Engineering Design GNG5140

Final Prototype Report - Automated Decal Placer

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Abstract

The Automated Punching System was developed to automate the hole-punching process for polyimide masks used in electroplating applications. The system integrates a repurposed 3D printer for precise X-Y positioning with a mechanical actuation method for hole creation. The objective was to design a repeatable, efficient, and scalable solution that could generate precise hole patterns based on digital inputs, reducing human error and manual labor.

The project successfully implemented motion control and positioning accuracy, but the chosen solenoid-based punching mechanism failed to generate sufficient force to pierce the polyimide film. Prototype testing further revealed indentations forming on the 3D-printed die, indicating the need for a harder or self-healing material. Alternative actuation methods—such as higher-powered solenoids, servo-driven punches, pneumatic actuators, laser cutting, and blade-based systems—were identified for further evaluation.

Although the system did not meet its primary objective of hole punching, the insights gained provide a strong foundation for future improvements. The report details the mechanical design, electronics and software integration, and prototype testing results, highlighting key challenges and potential solutions for achieving a functional automated punching system.

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1. Introduction

The Automated Punching System is designed to streamline the hole-punching process for polyimide masks, addressing a key challenge in electroplating applications for hydrogen generation. The system aims to provide precise, repeatable hole placement while minimizing manual labor and human error. Current methods for creating these masks involve manual punching or laser cutting, both of which have limitations in speed, accuracy, and scalability. This project seeks to develop a solution that integrates automated motion control and a reliable punching mechanism to produce masks efficiently and consistently.

The primary objective of the system is to automate the hole-punching process using a controlled mechanical actuation method, allowing for customized hole patterns based on digital designs. To achieve this, the system repurposes components from a 3D printer for precise X-Y positioning, while the punching mechanism operates along the Z-axis. The polyimide film is fed into the system, aligned according to predefined coordinates, and punched to create the required hole pattern. The key challenge lies in selecting a suitable actuation method that can generate enough force to cleanly pierce the polyimide material without deforming the film.

This report details the design, prototyping, and evaluation of the Automated Punching System, covering both the mechanical and electronics/software aspects. The mechanical design section explores the selection of off-the-shelf components, the punch-die system, and structural considerations. The electronics and software section discusses the motion control system, firmware integration, and user interface design. Additionally, prototype testing and evaluation provide insights into system performance, limitations, and areas for future improvement.

By developing an efficient and scalable punching solution, this project aims to enhance the manufacturing workflow for polyimide masks, ultimately contributing to advancements in electroplating processes and hydrogen production technologies.

2. Final Prototype

The automated punching system consists of multiple subsystems working together to achieve precise hole punching in polyimide masks. The figure 1 illustrates the key components and their interactions. The Power Supply provides the necessary energy for the system's operation. Safety Monitoring ensures the system functions within safe limits throughout the process. The Software Interface is responsible for processing design input and generating punching instructions. These instructions are executed by the Movement Control system, which positions the punch accordingly. Finally, the Punching Mechanism creates holes in the polyimide mask based on the input data.

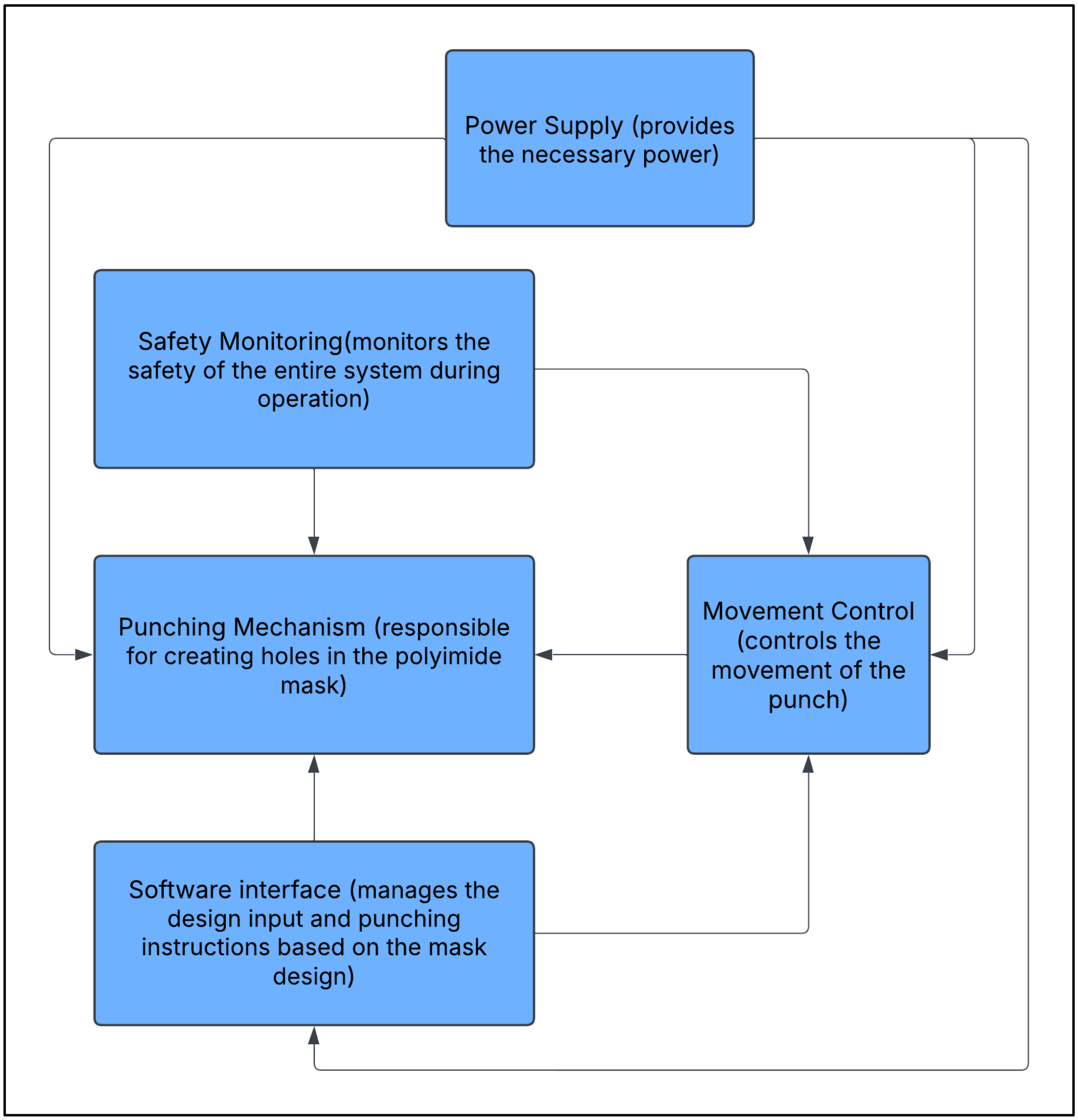

Figure 2.1: Global System Diagram

2.1. Mechanical Design

The Automated Punching System was designed to enable precise hole-punching in polyimide film while maintaining modularity and ease of assembly. The mechanical design consists of a punching mechanism, die, frame, and motion system, each playing a critical role in the system's functionality. Instead of fabricating custom components, standard off-the-shelf parts were sourced to simplify assembly, reduce costs, and ensure compatibility with available components.

The punch mechanism consists of a spring steel collet that secures the punch in place while allowing quick removal and replacement. The collet was initially considered for 3D printing in PLA, but concerns about wear due to friction led to the decision to use a commercially available metal collet. The collet holder was also replaced with a metal alternative instead of a 3D-printed version, ensuring durability under repeated use. The punch and die setup was designed to provide clean, precise perforations in the polyimide sheet, with the die serving as a support and guide for the material during punching. For prototyping purposes, the die was 3D printed to validate alignment and fit, but in future iterations, a hardened steel die may be required for improved longevity and cutting precision.

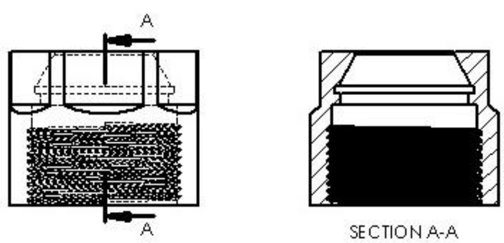

Figure 2.2: CAD Drawing of Collet Nut

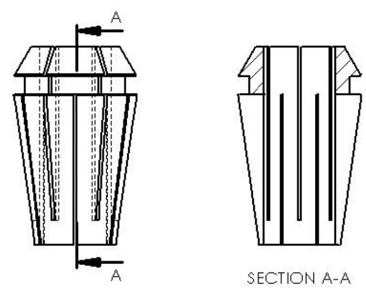

Figure 2.3: CAD Drawing of Collet

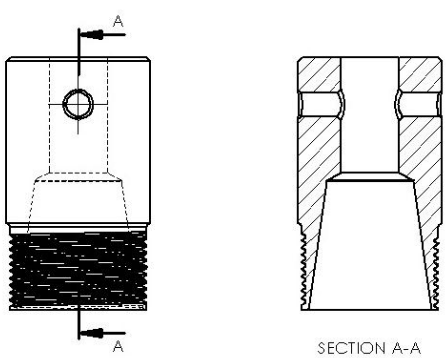

Figure 2.4: CAD Drawing of Collet Holder

Figure 2.5: Exploded View of the Assembly

The Z-axis actuation was implemented using a solenoid to drive the punch downward. While solenoids provide rapid actuation, the force generated in this setup was insufficient to reliably pierce the polyimide film. This remains an unresolved limitation, and alternative methods—such as a servo-driven or pneumatic actuator—are being considered to improve force delivery. The motion system controlling the X-Y positioning of the polyimide film was repurposed from an existing 3D printer. The stepper motors and linear rails ensure accurate alignment before each punch, enabling the system to create hole patterns based on predefined digital inputs. The 3D printer's Z-axis movement, however, was too slow and lacked the required force, which is why a separate actuation mechanism was integrated for the punching operation.

The frame and structural components were designed for stability while keeping the system lightweight. The frame primarily consists of aluminum extrusions, providing a rigid support structure for the punch assembly, die, and motion system. Additional brackets and fasteners were sourced from the market to facilitate quick assembly and ensure mechanical stability. While 3D-printed components were used in non-load-bearing areas, critical load-bearing parts were replaced with metal alternatives to enhance strength and reliability.

The assembly process focused on ensuring proper alignment of components, particularly the collet, punch, and die, to minimize deflection and ensure repeatability. While the system successfully demonstrates functional hole-punching, refinements are needed—particularly in the actuation mechanism—to improve force generation and efficiency. Additionally, future iterations may explore adjustable punch depth control and interchangeable dies for flexibility in hole sizes.

Figure 2.6: The Complete System

This section provides a complete understanding of the mechanical design, detailing each subsystem's functionality, the rationale for material choices, and areas for improvement in future versions.

2.2. Electronics & Software Design

A USB cable connects between the raspberry pi and the USB type C port on the Marlin 3D printer. [1] It acts as a communication link between the 3D printer and the controlling Raspberry Pi. During the course of the design, a control circuit of the solenoid is designed to activate and deactivate the solenoid from a Raspberry Pi GPIO pin. Figure 2.6 shows the schematic diagram of the circuit.

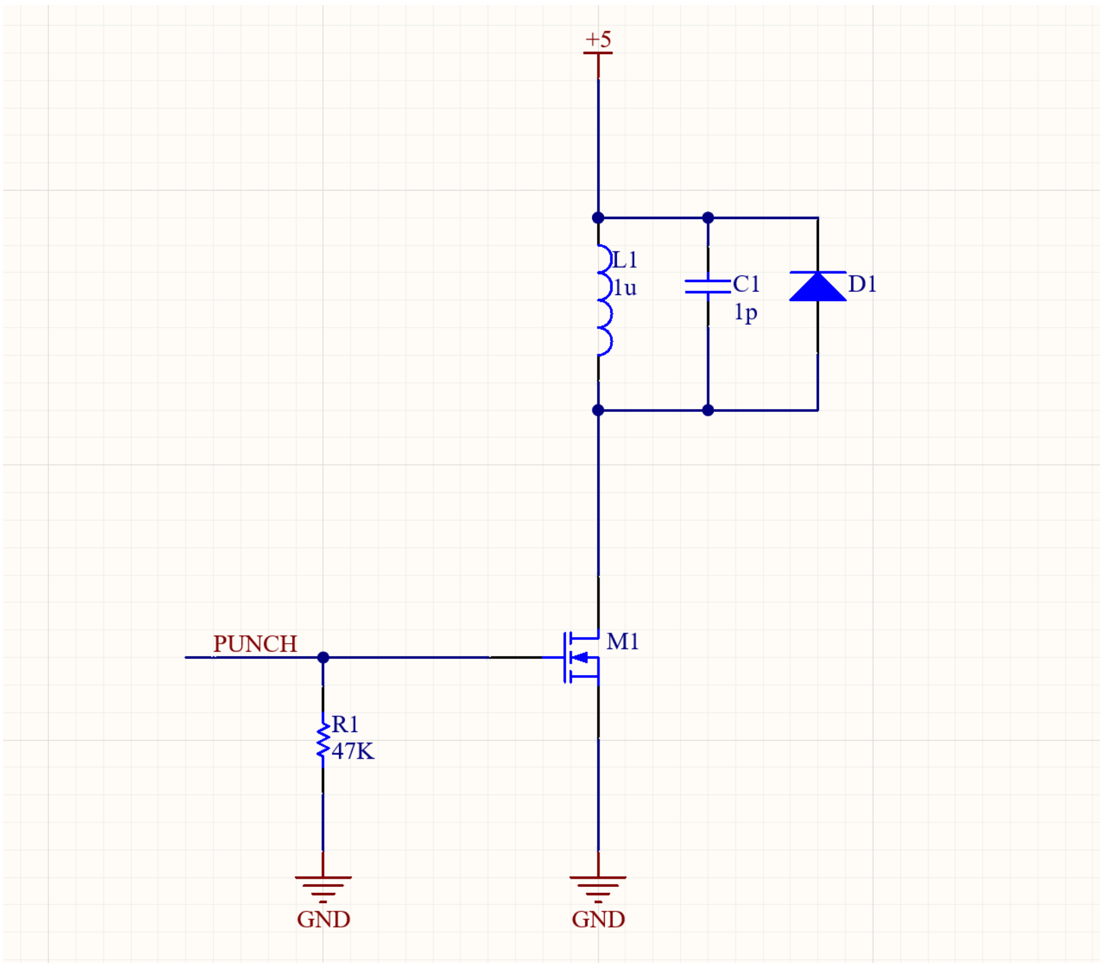

Figure 2.7: Solenoid Control Circuit Schematic Diagram

The circuit would be powered externally via a 5V power supply. [2] A MOSFET is connected between the negative terminal of the solenoid and circuit ground to act as a switch. When the control pin goes high, the MOSFET is activated and thus starts conducting, and vice versa. The pull-down resistor on the MOSFET gate ensures that it stays deactivated when the system is turned off. It is sized such that the current on the Raspberry Pi pin does not exceed its maximum rating when the circuit is activated. The inductor symbol in this diagram represents the solenoid. A capacitor and a diode are connected parallel to the solenoid to suppress inductive voltage spike on the MOSFET when the solenoid is turned off. However, further testing with the hole punch showed that it did not generate adequate force or momentum to be able to punch through the film. We have tried lowering the hole punch head assembly to let the tool punch the hole, however the film peeled off the printer bed before any hole was able to be created.

The control software has a simple interface and is installed on a spare Raspberry PI 4 Model B available in the client's lab. Figure 2.7 shows the software interface.

With the software, the workflow is as follows: the client designs the hole pattern to be punched in a graphic design tool such as Inkscape, which can specify the physical dimensions of the SVG image. He will then copy the SVG file to the control computer via e.g. a USB thumb drive, then select the file in the application in the file selection window that pops up after clicking on the "Browse…" button. The client can then find the port name of the connected 3D printer and specify connection parameters in the serial configuration window that pops up after clicking on the "Serial Configuration…" button. After that, the client may start the punching process by clicking on the "Start" button. The client may also stop the punching process at any time by clicking on the "Stop" button, which will be active after the punching process has been started. Figure 2.8 and Figure 2.9 show the file selection dialog window and the serial configuration window respectively. All graphical windows shown in this report are screenshotted from a Windows build.

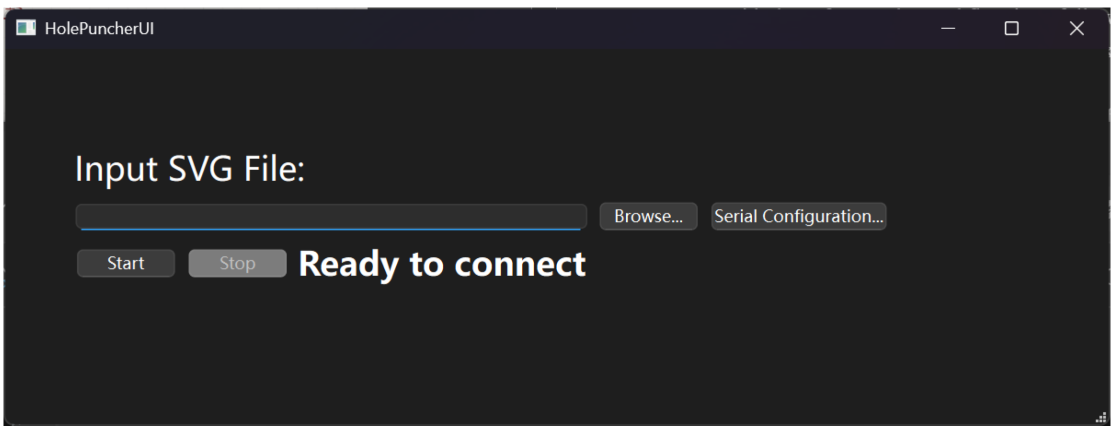

Figure 2.8:Control Software User Interface

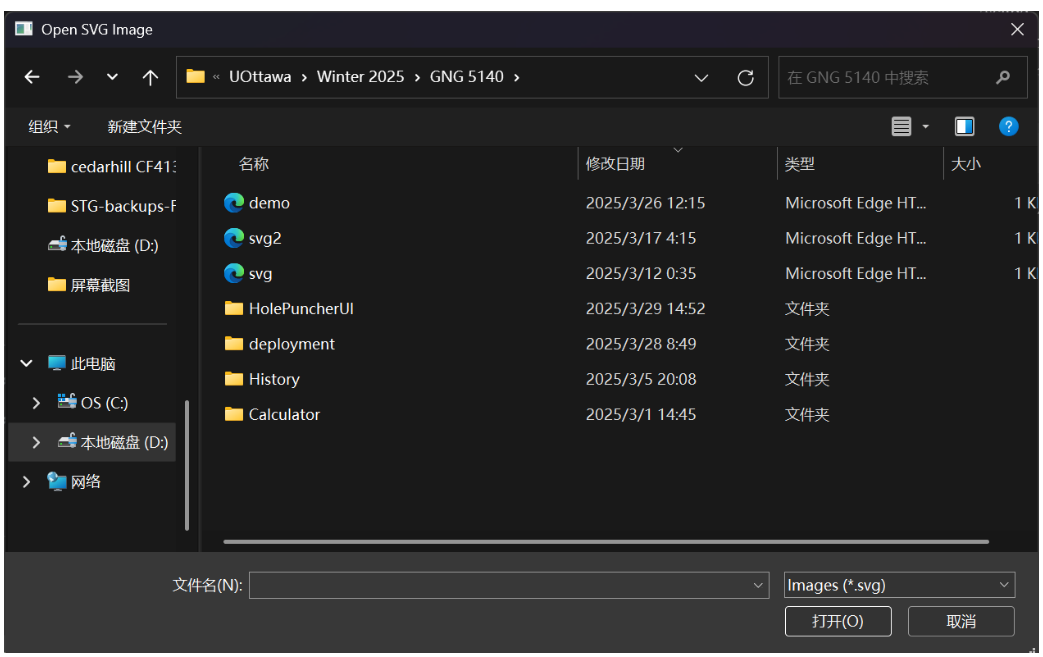

Figure 2.9: File Selection Dialog

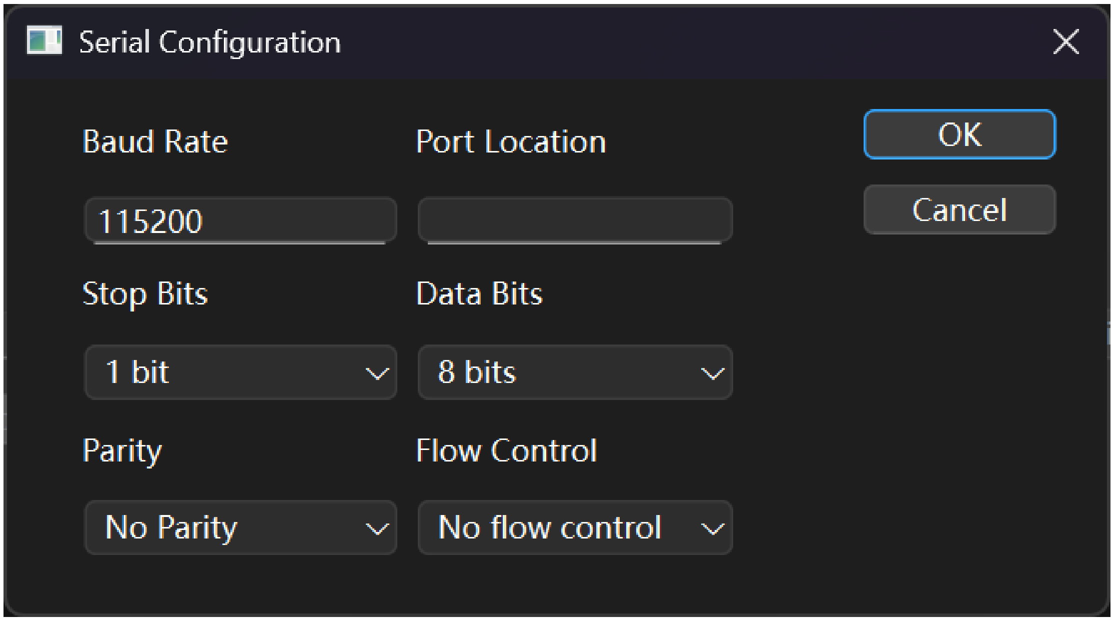

Figure 2.10: Serial Configuration Dialog

The software has two threads: the main GUI thread and the serial worker thread and is written using the Qt framework. The main thread renders the windows and handles user inputs. The worker thread parses the SVG file, opens a serial connection to the printer, and communicates with the printer by sending G-code commands over the serial connection and listening for the responses. When a user clicks on the start and stop buttons, the main thread will signal the worker thread to start and stop punching.

The punching process works as follows: when the worker thread receives the starting signal, it will try to parse the SVG XML and find the circle elements and their center positions, which will be mapped onto the printer bed dimensions. It then checks the serial connection with the printer by sending out the "M115" G-code and checking the responses to make sure it is talking to a 3D printer using the Marlin firmware, which the Ender-3 3D printer is. Then it sends out the G28 "Auto Home" command to place the hole punch over the center and waits for the homing process to complete. After that, it sends the "M114" command to read the current position of the 3D printer head, which will be used to determine the dimensions of the printer bed. It then calculates the coordinates on the printer bed for each hole and commands the printer to go to that position using the "G0" command. The "M400" command is used to make sure the printer head has been moved into position before punching. A complete reference of the G-code commands used in printers flashed with Marlin firmware can be found in [3].

Figure 2.11 shows a flowchart of the normal hole punching process.

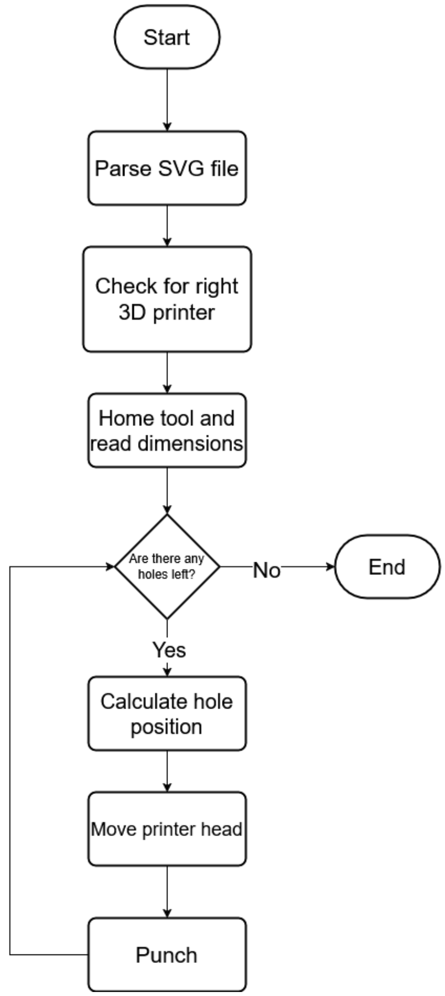

Figure 2.11: Normal Hole Punching Process Flowchart

3. Prototype Testing and Evaluation

The prototype testing phase of the Automated Punching System was crucial for assessing its overall performance, specifically focusing on mechanical stability, force generation, and motion accuracy. The goal was to determine whether the system could consistently punch holes in polyimide film while maintaining precise alignment and quality in each perforation. Through rigorous testing, several key performance characteristics were identified, along with areas in need of further refinement.

3.1. Mechanical Stability and Structural Integrity:

The mechanical framework of the system, including the punch-collet-die assembly, remained stable throughout multiple test cycles. The alignment held up well under repeated testing, and there were no significant structural failures. However, over time, the 3D-printed die began to show signs of wear. Specifically, indentations started forming on the die surface after repeated punching, which affected the quality of the cuts and the consistency of the punching process. This degradation suggested that while 3D printing was suitable for initial testing, the material properties of the die were insufficient for long-term use. The surface wear caused by the constant friction between the punch and the die could be mitigated by using harder materials or self-healing surfaces that can better resist wear. Potential alternatives include a metal die or a high-performance polymer engineered for wear resistance. This change would improve the longevity and repeatability of the punching process over extended use, ensuring more reliable results.

3.2. Force Generation and Actuation System Challenges:

One of the most significant challenges encountered during testing was the insufficient force generated by the Z-axis actuation system, which initially utilized a solenoid. The solenoid, which was expected to deliver the necessary force to punch through the polyimide film, proved to be completely ineffective in penetrating the material. Instead of producing clean perforations, the solenoid failed to apply enough force to even begin cutting, resulting in no holes at all. This issue highlighted the need for a more robust actuation system capable of delivering the required force for punching. Several approaches are being considered to address this limitation:

- Overdriving the Solenoid: One possibility is to test the solenoid beyond its rated specifications, pushing it to its limits to see if it can generate the necessary force.
- Higher-powered Solenoid Alternatives: Exploring stronger solenoids could provide the additional power needed for clean cuts.
- Servo-driven Mechanism with Lead Screw: A more controlled, precise force application method could be achieved by switching to a servo-driven mechanism with a lead screw, which would allow for better modulation of force during the punching action.
- Pneumatic or Hydraulic Actuators: These systems offer higher force capacity, which could enable the punching system to generate enough power to cut through the polyimide film. However, this comes with the trade-off of increased complexity and potential additional safety concerns.
- Non-contact Alternatives: Non-mechanical alternatives, such as laser cutting or vinyl cutter blade systems, are also being explored. These options could provide a cleaner, more precise

cut without the need for direct mechanical contact, although they may introduce their own set of challenges, particularly in terms of system integration and cost.

Additionally, refining the punch geometry itself could help reduce the force needed for effective perforation. By improving the sharpness and design of the punch, it may be possible to create cleaner holes with less force, optimizing the process for the material.

3.3. Motion Control and Film Securing:

The X-Y motion system, which was repurposed from a 3D printer, performed well in terms of positioning accuracy. The stepper motors and linear rails delivered precise movement, allowing the polyimide film to be positioned accurately for each punching operation. However, a critical challenge emerged with securing the film during the punching process. Minor shifts in the film's position led to inconsistencies in hole placement, causing alignment issues and compromising the accuracy of the cuts. This indicated that the current film-holding mechanism was inadequate for maintaining consistent positioning throughout the process.

To address this, a more robust securing system is needed. Possible solutions include implementing a vacuum bed, which could hold the film in place by suction, or using mechanical clamps to fix the film securely during operation. These enhancements would improve the system’s stability, reducing the chances of film displacement and ensuring that the holes are punched in the correct locations with every cycle.

3.4. Next Steps and Refinements:

Overall, the testing phase provided valuable insights into the limitations and areas requiring further development. While the mechanical framework and motion control system performed as expected, the actuation mechanism and film handling are key areas for improvement. The next steps will focus on evaluating alternative punching mechanisms, refining the punch geometry to reduce force requirements, and enhancing the material handling process to ensure consistent alignment and stability throughout the punching cycle. These improvements will be crucial for moving towards a fully automated punching system that delivers reliable, high-quality results.

4. Scalability Aspects

The Automated Decal Placer is designed with scalability in mind, ensuring that it can be efficiently mass-produced and adapted to various production needs. Its modular design allows components to be easily manufactured, assembled, and upgraded, making repairs and future enhancements seamless. The use of standardized parts, such as commonly available motors, sensors, and controllers, helps reduce production costs and simplifies supply chain management. This reliance on industry-standard components ensures affordability and ease of maintenance. Additionally, the system is engineered for automated assembly line integration, enabling it to operate within high-speed production environments, enhancing productivity for large-scale industries requiring precise decal placement.

Adaptability is a core feature of the system, ensuring that it meets the needs of different users across industries. The customizable software interface allows users to modify decal placement patterns, adjust pressure settings, and optimize workflows to suit specific applications. Furthermore, interchangeable fixtures enable the system to accommodate various decal sizes and materials, allowing manufacturers to switch between different products without extensive modifications. The system is also compatible with multiple industries, including electronics, textiles, automotive, and aerospace, making it a versatile solution for manufacturers with diverse decal application needs.

Future enhancements aim to improve both functionality and efficiency. The integration of AI-powered alignment could enhance decal placement accuracy through machine learning algorithms, reducing errors and improving precision. Additionally, cloud-based monitoring could allow for real-time performance tracking, remote operation, and early issue detection, optimizing system uptime. The system's energy-efficient components, including low-power motors and intelligent actuation systems, help reduce energy consumption, supporting sustainable production practices while lowering operational costs. Further advancements could also see the inclusion of robotic arm integration, allowing for multi-angle decal placements, which would expand the system’s capabilities for more complex applications requiring high precision.

5. Quality Considerations

The Automated Decal Placer follows the principles of Kaizen (Continuous Improvement) to ensure ongoing enhancements in performance and efficiency. By making incremental improvements based on real-time feedback and performance analysis, the system continuously evolves to meet industry standards and user demands. Regular performance assessments help identify and rectify inefficiencies quickly, reducing downtime and optimizing production throughput. This iterative approach ensures sustained operational excellence and long-term reliability.

To improve accuracy and durability, the system incorporates precision calibration through high-resolution sensors and automated calibration routines, minimizing alignment errors and reducing rework. Its durable construction, made from high-quality, wear-resistant materials, ensures longevity and consistent performance even under prolonged use. Reinforced structural integrity prevents alignment drift, maintaining precision over time. Additionally, software enhancements are planned to further refine motion control algorithms, improve repeatability, and implement advanced error compensation mechanisms for enhanced reliability.

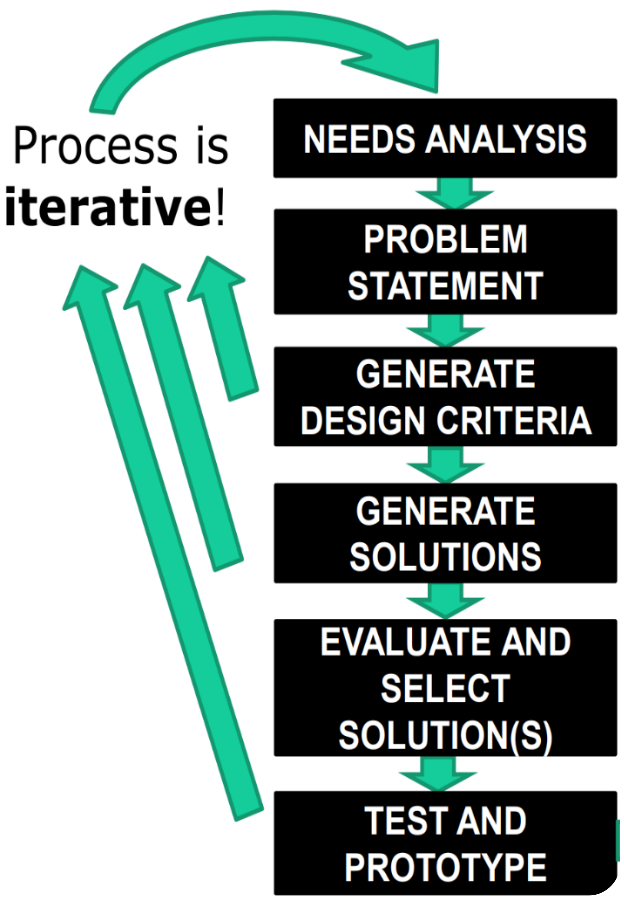

Figure 5.2: Waterfall and iterative design process steps to be followed for further improvement

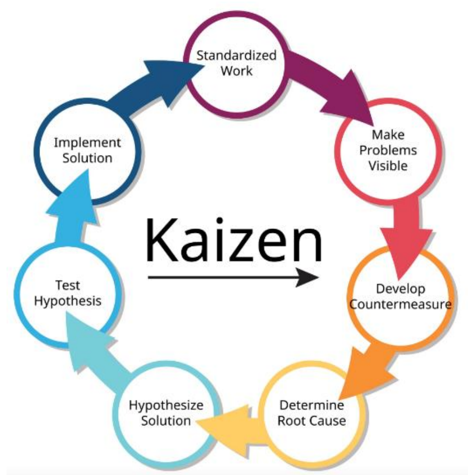

Figure 5.1: Steps involved in Kaizen process for further quality improvements

6. Sustainability & SDG Alignment

The Automated Decal Placer aligns with environmental, economic, and social sustainability goals. From an environmental perspective, the system minimizes material waste by ensuring precise decal application, reducing errors and scrap rates. Its energy-efficient design, featuring low-power motors and optimized operation cycles, significantly lowers energy consumption compared to manual processes. Moreover, whenever feasible, the system incorporates recyclable components, promoting eco-friendly manufacturing practices.

Economically, the system supports cost reduction by automating processes, reducing labor costs, minimizing human error, and optimizing material usage. Its long-term return on investment (ROI) is ensured through durable construction and low maintenance requirements, making it a financially viable solution for industries. The modular design further allows for easy scalability, enabling manufacturers to expand production without overhauling the entire system.

On a social level, the system enhances workplace safety by minimizing manual handling, reducing risks associated with repetitive strain injuries and hazardous exposure. It also contributes to workforce upskilling, shifting labor demands from manual work to skilled technical roles, creating higher-paying job opportunities. Additionally, its user-friendly interface ensures accessibility for a diverse range of operators, including those with limited technical expertise, fostering inclusivity in manufacturing.

Potential improvements for sustainability include integration with renewable energy sources, such as solar-powered modules, to further reduce the system's carbon footprint. Advanced waste reduction strategies could leverage machine learning for predictive maintenance, optimizing material usage while minimizing downtime-related waste. Lastly, using sustainable packaging for components, such as biodegradable or recycled materials, would further align the system with sustainability goals, ensuring an environmentally responsible manufacturing process.

7. Usability Aspects

The user interface of the control software is simple and easy to use. The client just needs to select a SVG design for a certain hole pattern and the hole puncher would punch holes in the specified position accurately. The SVG files can be reused to produce common patterns. There are graphics design software available on the market e.g. Inkscape that lets you set the dimensions of the canvas and the size and positions of the holes easily. However, those graphical design software do not let you specify the gaps between hole patterns easily, and engineering design software are better in this regard. The reason we ended up using the SVG format is that it is an open textual standard, so that parsing the SVG file to look for circles and ellipses becomes easy. Popular formats generated by engineering design software, for example, the DWG format, have closed specifications and documentation is scant on how to decode those formats. There is no good quality, free libraries that can decode engineering design files, either. The only available option we can find is the Drawings SDK produced by Open Design Alliance, of which Autodesk® is a member. [4] It is not open source and costs around 3000 USD for the first year and 2250 USD for subsequent years.

For improvements to the project, a companion application that outputs SVG files but has all the dimensioning capabilities of engineering design software can be designed to simplify the pattern creation process. We can also provide pre-made templates for hole patterns that are commonly used in client's research.

8. Conclusion

The development of the Automated Punching System provided valuable insights into the challenges of automating the hole-punching process for polyimide masks. While the system successfully demonstrated precise motion control using a repurposed 3D printer for X-Y positioning, the punching mechanism itself did not achieve the intended functionality. The solenoid-based actuation system was unable to generate enough force to pierce the polyimide film, highlighting the limitations of the chosen actuation method and the need for a more robust alternative.

Prototype testing revealed that indentations formed in the 3D-printed die, leading to inconsistent results and potential long-term durability concerns. This suggests that a harder material or a self-healing die surface may be necessary to ensure reliable operation over multiple cycles. Additionally, securing the polyimide film during punching presented challenges, emphasizing the need for a more effective holding mechanism to maintain accuracy and prevent shifting.

Despite not achieving the primary objective of successfully punching holes, the project provided critical data for future iterations. Several alternative actuation methods—including higher-powered solenoids, servo-driven systems, pneumatic actuators, and even non-contact solutions like laser cutting—have been identified for further investigation. Refinements in punch geometry, die material selection, and film holding mechanisms will also be crucial for improving performance.

The work done in this project lays the foundation for a more effective automated punching solution. Future efforts should focus on addressing the force generation issue, testing alternative punching techniques, and optimizing material interactions to achieve a fully functional system. The lessons learned from this prototype phase will guide the next steps in developing a scalable and efficient punching system for electroplating applications.