP system data when parts were competed from our machining centers.

**Table 4: Final Results**

| Part Costs | Labor Costs | Total Prototype Cost |
|---|---|---|
| $4,887.31 | $1,500 | $6,387.31 |

This budget surplus of **$5,612.69** is available to be used for further optimization at the conclusion of testing. This project has resulted in an immediate cost savings of **$13,574.09** from the current ATC used on current CLX machines in the field.

## *SCHEDULE, PROPOSED /ACTUAL*

While in the office, project scheduling was managed using HIVE, a collaborative project management platform. HIVE allowed for the creation of detailed Gantt charts that outlined key phases including design, procurement, fabrication, and testing. Tasks were created with built-in deadlines, reminders, and status updates, ensuring alignment across the team. This centralized approach improved accountability, streamlined progress tracking, and helped keep the project on schedule from concept to final prototype delivery.

The following schedule was developed to guide the Automatic Tool Changer (ATC) project through all phases of design, prototyping, and testing. This satisfied the school requirements regarding project management.

**December 2024 – Prototype Design**

- Finalize first iteration of the ATC design, incorporating priority features from the QFD process
- Conducted during a full-time work week after final exams

**January 2025 – Prototype Development**

- Design review meetings held with CI engineers
- Finalized machining and assembly drawings
- Ordered long lead-time components
- Conducted during a full-time work week prior to Spring classes

**February 2025 – Prototype Build**

- Full mechanical assembly of prototype
- Initiated functional testing and design validation by mid-February

**March 2025 – Testing and Optimization**

- Optimized ATC based on test results
- Performed system refinements for improved durability and reliability

**April 2025 – Final Presentation**

- Present ATC prototype at the Tech Expo
- Final documentation and defense of project findings

### *PLAN TO FINISH*

Two minor delays occurred during the ATC prototype assembly, both of which were quickly addressed to maintain alignment with the broader project timeline. The first delay involved a pneumatic cylinder with a male-threaded end originally specified for the lid actuation system. Due to long lead time constraints, the design was adjusted to accommodate a female-threaded cylinder that was more readily available, allowing component delivery and integration to proceed without significant impact to the build sequence.

The second delay stemmed from a one-week holdup in receiving the quoted enclosure material. This occurred because a high-priority customer order at the facility required the same material, temporarily pushing back the fabrication schedule for the ATC housing. While both issues were unavoidable, they were resolved efficiently and documented as part of ongoing production planning improvements.

### *SUSTAINABILITY AND MATERIAL USAGE*

The ATC project prioritized the use of materials already approved and stocked by Cincinnati Incorporated to minimize environmental impact from new sourcing. By selecting medium carbon steel commonly used in CI’s manufacturing processes, the project limited excess waste and reduced the need for custom raw material shipments. Fabrication was completed in-house using CI’s CNC machining centers and laser cutting systems, which minimized transportation emissions and packaging waste typically associated with outsourcing. Material offcuts were either reused for prototype iterations or returned to CI’s scrap recycling stream.

Future improvements could include more sustainable material substitutions such as high-strength aluminum alloys or recycled steel, as well as modular redesigns that allow damaged sections to be replaced individually rather than replacing the full unit. Additionally, incorporating design-for-disassembly principles in future iterations would further enhance reuse and recyclability at the end of product life.

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## APPENDIX A

## LIST OF FIGURES



## LIST OF TABLES

## APPENDIX B

**Survey:** Development of In-House Automatic Nozzle Changer (ATC)

**Objective:** This survey is designed to gather feedback on the critical features, importance, and satisfaction levels regarding the Automatic Nozzle Changer (ATC) used in Cincinnati Incorporated's CLX fiber laser systems.

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### Section 1: Importance of Features

Please rate the importance of each feature listed below for the in-house ATC.
(1 = Not Important, 5 = Extremely Important)

1. **Cost-effectiveness**
   How important is reducing the cost of the ATC to the overall project?

2. **Reliability and Durability**
   How important is the reliability and durability of the ATC during high-volume production?

3. **Ease of Maintenance**
   How important is ease of maintenance and repair for the ATC?

4. **Speed of Nozzle Changes**
   How important is minimizing downtime through fast and efficient nozzle changes?

5. **Safety Standards Compliance**
   How important is compliance with industry safety standards?

6. **Customization for Different Applications**
   How important is the ATC's ability to handle various nozzle sizes and cutting applications?

7. **Supplier Independence**
   How important is reducing dependency on external suppliers by manufacturing the ATC in-house?

---

**Section 2: Satisfaction with Current Solution**

Please rate your satisfaction with the current third-party ATC on the following features.
(1 = Very Dissatisfied, 5 = Very Satisfied)

1. **Cost-effectiveness**
2. **Reliability and Durability**
3. **Ease of Maintenance**
4. **Speed of Nozzle Changes**
5. **Safety Standards Compliance**
6. **Customization for Different Applications**
7. **Supplier Independence**

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**Section 3: Additional Comments**

1. What are the biggest challenges you have experienced with the current third-party ATC system?

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2. In your opinion, what should be the highest priority for the in-house ATC development?

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3. Do you have any specific suggestions or ideas for features you would like to see in the new ATC?

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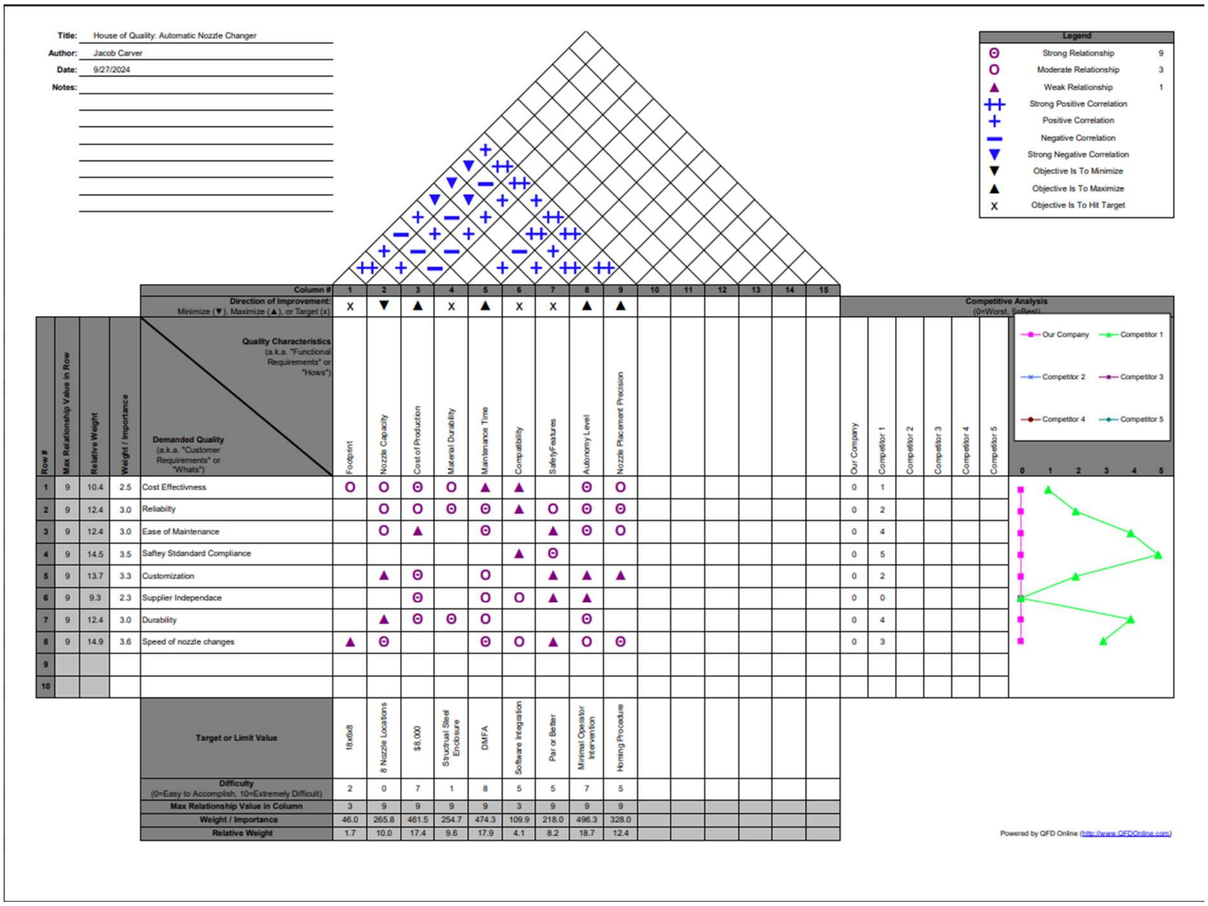
4. **Additional Feedback**
   Please provide any additional feedback or considerations that may not have been covered in the survey but that you believe are important for the development of the in-house ATC.

# APPENDIX C

## House of Quality:




| Row # | Max Relationship Value in Row | Relative Weight | Weight / Importance | Demanded Quality (a.k.a. "Customer Requirements" or "Whats") | 1 Footprint | 2 Nozzle Capacity | 3 Cost of Production | 4 Material Durability | 5 Maintenance Time | 6 Compatibility | 7 SafetyFeatures | 8 Autonomy Level | 9 Nozzle Placement Precision | 10 | 11 | 12 | 13 | 14 | 15 | Our Company | Competitor 1 | Competitor 2 | Competitor 3 | Competitor 4 | Competitor 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x) | x | ▼ | ▲ | x | ▲ | x | x | ▲ | ▲ | | | | | | | | | | | | |
| 1 | 9 | 10.4 | 2.5 | Cost Effectivness | O | O | Θ | O | ▲ | ▲ | | Θ | O | | | | | | | 0 | 1 | | | | |
| 2 | 9 | 12.4 | 3.0 | Reliabilty | | O | O | Θ | Θ | ▲ | O | Θ | Θ | | | | | | | 0 | 2 | | | | |
| 3 | 9 | 12.4 | 3.0 | Ease of Maintenance | | O | ▲ | | Θ | | ▲ | Θ | O | | | | | | | 0 | 4 | | | | |
| 4 | 9 | 14.5 | 3.5 | Saftey Stdandard Compliance | | | | | | ▲ | Θ | | | | | | | | | 0 | 5 | | | | |
| 5 | 9 | 13.7 | 3.3 | Customization | | ▲ | Θ | | O | | ▲ | ▲ | ▲ | | | | | | | 0 | 2 | | | | |
| 6 | 9 | 9.3 | 2.3 | Supplier Independace | | | Θ | | O | O | ▲ | ▲ | | | | | | | | 0 | 0 | | | | |
| 7 | 9 | 12.4 | 3.0 | Durability | | ▲ | Θ | Θ | O | | | Θ | | | | | | | | 0 | 4 | | | | |
| 8 | 9 | 14.9 | 3.6 | Speed of nozzle changes | ▲ | Θ | | | Θ | O | ▲ | O | Θ | | | | | | | 0 | 3 | | | | |
| 9 | | | | | | | | | | | | | | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | Target or Limit Value | 18x6x8 | 8 Nozzle Locations | $8,000 | Structrual Steel Enclosure | DMFA | Software Integration | Par or Better | Minimal Operator Intervention | Homing Procedure | | | | | | | | | | | | |
| | | | | Difficulty (0=Easy to Accomplish, 10=Extremely Difficult) | 2 | 0 | 7 | 1 | 8 | 5 | 5 | 7 | 5 | | | | | | | | | | | | |
| | | | | Max Relationship Value in Column | 3 | 9 | 9 | 9 | 9 | 3 | 9 | 9 | 9 | | | | | | | | | | | | |
| | | | | Weight / Importance | 46.0 | 265.8 | 461.5 | 254.7 | 474.3 | 109.9 | 218.0 | 496.3 | 328.0 | | | | | | | | | | | | |
| | | | | Relative Weight | 1.7 | 10.0 | 17.4 | 9.6 | 17.9 | 4.1 | 8.2 | 18.7 | 12.4 | | | | | | | | | | | | |

**APPENDIX D**

**ANC Test Plan:**

# Purpose

Comprehensive test of automatic nozzle changer for CLX laser system. This test will verify all required functions of the ANC and validate its use on the CLX. This test will qualify overall geometry, individual functions, and communication between the ANC and the CLX. All portions of this test must be completed and all definitions of success achieved before the ANC is shipped to a customer.

# Definition of success

- Correctly identifies the nozzle that is currently in use.
- Correctly removes the current nozzle and stores it in the nozzle holder.
- Correctly selects the next nozzle to be used and installs it in the machine spindle.
- Can repeat the nozzle-changing process multiple times without errors.
- Compatible with all nozzles that are intended to be used with it.
- Measure the accuracy of the ANC when positioning the nozzles and compare it to the specified tolerance.
- ANC stops immediately if any safety limits are exceeded.
- ANC does not damage the nozzles or the machine during operation.
- ANC can be installed and integrated with the machine without any issues.
- ANC can communicate with the machine controller correctly.

# Test Scenarios

## Geometry Validation

### Test 1: Head-up position validation

Verify that the head is able to drive over the camera and each of the nozzle locations. There should be clearance with the head all the way up to avoid the ANC.

_______ (Int.) _________ Date

### Test 2: Manual Nozzle Install

Have a nozzle installed in the head. Drive the head over a nozzle location and lower the head to install height, then retract to the z-up position. The nozzle should drop out into the cup when the head reaches install height.

_______ (Int.) _________ Date

### Test 3: Purge check

Ensure that the purge line is expelling air. The pressure inside the box must be a minimum of 2 psi greater than atmospheric pressure.

_______ (Int.) _________ Date

## Verify Communication

*Once communication and power have been connected. Test controls in the following order:*

### Test 4: Lid Communications

Open and close the lid 5 times. The lid should react within 1s and not slam open or closed. The lid should take no more than 2s to open or close. Flow controls may be adjusted if the test fails and run again.

_______ (Int.) _________ Date

### Test 5: Nozzle engagement

Raise and lower the nozzle tray 5 times. The tray should react within 1s and not slam up or down. Tray should take no more than 2s to raise or lower. Flow controls may be adjusted if the test fails and run again.

_______ (Int.) _________ Date

### Test 6: Camera

Install a 12 mm nozzle into TRA before beginning this test. Move the head to the camera position and activate the camera. HMI must display the nozzle completely and clearly show the outer nozzle orifice and the red aiming beam.

_______ (Int.) _________ Date

## Function Test

### Test 7: Automatic Alignment Routine

To complete this test the CI HMI must be able to automatically calculate the positions of all nozzle holders and the beam-centering camera. There should be a nozzle installed in the quick-connect TRA on the laser head, and no nozzle in nozzle location one of the ANC.

The operator will drive the laser head over the X1 reference mark, using the aiming beam to guide and use a button on the HMI to capture the current coordinates. The operator will do the same for the X2 reference mark. The operator will use an HMI button to automatically calculate the position of all nozzle holders and the beam-centering camera.

Once that is complete all positions must be verified by moving the head to each nozzle position and lowering the head with the pendant until the installed nozzle is released into the position.

_______ (Int.) _________ Date

### Test 8: Automatic Nozzle Change

Using a button on the HMI the laser head must be able to automatically remove an installed nozzle (A) into a known empty nozzle location and record that nozzle A is now present in that location. Then move to the position of the selected nozzle (B) and install the nozzle B. The HMI must record that nozzle B is no longer in its holder.

_______ (Int.) _________ Date

### Test 9: Beam Center

With a button on the HMI, the laser head must jog automatically to the beam-centering camera and lower to the photo height. The camera must display an image of the nozzle with sn ‘in-focus’ aiming beams on the HMI for the operator to inspect.

_______ (Int.) _________ Date

## Endurance Test

### Test 10: Cyclical Endurance test

With nozzles in all slots, cycle between changing nozzles from 1 to 2 to 3, and so on. After every 9 cycles, check beam centering, and cycle the lid. This counts as 9 nozzle swaps.

Complete 250,000 nozzle swaps of automatic nozzle exchanges. Once complete, all previous tests must be reverified to ensure no loss of functionality.

Achieve 25,000 nozzle swaps without error or intervention.

___________ Date of 25,000 cycles without failure _______ (int.)

___________ Date of 250,000 cycles complete _______ (int.)

___________ Date of tests 1-9 reverified _______ (int.)

# Signoff

___________ Date of completion ____________________ Signature