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Master's Thesis
Academic Year 2024

Design and Fabrication of Interactive Circuits with 3D Pen and Conductive Filament

Keio University
Graduate School of Media Design

Yun-Ju Wang

A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

Yun-Ju Wang

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Professor Hideki Sunahara	(Co-Reviewer)

Abstract of Master's Thesis of Academic Year 2024

Design and Fabrication of Interactive Circuits with 3D Pen and Conductive Filament

Category: Design

Summary

This research explores the design and fabrication of interactive circuits using a 3D pen and conductive filament, targeting creative individuals. The proposed approach emphasizes the hands-on process of using a 3D pen, supported by laser cutting. Additionally, a web-based Design Tool was developed to support the customizable circuit design process.

To validate the approach, prototypes were developed, and two demonstrations and two workshops were conducted to gather feedback. The workshops highlighted the approach's accessibility and potential, offering valuable insights for future improvements.

Overall, this research presents a fabrication process for creating interactive circuits and applications, examining the benefits of the hands-on process and customization in circuit fabrication, and providing insights into their effects on user experience and design outcomes.

Keywords:

3D pen, conductive filament, interactive electronic circuits, design tool

Keio University Graduate School of Media Design

Yun-Ju Wang

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Chapter 1
Introduction

1.1. Background

The fabrication and application of electronic circuits have advanced significantly in the field of HCI (human-computer interaction) in recent years. Beyond traditional fabrication methods, various approaches have been developed, incorporating new processes, techniques, and materials. These innovations provide greater flexibility and compatibility, enabling circuits to be integrated into diverse digital systems and expanding their potential applications.

These advancements have contributed to the realization of ubiquitous computing [1], where electronics seamlessly integrate into everyday objects and environments, providing smart and interactive functionalities. As a result, various physical computing systems have been developed, enabling real-time interactions between users and devices through applications integrating electronic circuits, microcontrollers, and other electronic components.

Moreover, working with electronics and interactive systems is no longer limited to engineers and specialists. Electronics are now more accessible to creative individuals, including designers, artists, makers, and DIY creators, allowing them to integrate technology into their projects. By utilizing accessible tools, they can explore applications in interactive installations, digital art, wearable technology, and DIY electronics projects, and more. These advancements lower the barrier to entry, allowing more people to experiment with electronic interactivity and expand the possibilities for innovation across multiple fields.

1.2. Current Methods and Limitations

1.2.1 Traditional Circuit Fabrication Methods

Manual soldering is one of the oldest methods, where components are attached to a board by melting solder to create connections. While effective for small-scale projects, it is time-consuming and difficult to modify once completed.

Breadboards are commonly used for prototyping, allowing components to be inserted and removed easily. They are ideal for quick experimentation but lack stability for long-term use.

PCBs (Printed Circuit Boards) are used for mass production, where circuit designs are etched onto copper boards, and components are soldered in place. PCBs are precise and reliable but are more expensive and time-consuming to produce.

These traditional methods generally require technical knowledge or specialized equipment in circuit design and fabrication, making them less accessible for those without an advanced engineering background.

1.2.2 Innovative Circuit Fabrication Methods

In the field of HCI, recent research has proposed various innovative approaches to circuit fabrication. Compared to traditional methods, diverse materials and innovative fabrication processes are used. For example, circuits can be created on different substrates or with various conductive materials. The process often assisted by digital fabrication such as laser cutting or 3D printing. These new methods complement traditional approaches, improving adaptability and accessibility and open up new possibilities.

However, each method comes with its own advantages and limitations. For instance, circuit designs often depend on predefined patterns or require specialized software, such as graphics software or CAD (Computer-Aided Design) tools. Few methods emphasize user customization, which can limit users' ability to fully personalize circuit designs and restrict creative expression.

1.2.3 Tools for Interactive System Development

Various tools, such as Arduino, Raspberry Pi, and Sony MESH, have been developed to enable individuals without advanced engineering backgrounds to create interactive digital systems. These tools allow users to integrate and control electronic components, such as sensors, motors, and LEDs, by connecting them into a functional system and programming them to respond to inputs or trigger actions.

By offering modularity, open-source support, and user-friendly interfaces, these tools simplify the development process. They lower technical barriers, encouraging users to experiment, design, and implement their own interactive circuits and systems, opening up new possibilities for innovation across various fields.

Conversely, while they offer simplified processes and modular structures, they often rely on templates and specific components, which restricts users from fully personalizing their designs.

1.3. Interactive Fabrication

On the other hand, while digital tools and digital fabrication provide powerful capabilities, they can separate designers from the hands-on making process and reduce direct visual and tactile contact with the material. In traditional craftsmanship, creators could directly work with materials, seeing and touching the result in real time. This immediate feedback enabled them improve their work through direct interaction.

Willis et al. [2] introduced the concept of Interactive Fabrication, which brings real-time feedback into digital fabrication workflow. This approach brings physical input and output closer together, establishing a stronger connection with materials and enabling designers to better understand their properties and nuances.

1.4. Proposal

After considering the current approaches and their limitations, and drawing inspiration from the concept of Interactive Fabrication to foster a closer connection between designers and their creations, I decided to apply the concept to circuits fabrication. I started to learn about a tool, 3D pen, which is a handheld tool that extrudes plastic filament to create 3D structures in real time. Unlike 3D printing, it offers hands-on control and flexibility. I thought of combining this tool with conductive filament, which would allow users to manually draw and create circuits.

This research aims to propose a fabrication process for creating interactive circuits using a 3D pen and conductive filament, targeting creative individuals such as designers, artists, makers, and DIY creators. The approach offers a hands-on method to create simple interactive circuits that achieve basic electronic functionality. Given that the target users often possess high creativity and strong manual or drawing skills, they can effectively utilize the 3D pen to explore and express their ideas in circuit design.

This research emphasizes the handmade process, highlighting its innovation and distinctiveness in comparison to automated or digital fabrication methods. Unlike fully digital fabrication techniques, manually using a 3D pen offers several advantages: it enables the creation of varied textures on circuit surfaces, the flexible construction of 3D shapes, easy real-time modifications and additions, and the use of conductive filament as an adhesive in 3D structures.

Additionally, the proposed approach involves developing a design tool to support the circuit pattern design process and improve customization.

In addition to introducing the fabrication process, this research also aims to explore the potential effects on user experience and design outcomes of integrating a hands-on process and customization into circuit creation.

1.5. Research Question

- Could a fabrication process using a 3D pen and conductive filament be designed to create interactive circuits and applications for creative individuals?
- What are the potential effects on user experience and design outcomes of integrating a hands-on process and customization into the fabrication of interactive circuits?

1.6. Research Goal

The goal of this research is to develop an approach that incorporates a hands-on process using a 3D pen and conductive filament to create interactive circuits and applications, targeting creative individuals. Additionally, the research aims to examine the potential effects on user experience and design outcomes of incorporating the hands-on process and customization into circuit fabrication.

Chapter 2
Related Works

2.1. Crafting Interactive Circuits in Varied Contexts

In the field of HCI, researchers have explored a wide range of fabrication processes and materials for producing electronic circuits with varied properties.

2.1.1 With Various Conductive Materials

Researchers in HCI have explored various conductive materials for circuit creation, such as conductive ink [3,4], conductive yarns [5], conductive epoxy [3], conductive tape [3], and conductive filament for 3D printing [6, 7]. These materials allow circuits to be crafted on unconventional substrates, such as textiles, paper, and 3D-printed objects, offering greater flexibility in design and functionality. This expansion of materials enables interactive electronics to be integrated into a wide range of applications.

2.1.2 On Various Substrates

Interactive circuits have been created on a variety of substrates beyond traditional circuit boards, including flexible materials such as fabric [8, 9], commonly used for e-textiles, and paper [10–12], which enables the development of flexible and foldable electronic composites. In addition, rigid materials like wood [13], acrylic [14] [15], and complex 3D surfaces like ceramics [16] have also been explored for interactive circuit applications.

Various techniques have been employed to adapt circuits to these diverse substrates. For example, Zheng et al. [16] introduced a method for using glazed ceramics as a platform for interactive interfaces. By utilizing resist-blasting, they successfully created interactive circuits on the intricate, three-dimensional surfaces of ceramic objects.

2.1.3 Customization in Circuit Design

Some research allows the customization of circuit patterns during the fabrication process, balancing both functionality and creativity expression. These approaches enable designers to create circuits that are not only functional but also visually integrated into the overall design of the creation, ensuring that the circuits complement the overall aesthetic of the creation.

For example, DuoSkin [17] is a rapid prototyping and fabrication process that uses gold leaf to create wearable, on-skin user interfaces. During a workshop evaluation, participants were able to customize their own personalized designs of on-skin music controllers, allowing them to incorporate their personal aesthetics into the design.

Additionally, Sun et al. [5] introduced Weaving a Second Skin, which incorporates circuitry into the textile structure to extend the weaving practice for creating on-skin interfaces. In their workshop study, textile practitioners successfully adopted the fabrication process to create personalized designs, while also reflecting on the rich materialities for a hybrid form factor that sits between textiles and body art.

2.2. Fabrication Techniques for Interactive Circuits

2.2.1 Using 3D Pens and Conductive Filaments

Several studies have explored the innovative use of 3D pens and conductive filaments for fabricating electronic components:

João et al. [18] reported using a 3D pen with biodegradable carbon black/polylactic acid filament to fabricate affordable electrochemical sensors for on-site monitoring of lead and copper in aqueous and hydroethanolic media.

Cardoso et al. [19] demonstrated that a commercially available 3D printing pen can be used to draw thermoplastic electrochemical sensors using conductive filaments over various formats and substrates. They used polylactic acid filaments containing graphene or carbon black to create three different electrode designs.

Pradela-Filho et al. [20] showcased the production of electrochemical sensors using 3D-printing pens and commercial conductive filaments without the need for (electro)chemical treatment, simplifying the fabrication process.

These studies highlight the versatility of 3D pens and conductive filaments as accessible tools for creating functional electronic components, broadening the scope of applications in rapid prototyping and sensor fabrication.

2.2.2 Using Laser Cutting

Researchers have utilized laser cutting in various ways to fabricate circuits. Laser cutting can be used to directly process conductive materials and circuit substrates to fabricate circuits. For example, LASEC [21] enables the instant fabrication of circuits with custom stretchability using a laser cutter. CircWood [13] introduces a method and workflow for producing various sensors and electrical circuits for interactive devices by partially carbonizing the wood surface with a laser cutting machine.

In addition, laser cutting can be used to cut masks or stencils to aid in forming circuit traces. For instance, MaskCircuit [14] presents a maker-friendly fabrication approach for 3D circuits using laser cutters and acrylic sheets, while E-Acrylic [15] also leverages laser cutting to embed circuits into acrylic sheets.

2.3. Summary

Various fabrication processes and materials exist for creating interactive circuits, but fewer studies focus on supporting customizability and hands-on processes. Current approaches, as seen in related work, often prioritize fixed designs and digital fabrication, limiting flexibility in customizing circuits.

Inspired by related works—such as using laser cutting for circuit fabrication, leveraging 3D pens with conductive filaments, and enabling customization of circuit patterns—I aim to integrate these ideas. Conductive filaments in 3D pens offer advantages like direct, hands-on fabrication and real-time design adjustments, which are less feasible in traditional circuit-making methods or digital fabrication methods.

Building on these insights, the research proposes a fabrication process that combines laser cutting digital fabrication method and 3D pen manual process to create interactive circuits. Laser cutting ensures precise circuit traces, while 3D pens allow for expressive, creative, and functional designs. Additionally, the introduction of a design tool could be beneficial in further supporting customization and creative expression. This integration could expand the potential of interactive circuit applications.

Chapter 3
Design Process

3.1. Concept Design

After reviewing related works, I decided to adopt a hands-on approach using a 3D pen to draw circuits, providing creatives with greater flexibility. Conductive filament, which is compatible with the 3D pen, is used as the circuit material. To improve the precision of manual drawing, I propose to introduce a laser cutter to engrave traces on the substrate as guides. As a result, a hybrid fabrication process is developed. Additionally, I aim to develop a design tool to support users in efficiently creating personalized circuit patterns.

3.1.1 Tools and Materials

The fabrication process needs the following tools and materials:

- **Substrate**: A laser-cuttable material, such as wood or acrylic sheet, serves as the foundation for the interactive circuit.
- **Laser Cutter**: Used for cutting and engraving circuit patterns onto the substrate material.
- **3D Pen**: A handheld tool that allows users to manually draw and extrude 3D printing filament. *MYNT3D 3D Pen Pro* is used in this research. (Figure 3.1)
- **Conductive Filament**: A PLA (Polylactic Acid) 3D printing filament with conductive properties. *Protopasta Electrically Conductive Composite PLA* is used in this research. (Figure 3.2)

(Source: 3D Pen PRO - MYNT3D, https://www.mynt3d.com/collections/3d-pens/products/3d-printing-pen)

Figure 3.1 3D pen used in the research.

(Source: Electrically Conductive PLA — Conductive 3D Printer Filament – Protoplant, makers of Protopasta, https://proto-pasta.com/products/conductive-pla)

Figure 3.2 Conductive filament used in the research.

3.1.2 Workflow

A complete workflow consists of three main stages, as shown in Figure 3.3:

1. **Design**: Users design and customize the base shape and personalize the circuit patterns using the Design Tool.
2. **Fabrication**:
   (a) Users laser-cut the base shape and engrave circuit pattern traces onto the substrate material using a laser cutter. These engraved traces act as both visual and physical guides for the manual 3D pen process.
   (b) Users fill the engraved traces with conductive filament using a 3D pen.
3. **Integration**: Users integrate the circuit with the physical computing system (e.g., using silicone jumper wires to connect components) to achieve electronic functionality.

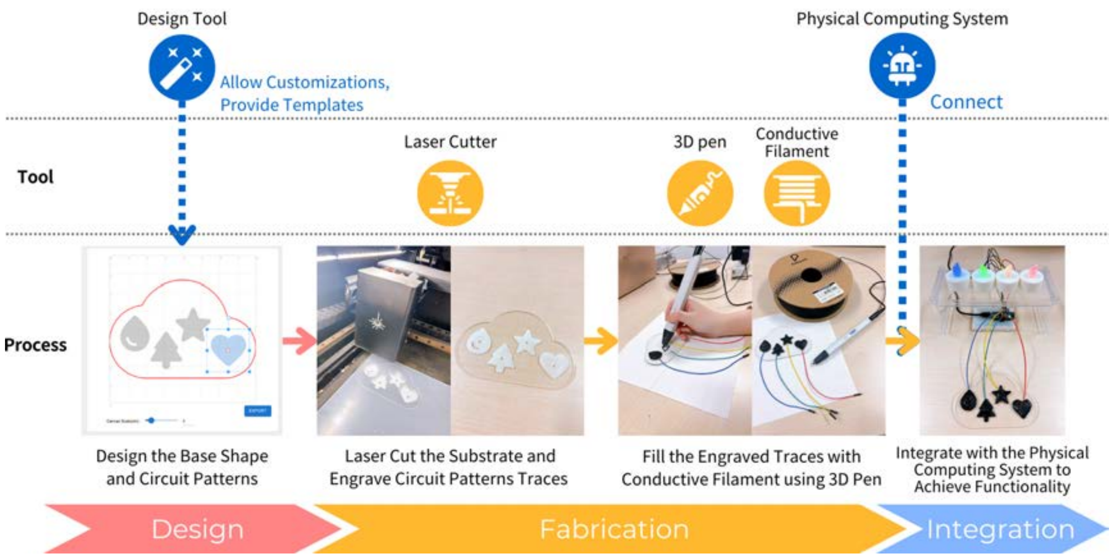

Figure 3.3 Fabrication workflow of interactive circuits.

3.2. Proof-of-Concept Prototype

To validate the fabrication stage of the workflow, I created PoC (proof-of-concept) prototypes to demonstrate the feasibility of circuit fabrication using a 3D pen and conductive filament.

3.2.1 Design

The design of circuit patterns are divided into three groups, labeled A, B, and C, as shown in Figure 3.4. Each group focusing on different operational variables:

- **Group A**: The circuit patterns have the same shape and length bu differ in thickness to explore the effect of circuit width.
- **Group B**: The circuit patterns have the same thickness but differ in length to explore the effect of circuit length.
- **Group C**: The outer circuit between the two endpoints forms a hollow circle, while the inner area is filled with circuits at different densities to explore the effect of circuit density.

In the design, red lines indicate the laser cutting path, and black areas represent the engraving parts. The cutting and engraving for each group are performed using consistent laser cutting settings (power and speed), with 3/32 inch basswood as the substrate material.

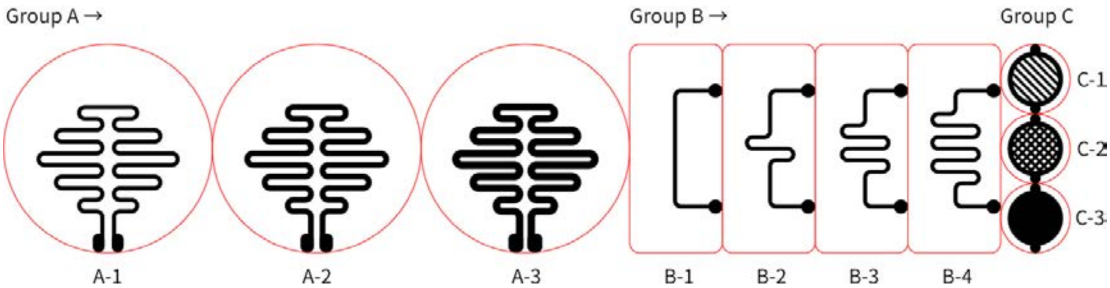

Figure 3.4 PoC prototypes' designs for laser cutting. Red lines are for cutting, and black filled areas are for engraving.

3.2.2 Process

1. Use a laser cutter to cut the base shape and engrave the circuit pattern traces.

2. Fill the engraved traces with conductive filament using a 3D pen.

3. Use a multimeter to test the circuit by placing the test leads at the two endpoints, checking for loop completion and measuring resistance.

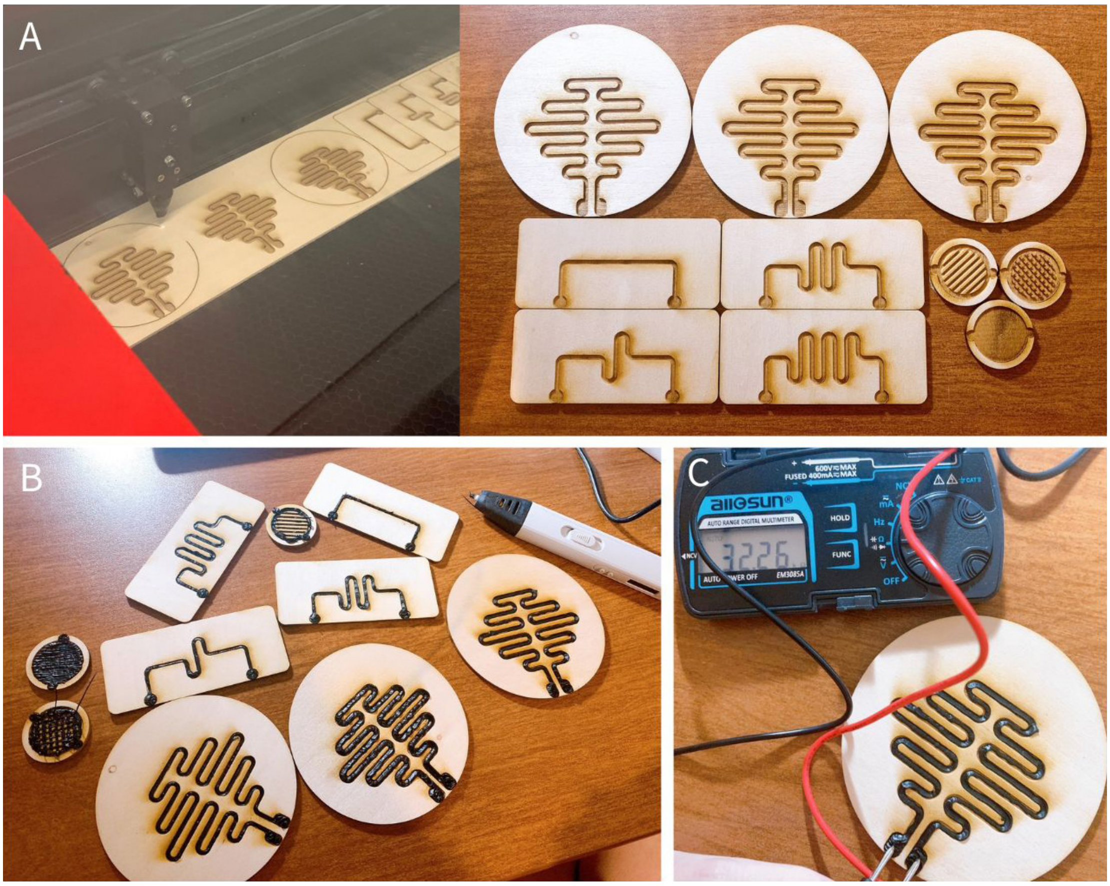

Figure 3.5 Process of making PoC prototypes. A: Laser cut the base shape and engrave the circuit pattern traces. B: Fill the engraved traces with conductive filament using a 3D pen. C: Check circuit completion and measure resistance with a multimeter.

3.2.3 Result and Measurement

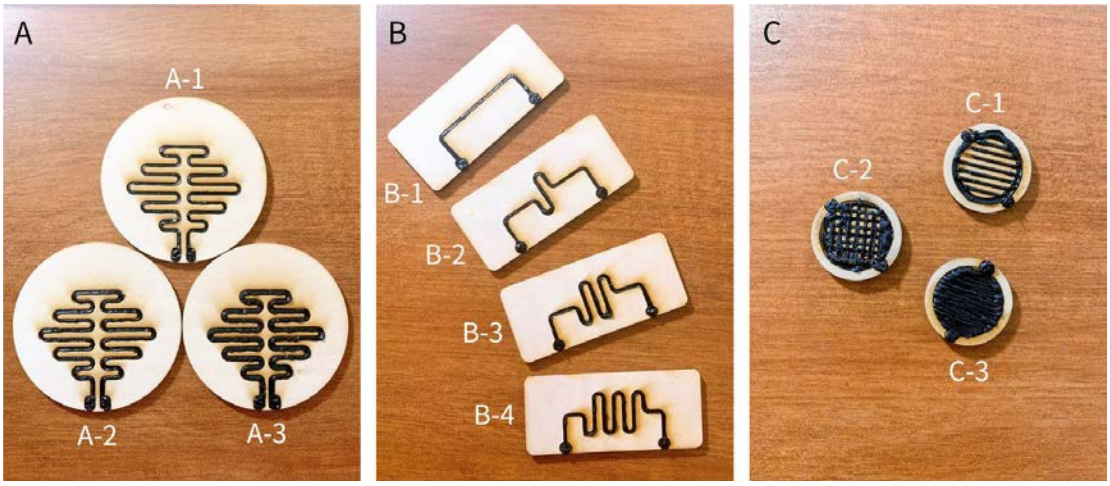

Figure 3.6 The completed PoC prototypes.

In Group A, the circuit length is fixed at 435.33 mm. Prototypes A-1, A-2, and A-3 have circuit widths of 5 pt (approximately 1.76 mm), 7 pt (approximately 2.47 mm), and 9 pt (approximately 3.18 mm), respectively, to investigate the effect of circuit width on resistance. The resistance measurements for Group A are shown in Table 3.1. As shown, the resistance decreases as the circuit width increases.

Prototype	**Circuit Width**	**Resistance** ($k\Omega$)
A-1	$5pt \approx 1.76mm$	41.9
A-2	$7pt \approx 2.47mm$	32.26
A-3	$9pt \approx 3.18mm$	16.69

Table 3.1 The relationship between circuit width and resistance in Group A of the PoC prototypes.

In Group B, the circuit width is fixed at 5 pt (approximately 1.76 mm). Prototypes B-1, B-2, B-3 and B-4 have circuit length of 77.19 mm, 111.04 mm, 146.40 mm and 182.07 mm, respectively, to investigate the effect of circuit length on resistance. The resistance measurements for Group B are shown in Table 3.2. As shown, the resistance increases as the circuit length increases.

Prototype	**Circuit Length** (mm)	**Resistance** $(k\Omega)$
B-1	77.19	6.92
B-2	111.04	10.17
B-3	146.40	10.51
B-4	182.07	15.07

Table 3.2 The relationship between circuit length and resistance in Group B of the PoC prototypes.

In Group C, the outer circuit between the two endpoints forms a hollow circle, while the inner area is filled with circuits at varying densities. Prototype C-3 has a completely filled solid circle with an area of 447.2789 mm^2, which seen as the baseline density (1). Prototype C-2 has a filled area of 345.6057 mm^2, resulting in a relative density of 0.773. Prototype C-1 has a filled area of 272.7846 mm^2, resulting in a relative density of 0.610. The resistance measurements for Group C are shown in Table 3.3. As shown in the table, the resistance decreases as the circuit density increases.

Prototype	**Circuit Relative Density**	**Resistance** $(k\Omega)$
C-1	0.610	1.287
C-2	0.773	1.230
C-3	1	0.866

Table 3.3 The relationship between circuit relative density and resistance in Group C of the PoC prototypes.

The resistance measurements obtained for each group of prototypes show a general trend that aligns with Resistivity Law, which is expressed as:

$$R = \rho \left(\frac{L}{A} \right) \tag{3.1}$$

Where:

- R = Resistance

- ρ = Resistivity of the material
- L = Length of the conductor
- A = Cross-sectional area of the conductor

Group A results indicate that increasing circuit width, which expands the conductor's cross-sectional area, tends to reduce resistance. Group B shows that greater conductor length tends to increase resistance. In Group C, higher filling density effectively increases the cross-sectional area and tends to reduce resistance. These trends align with theoretical expectations from the Resistivity Law.

3.2.4 Conclusion

The PoC prototypes show the feasibility of creating interactive circuits using a 3D pen and conductive filament, with the aid of laser-cut traces. The circuit pattern traces were successfully filled with conductive filament, forming continuous paths capable of conducting electricity.

However, these circuits have higher resistance than conventional wires, and variations in drawing direction and filament thickness during the 3D pen extrusion process can cause resistance fluctuations.

Due to the limitations mentioned above, These circuits are hard to achieve the same structural consistency and conductivity as traditional materials like copper wire, making them unsuitable for stable, low-resistance connections. This technique is better suited for interactive designs and sensing applications, such as capacitive sensing, where flexibility and adaptability are more important than efficient power transmission. Capacitive sensing is responsive to changes in touch, proximity, and environmental factors, making it ideal for interactive applications.

3.3. Physical Computing System

To achieve electronic functionality, additional components such as a microcontroller and power supply are required. In this research, an Arduino Nano is used as the microcontroller unit, with silicone jumper wires used as the interface between the interactive circuit to function as a physical computing system.

The system utilizes input through capacitive touch sensing and output through LED control to demonstrate simple interaction functionality. The wiring diagram is shown in Figure 3.7. It includes four input channels (I_1 to I_4) and four corresponding output channels (O_1 to O_4). The inputs are connected to the interactive circuit application, while the outputs are connected to LEDs, enabling real-time responses when the user touches the interactive circuit.

The Arduino code is referenced in Appendix B.

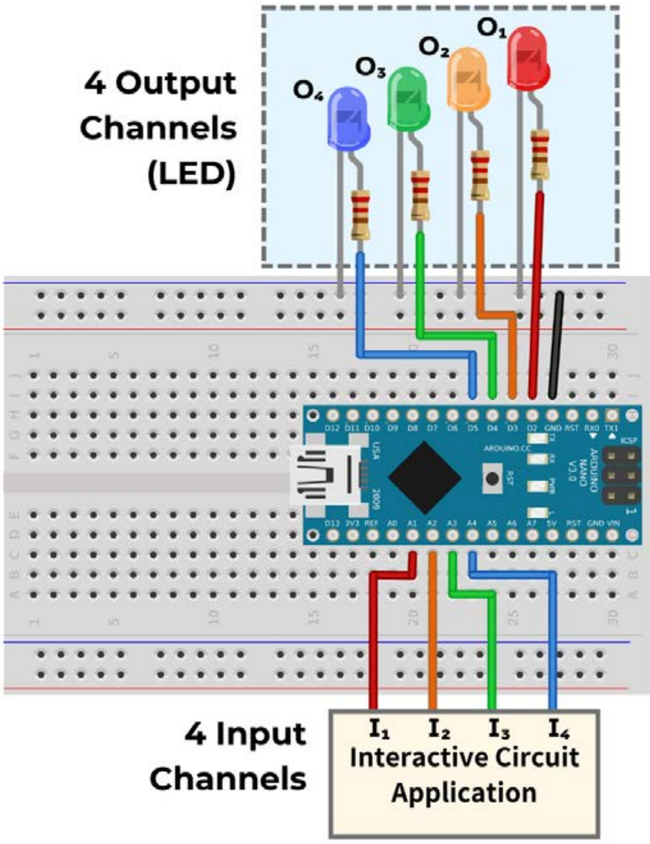

Figure 3.7 Wiring diagram of the physical computing system with Arduino Nano, four input channels (I_1 to I_4), and four output channels (O_1 to O_4) connected to LEDs.

3.4. Design Tool Development

To make the design process more easy and accessible, I developed a Design Tool that allows users to easily customize interactive circuit patterns.

The Design Tool is a web-based platform developed using ReactJS. As a dynamic SPA (single-page application), it offers an intuitive and interactive user interface. Being web-based, users can access the platform simply by entering the URL in their browser, making it independent of device, time, and location.

The purpose of the Design Tool is to enable users to create and customize interactive circuit patterns without the need for professional graphic software or CAD software. The design process can be completed quickly, as it provides templates to help users get started. Alternatively, users can begin from scratch and choose from over 2000 available options to add circuit patterns, which can then be freely combined and edited to suit their creative expression and functional requirements.

3.4.1 Version 1

The user interface of the first version of the Design Tool is shown in Figures 3.8, 3.9 and includes following features:

Settings Section

- **Base Selection**: Users can select one of the available base shapes.
- **Circuit Selection**: Users can add multiple circuit patterns by clicking the "Add New Pattern" button. This will open a pop-up Select Pattern Dialog, allowing users to search for and select patterns. The icons of the added patterns will appear in the section, where users can select them for further editing in the editor.
- **Select Pattern Dialog**: Users can choose a circuit pattern from over 2,000 available options and add into their design. It also includes a search-by-text feature to enable users to quickly find their desired pattern. (Figure 3.10, 3.11)

- **Circuit Editor**: Users can transform each circuit pattern by editing its position, scale, and rotation to customize various circuit designs. They can also delete patterns as needed.
- **System I/O Selection**: Users can select the expected input and output for the system with the dropdown menus. The instructions provided will adjust according to the selections. (Deprecated in Version 2)

Result Section

- **Canvas**: The Canvas displays the selected base (indicated by red lines) and circuit patterns (filled with semi-transparent black). It updates dynamically according to current settings, providing real-time feedback to users.
- **Export Button**: Use can save the design as an SVG file and download it locally by clicking the button.
- **Instruction**: It provides step-by-step detailed instructions for users to complete their interactive circuit.

3.4.2 User Feedback for the Version 1

After user testing Design Tool Version 1 with two users, I received the following feedback:

- The user suggested providing templates for inspiration and give a clearer idea of potential outcomes.
- Currently, the user must first add a pattern and then click on its icon to edit, which feels unintuitive. The user suggested separating the “Add” and “Edit” sections to create a more intuitive workflow.
- The user would like to include the zigzag circuit pattern used in the prototypes as one of the selectable circuit patterns.
- The user would like to see real-world dimensions indicated on the canvas with scale and unit markers.

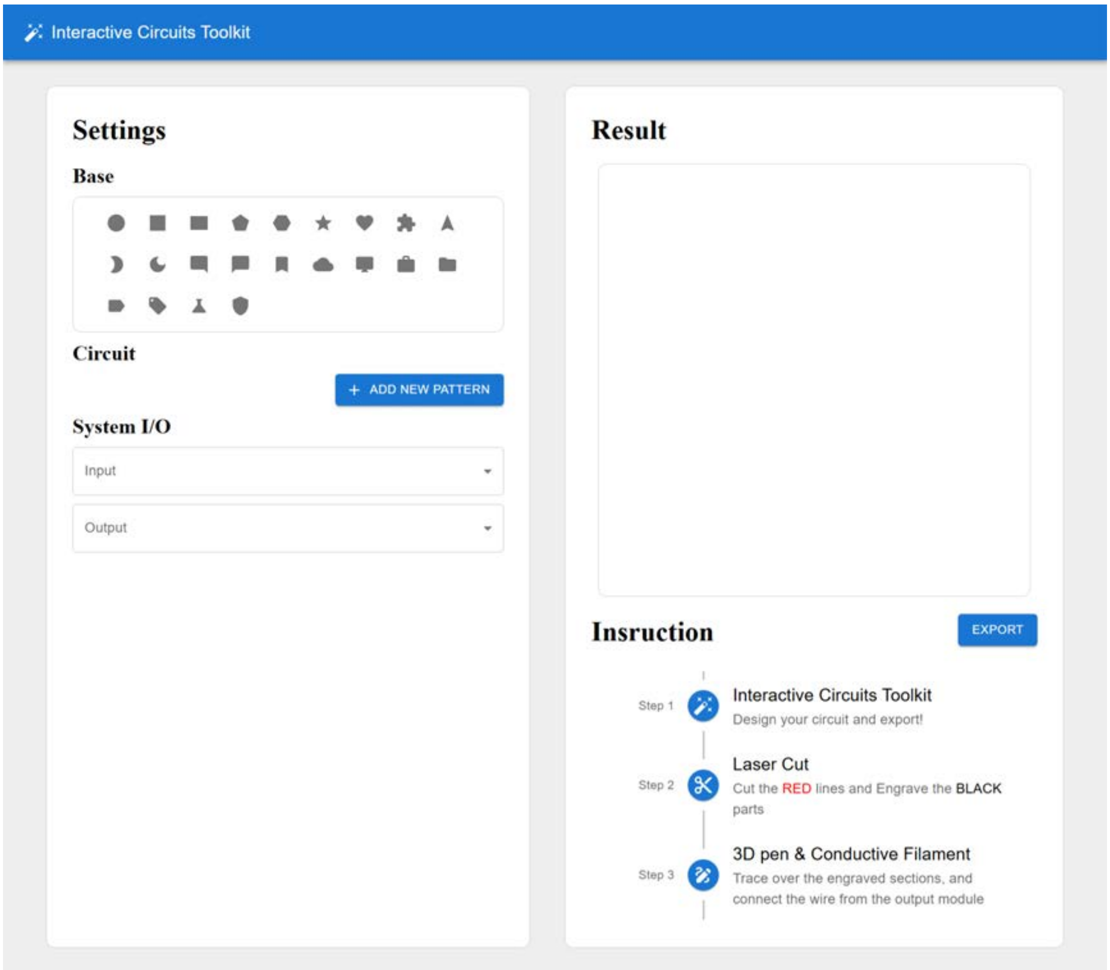

Figure 3.8 Default user interface of version 1 of the Design Tool.

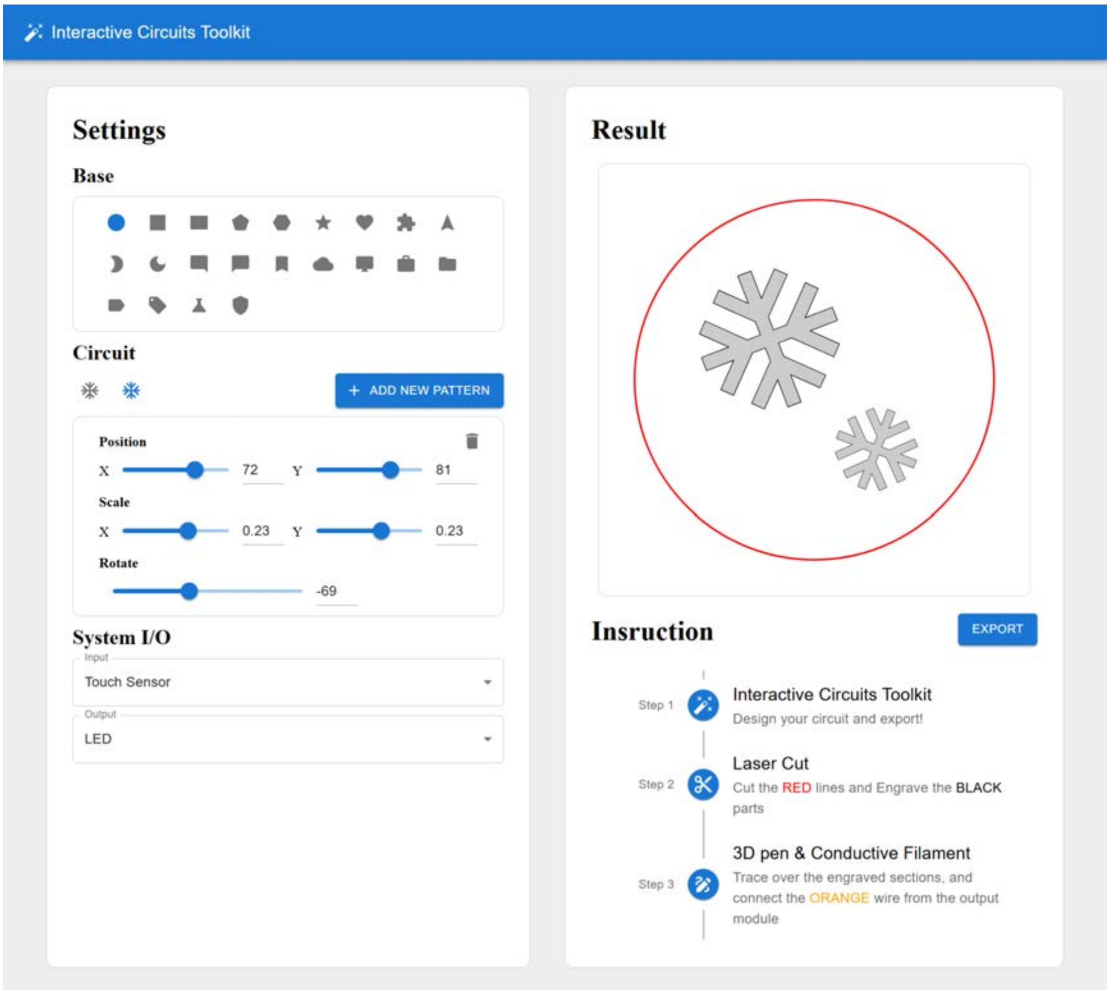

Figure 3.9 User interface after setting the base and circuit patterns.

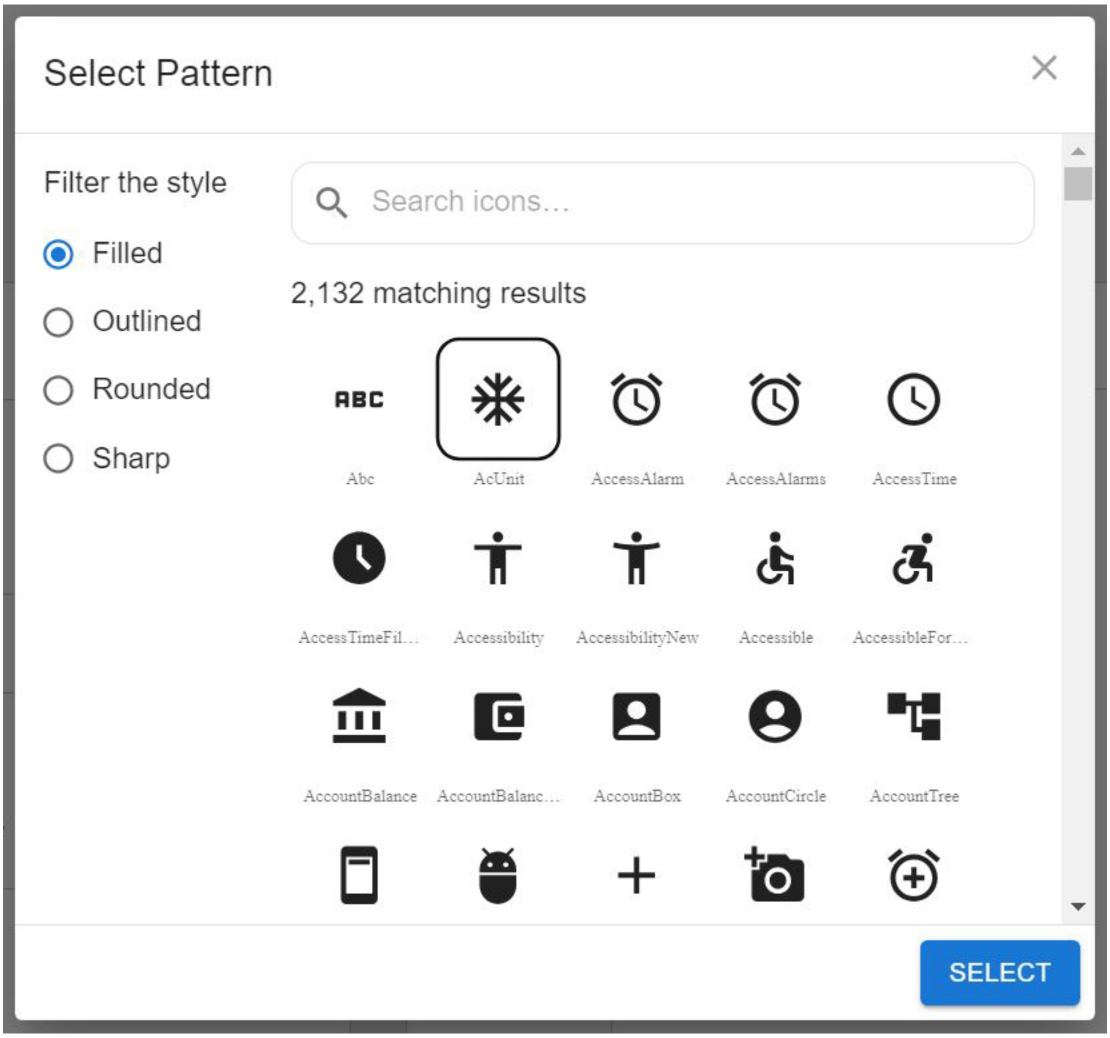

Figure 3.10 Default user interface of Select Pattern Diagram: enable searching and selecting the desired circuit pattern.

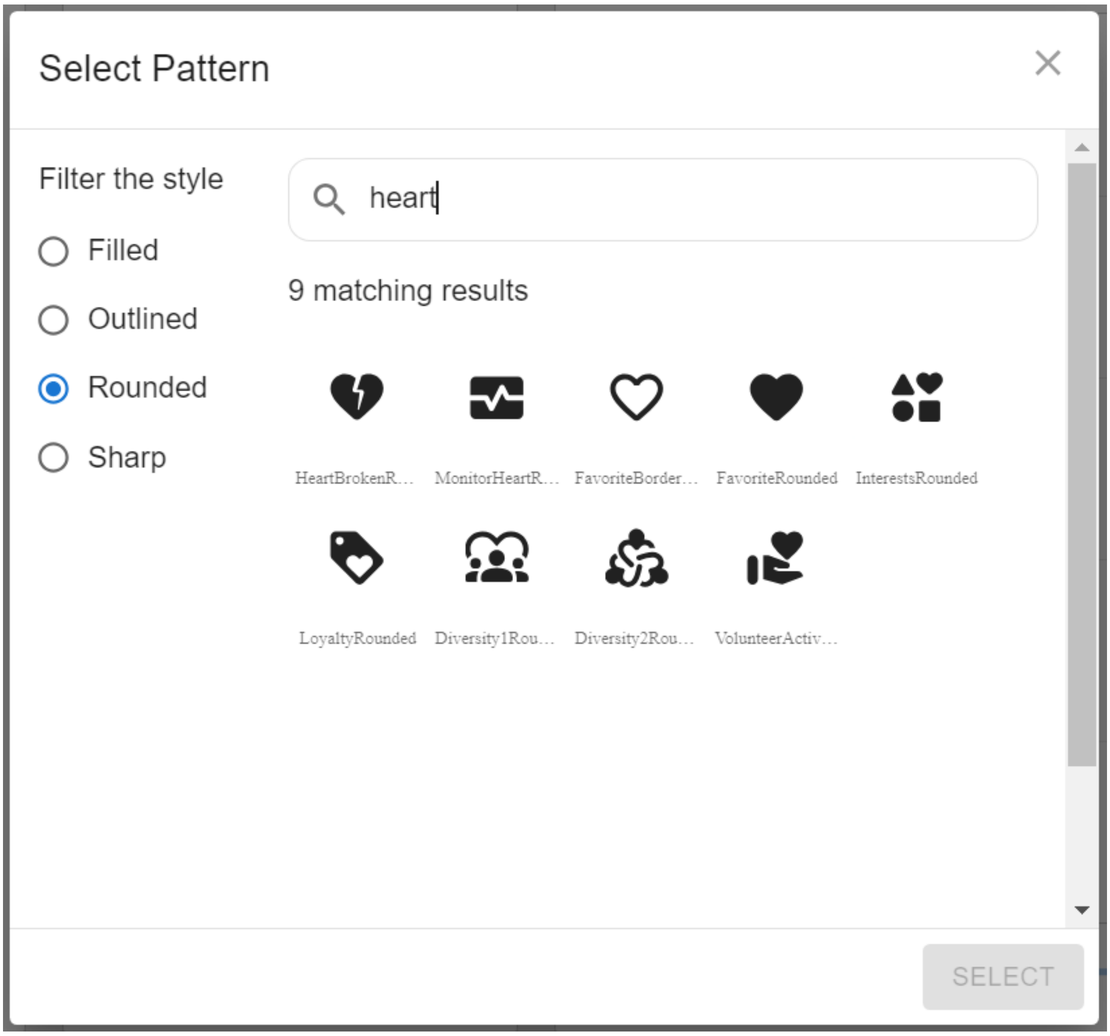

Figure 3.11 User interface of Select Pattern Diagram: after entering the query string ("heart") to search for related patterns.

- While the editor currently allows pattern transformations (position, scale, and rotation) only through sliders or text input, the user suggested enabling direct manipulation on the canvas, such as dragging to move, scaling, and rotating, for a more intuitive experience.

According to the feedback, the second version of the Design Tool is developed.

3.4.3 Version 2 (Final Version)

Based on the feedback from Version 1, the second version separated more sections for a more intuitive workflow, and include new and improved features for better user experience (As shown in Figure 3.12, 3.13):

Template Section

- **Template Selection**: A new template feature allowing users to directly select designs of the preset prototypes and further adjust the design.

Add Base/Circuit Section

- **Base Selection**: Users can now add multiple base shapes to create more complex patterns, which can also be transformed and edited like circuits.
- **Circuit Selection**: Zigzag and other circuit patterns (e.g., lines, corners for easily combining different patterns) are added. Users can still click the 'MORE" button to open the pop-up Select Pattern Dialog for more options.
- **Select Pattern Dialog**: The function is the same as in Version 1.

Editor Section

- **Pattern Selection**: The icons of the added base and circuit patterns will show in this section, where users can choose to edit, duplicate, or delete them.
- **Circuit Editor**: Users can transform each circuit pattern as in Version 1, with added features like locking the aspect ratio during scaling and flipping the pattern.

Result Section

- **Canvas**: Users can now transform the pattern's position, scale, and rotation by directly dragging on the canvas. The transformation data will update synchronously in the editor. Additionally, ruler guides and grid lines are added for better alignment.
- **Scale Slider**: Users can adjust the scale of the canvas. Ruler guides and grid lines on the canvas will update accordingly.
- **Export Button**: The function is the same as in Version 1.

The actual design process using the Design tool, the exported file, and the sample after laser cutting based on the design are shown in Figure 3.14.

This is the final version of the design tool. It was utilized in Prototype III (Section 4.6) and applied in Workshop 2 (Section 5.2).

The source code and deployed website can be accessed in Appendix A.

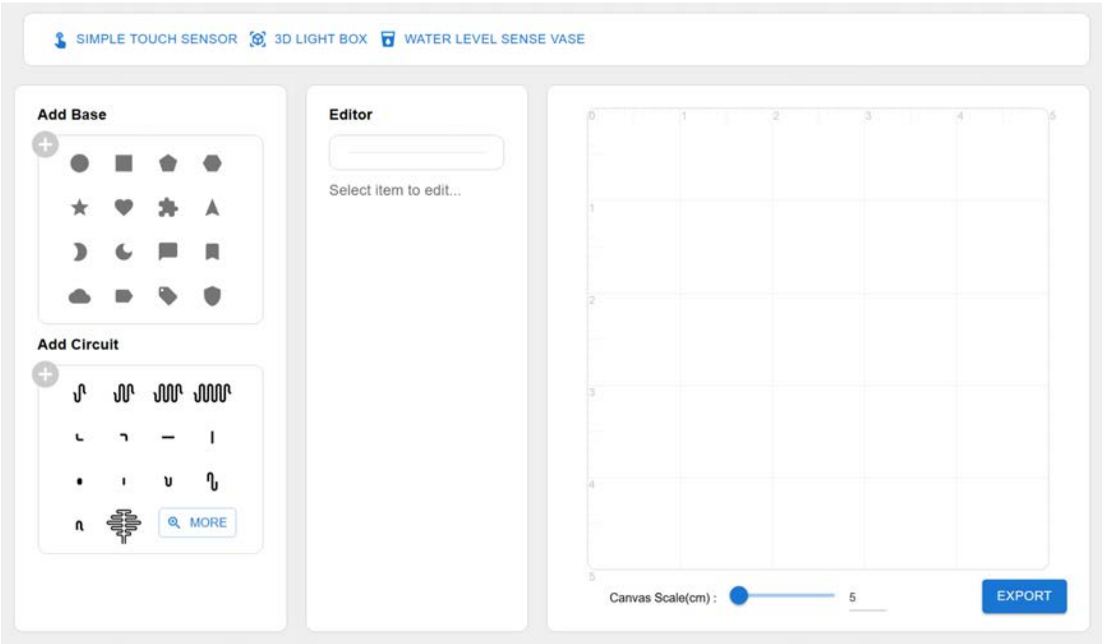

Figure 3.12 Default user interface of Version 2 of the Design Tool.

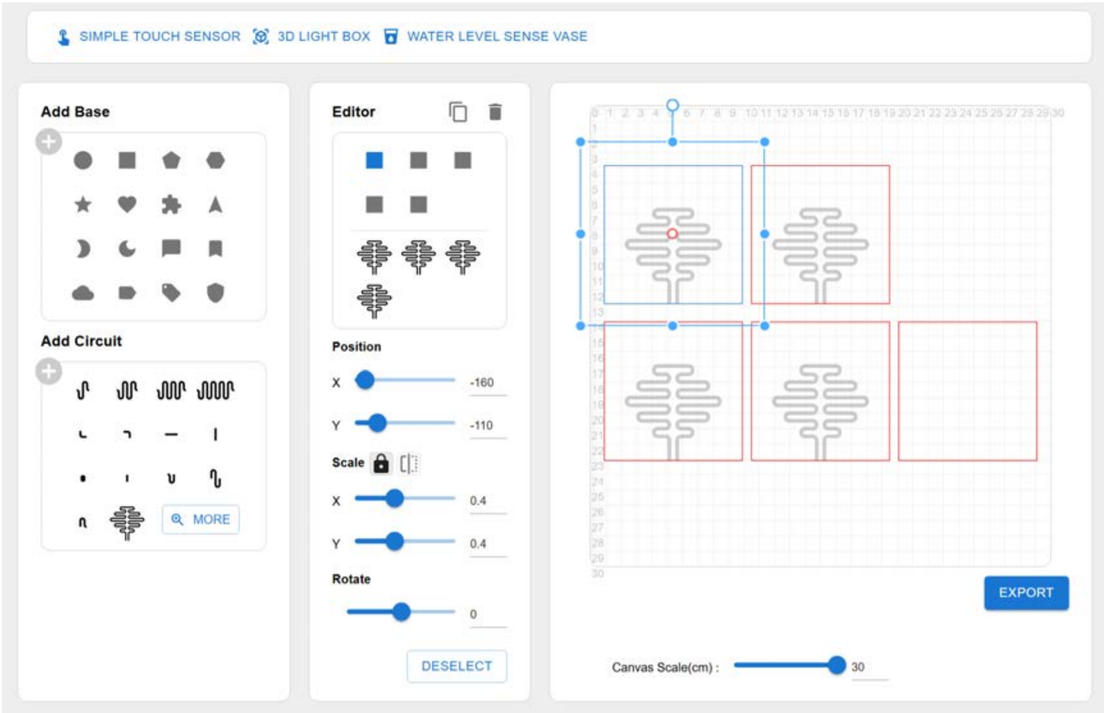

Figure 3.13 User interface after applying a template of 3D Light Box prototype mentioned in Section 4.3.

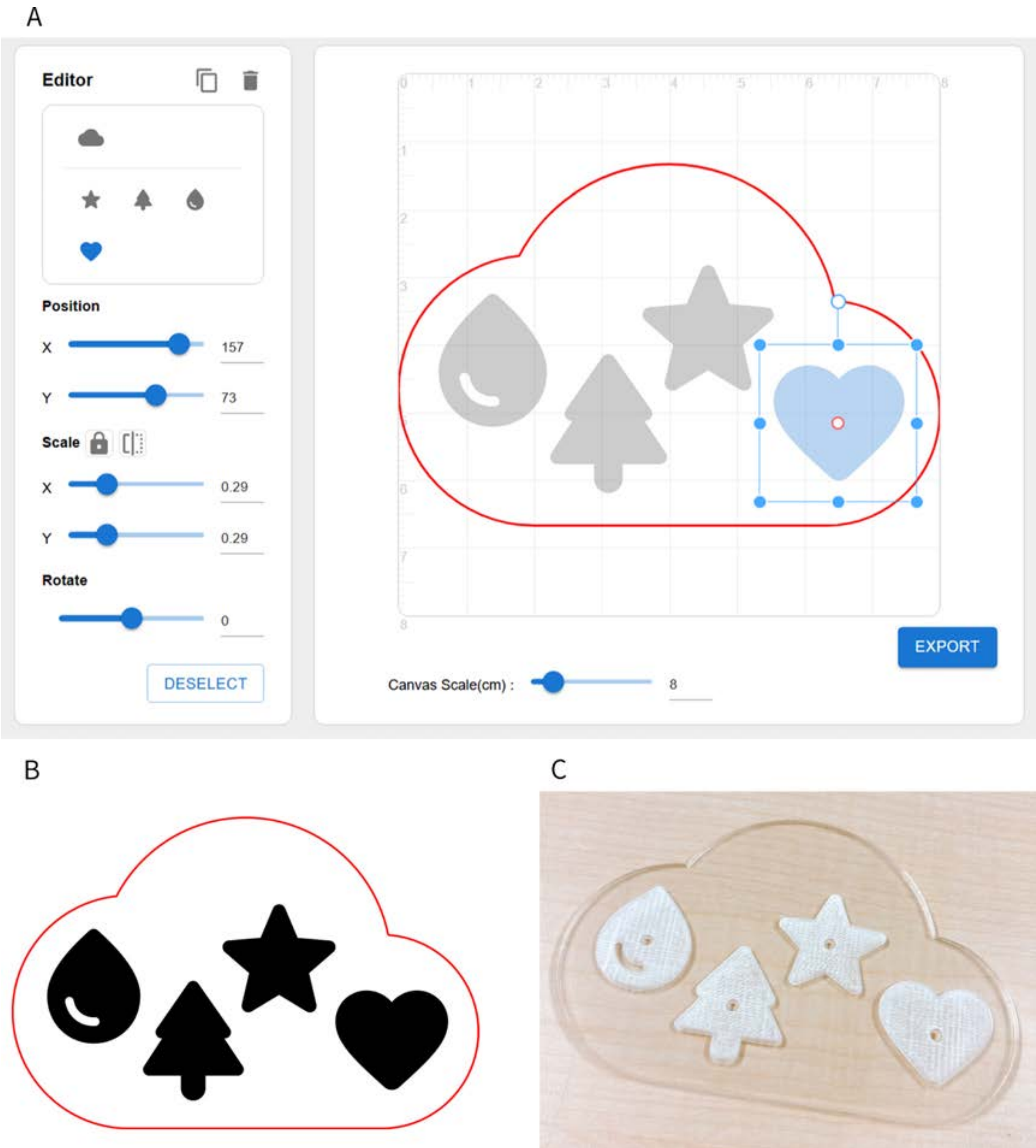

Figure 3.14 A: User interface (editor section and result section) during design process. B: The design exported as an SVG file. C: A sample laser-cut based on the design.

Chapter 4
Prototype Development

4.1. Objectives

The purpose of developing the prototypes is to test and validate the workflow, demonstrate the capabilities of the fabrication process for creating interactive circuits, showcase the advantages of the 3D pen manual approach, and provide users with inspiration for potential applications.

Additionally, demonstrations were conducted to gather feedback, providing insights into people's opinions and expectations regarding the prototype and the fabrication method, and suggested potential improvements.

4.2. Prototype I: Simple Touch Sensor Buttons

In Prototype I, simple capacitive touch sensor buttons, created using interactive circuits, were developed as key components of a small interactive device to control LEDs. Each button, made with red, yellow, or blue acrylic sheets, corresponds to an LED of the same color. When a button is touched, the corresponding LED lights up, allowing users to control the LEDs both simultaneously and separately. The LEDs are hidden inside translucent gummy bear-shaped light covers, creating a playful glowing effect.

This prototype demonstrates the feasibility of using a 3D pen and conductive filament to create interactive circuits for simple applications.

4.2.1 Design

1. **Touch Sensor Buttons**: The buttons are circular with a diameter of 2.8mm. Smaller circles are engraved inside to provide areas for conduc-

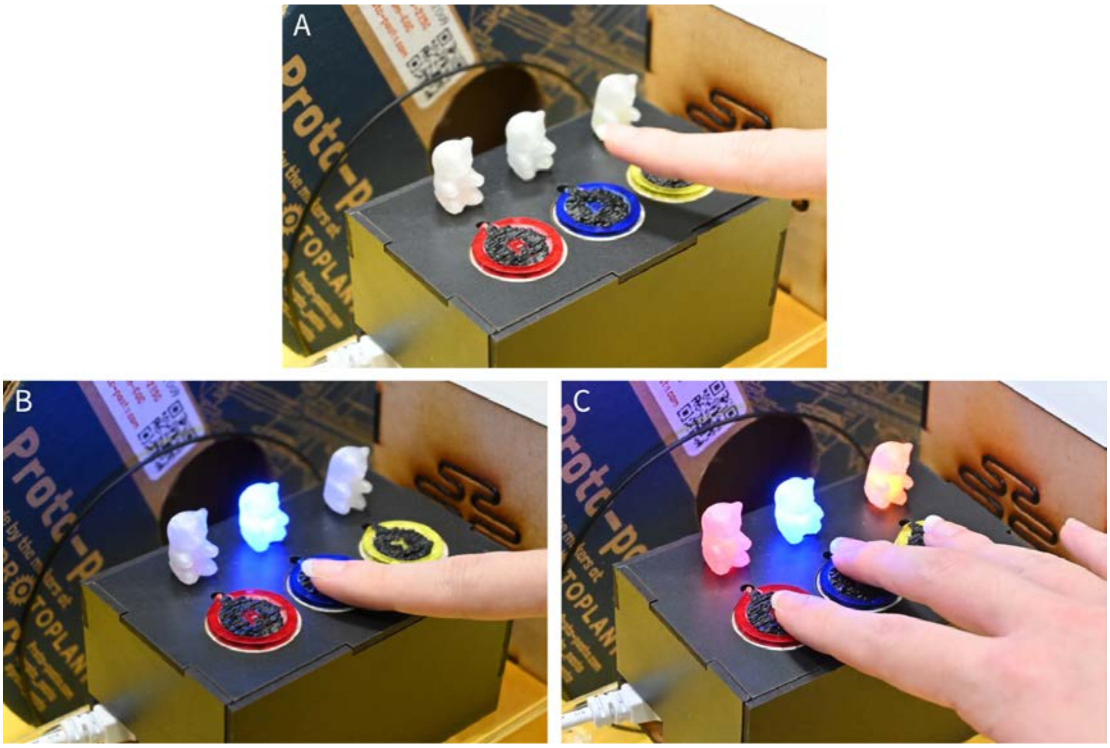

Figure 4.1 Interactive device with simple touch sensor buttons. A: When no button is touched. B: When a button is touched, the corresponding LED lights up. C: When multiple buttons are touched simultaneously.

Figure 4.2 Touch sensor buttons' design for laser cutting. Red lines are for cutting, and black filled areas are for engraving.

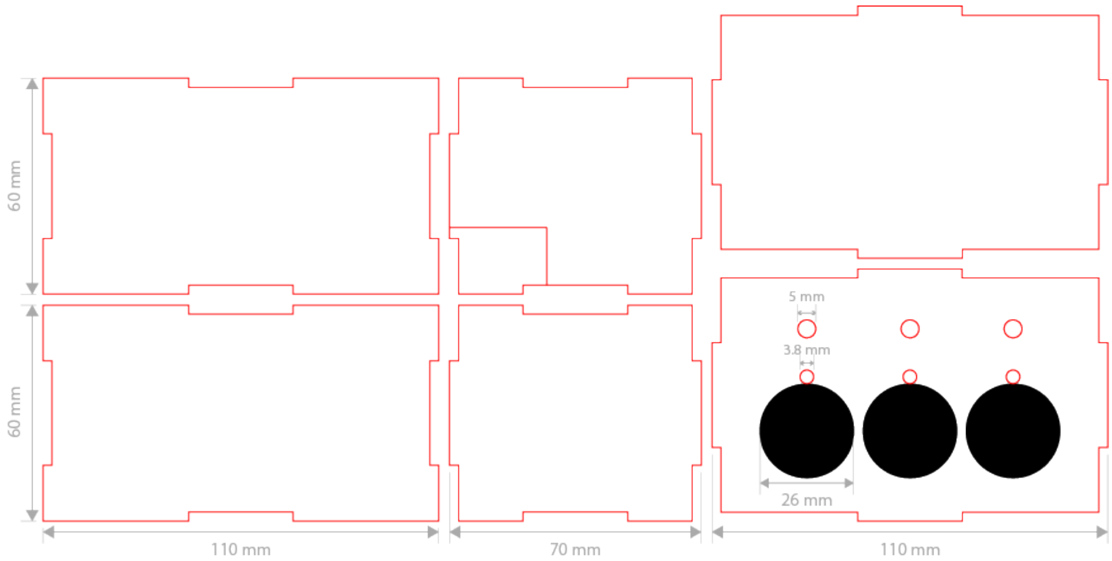

Figure 4.3 Display box's design for laser cutting. Red lines are for cutting, and black filled areas are for engraving.

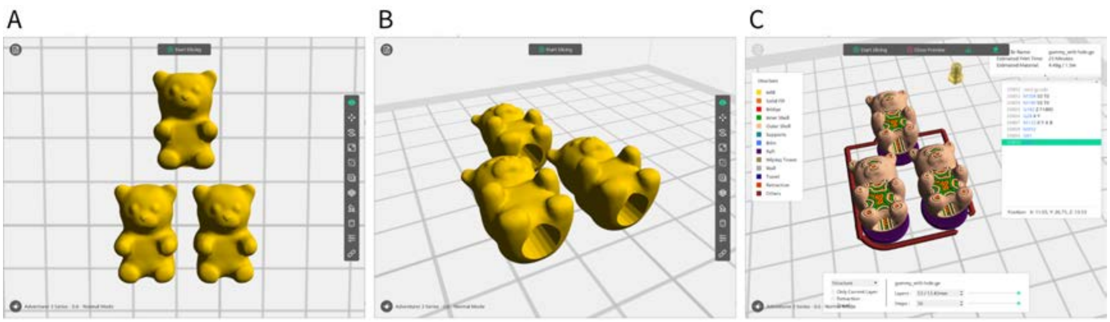

Figure 4.4 Light cover's design for 3D printing. A: Top view of the 3D models. B: A hole is hollowed out at the bottom of each model to fit the LEDs. C: sliced model for 3D printing.

tive filament filling. English letters indicating the color of the LED they control (e.g., 'R' for red) are left unengraved within the smaller circles, as shown in Figure 4.2.

The substrate materials are 2mm acrylic sheets in red, yellow, and blue, with each color corresponding to the LED controlled by the respective button.

2. **Display Box**: The display box is designed as a 110mm x 70mm x 60mm enclosure to hide the Arduino board inside. The top surface includes holes for LEDs and wiring to pass through, as well as engraved areas for positioning the touch sensor buttons. The other hole is cut on the side for the Arduino's cable to pass through, as shown in Figure 4.3.

   The 2.5mm black MDF board is used as the material.

3. **Light Cover**: The light covers are designed as gummy bear 3D models measuring 20mm x 13mm x 12.33mm. A hole is hollowed out at the bottom of each model to fit the LEDs (as shown in Figure 3).

   The models are 3D printed using translucent filament to allow light diffusion.

4.2.2 Process

1. Building Input Module: Touch Sensor Buttons
   - Laser cut the baseboards for the buttons according to the design.
   - Use a 3D pen with conductive filament to trace along the engraved pattern, creating the interactive circuits for the touch sensor buttons.
   - Connect wires to the endpoints of each touch sensor button to enable integration with the output module.
2. Building Output Module: LED and Arduino Setup
   - Program the Arduino board to light up the corresponding LED when a change in capacitance (caused by touching the input module) is detected. Configure three separate input-output pairs, where each touch sensor button controls the LED of its corresponding color.

- Connect three LEDs (red, yellow, and blue) to the Arduino board.

3. Building Display Box

   - Laser cut the pieces of display box according to the design.
   - Assemble and glue five sides of the box together, leaving the lid unassembled.

4. Building Light Cover

   - 3D print the light covers according to the design.

5. Assembly

   - Place the Arduino board inside the display box.
   - Insert the three LEDs into the holes on the top row of the display box lid.
   - Thread the wires from the touch sensor buttons through the bottom row of holes in the display box and connect them to the Arduino board, ensuring each touch sensor button corresponds to its respective LED color.
   - Close the display box lid.
   - Fix the touch sensor buttons onto the engraved areas of the display box.
   - Place the light covers over each LED to complete the setup.

4.3. Prototype II: 3D Light Box

Prototype II is a 3D box-shaped lamp. The LED is enclosed inside the box, allowing light to shine through the translucent white lid. Each side of the box features interactive circuits, all connected at the base to form a touch-sensitive switch. Touching the interactive circuit on any side toggles the internal LED to turn on or off.

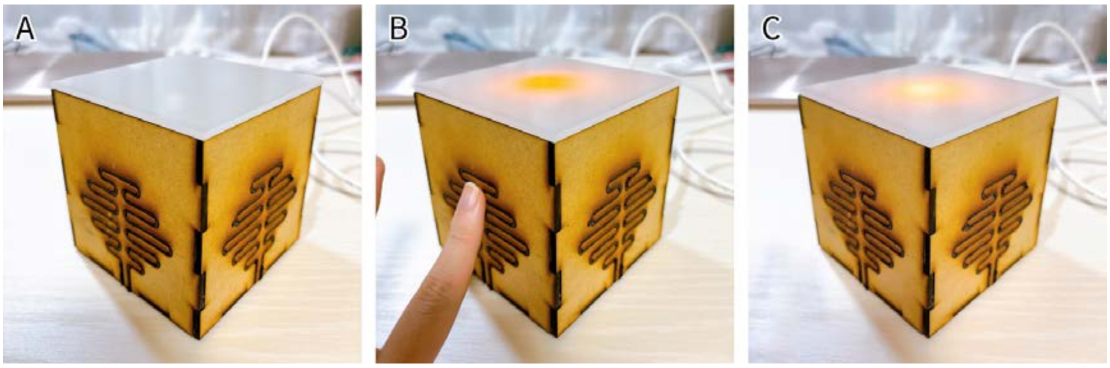

Figure 4.5 3D box-shaped lamp with interactive circuits functioning as a touch-sensitive switch. A: Light is off. B: Touching the interactive circuits toggles the light. C: Light remains on until the next touch.

This prototype demonstrates the possibility of creating interactive circuits on a 3D structure. It also shows that switch-like touch sensors can be created using this process to develop interactive applications.

4.3.1 Design

The box measures 90mm x 90mm x 90mm, consisting of five faces that form the 3D box structure. On each side, zigzag-shaped circuit patterns are designed and engraved for conductive filament filling. The circuits on all sides are designed to connect together and form a complete circuit. The circuit patterns are joined at the edges of each face with conductive filament.

The 2.5mm MDF board is used as the substrate material.

4.3.2 Process

1. Building Input Module: 3D box

    - Laser cut the baseboards for the box according to the design.
    - Use a 3D pen with conductive filament to trace along the engraved pattern on each face.

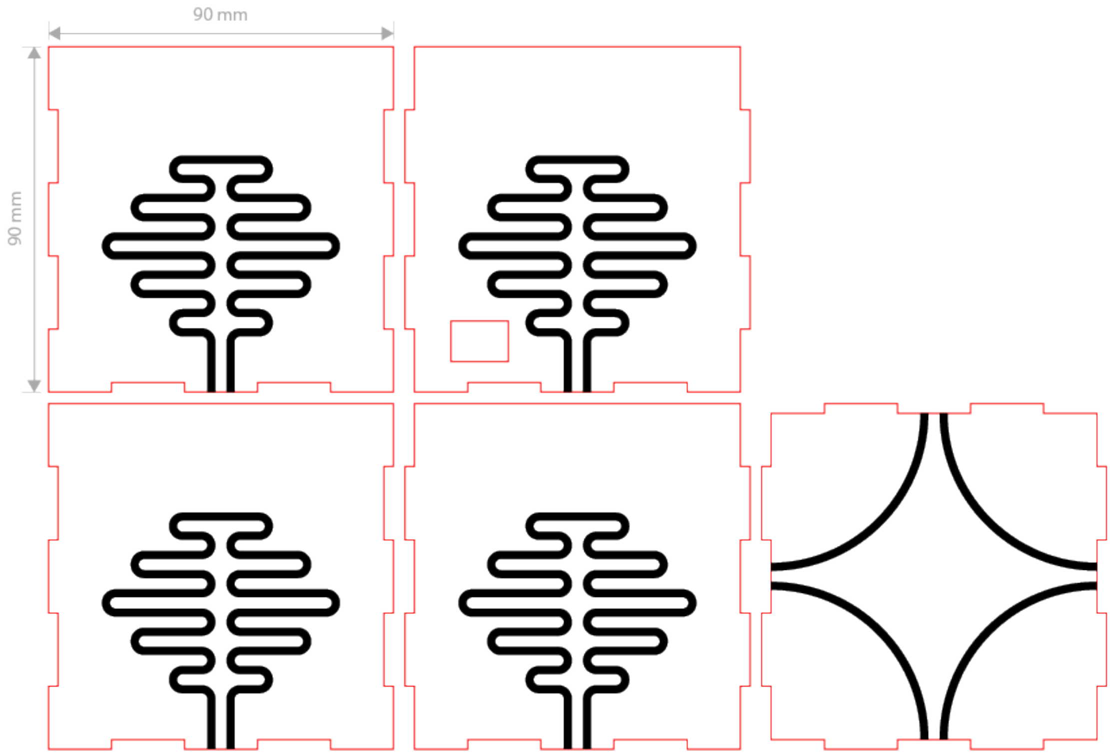

Figure 4.6 3D light box's design for laser cutting. Red lines are for cutting, and black filled areas are for engraving.

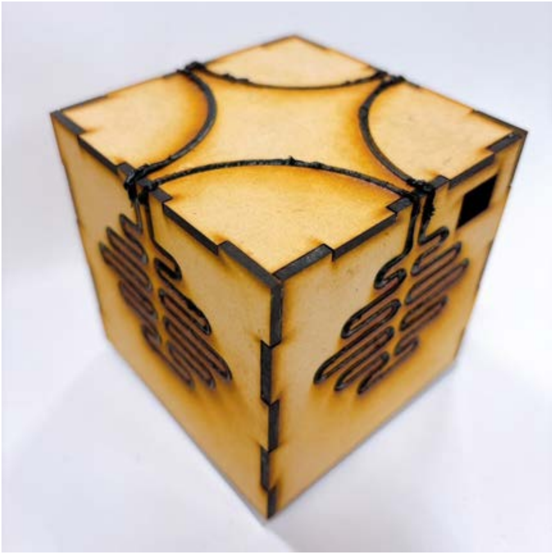

Figure 4.7 The bottom face of the box, showing how the interactive circuits on each side are connected together to form a complete circuit.

- Connect a wire to one endpoint of a side face to enable integration with the output module later.
- Assemble each face of the box, and pull the wire through the junctions between two faces into the interior of the box. Glue each face together using white glue.
- Use a 3D pen with conductive filament to connect the interactive circuits on each face to form a complete circuit (as shown in Figure 4.7).

2. Building Output Module: LED and Arduino Setup

    - Program the Arduino board to toggle the LED when a change in capacitance (caused by touching the input module) is detected. Configure one input-output pair, where the interactive circuits on each face of the box controls the LED.
    - Connect the LED to the Arduino board.

3. Building Box Lid

- Laser cut a 90mm x 90mm square from translucent white acrylic sheet to serve as the lid of the box.

4. Assembly
   - Place the Arduino board and LED inside the box.
   - Connect the wire to the Arduino board.
   - Place the lid on top of the box to complete the setup.

4.4. Demonstration I: Tokyo Maker Faire

- Date and time: Sunday, September 22, 2024, 10:00 a.m.–5:00 p.m. (JST)
- Location: Tokyo Big Sight West Hall 4, 3-11-1 Ariake, Koto-ku, Tokyo, Japan
- Participants: Open to the public; attendees of Maker Faire Tokyo 2024, mostly makers.
- Experimental purpose: To show the developed prototypes and receive feedback from public.
- Experimental process: Prototypes I and II were displayed at the booth, with captions introducing each prototype and "Touch OK" signs, allowing visitors to freely interact with the prototypes. Additionally, a 3D pen and conductive filament were placed at the booth to illustrate the fabrication process.

4.4.1 Procedure

Prototype I and Prototype II were displayed at the booth with "Touch OK" signs, inviting visitors to freely interact with the prototypes. A 3D pen and conductive filament were also showcased to demonstrate the fabrication process.

An explanatory caption was displayed alongside the prototypes: "By using a 3D pen and conductive filament to trace along the engraved marks from laser

Figure 4.8 Prototype I and II were demonstrated at the Tokyo Maker Faire.

Figure 4.9 People tried to interact with the prototype during the demonstration.

cutting, it becomes easy to create both 2D and 3D conductive structures and circuits, showcasing a variety of potential applications. In the demonstration, this technique was used to create a capacitive touch sensor, where the LED lights up when the conductive part is touched, providing real-time interactive feedback."

4.4.2 Feedback and Insights

Many people passed by were willing to interact with the prototypes, with some stopping to read the caption or ask questions.

Based on observations, the button-like design of the interactive circuit in Prototype I intuitively encouraged people to touch it and trigger interaction. On the other hand, Prototype II seemed less immediately recognizable as interactive, with most people realizing it could be interacted with only after receiving an explanation.

The questions people asked generally fell into a few categories. Some were curious about the fabrication process, while others wanted to know how to use the 3D pen. Many expressed interest in the conductive filament, with some surprised that it could be used not only with 3D printers but also with 3D pens. One person even took note about the filament's production details.

These interactions revealed that the interactive circuit application captured the attention and curiosity of the public. In particular, many participants were makers or individuals familiar with 3D pens and 3D printing. However, it also highlighted that the tools and materials may be unfamiliar to some people. This suggests that providing detailed explanations and instructions would improve understanding and make the approach more accessible to a broader audience. Overall, the feedback demonstrates the potential of this approach.

4.5. Demonstration II: KMD Forum

- Date and time: October 12th (Sat)–13th (Sun), 2024, 11:00–17:00
- Location: Tokyo Port City Takeshiba, Tokyo Metropolitan Industrial Trade Center Hamamatsucho Hall 3F Exhibition Room

- Participants: Open to the public; attendees of KMD Forum 2024 -Voyage-, mostly KMD students
- Purpose: To show the developed prototypes and receive feedback from public

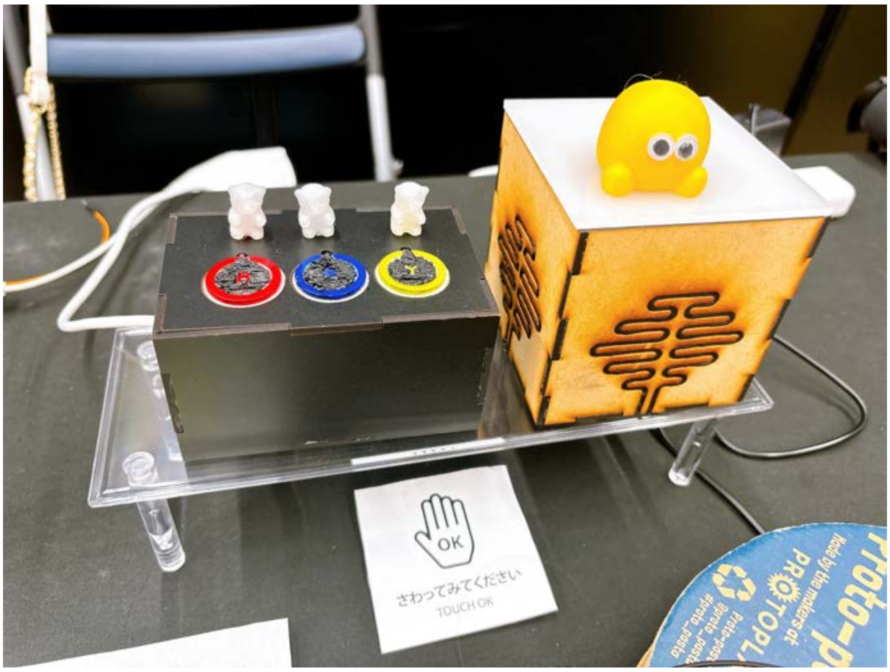

Figure 4.10 Prototype I and II were demonstrated at the KMD Forum.

4.5.1 Procedure

The procedure was similar to Demonstration I. At the booth, Prototype I and Prototype II were displayed, along with an explanatory caption and "Touch OK" sign. The difference was that, in addition to the display, Workshop I was held at the booth. The tools and materials used in the workshops (e.g., 3D pen, conductive filament, pre-cut baseboards) were place on the table. People who were interested could participate in the workshop, experience the process of using 3D pen and creating interactive circuits firsthand.

4.5.2 Feedback and Insights

The participants of this event are more students and individuals without a maker background compared to the previous demonstration, leading to different focal points of interest among participants. Compared to questions about the technology or materials, they were more focused on the applications and use cases of the interactive circuits, as well as the user experience during the fabrication process. After participating in the workshop, they provided extensive feedback (see Section 5.1).

Additionally, some families with children also attended, and it was observed that children were especially interested in the interactive prototypes. They were excited and curious when using the 3D pen, showing lots of enthusiasm for the process. This suggests the approach could be great for educational use, especially for introducing children to electrical circuits in a fun and engaging way.

4.6. Prototype III: Samples Showcasing 3D Pen Capabilities

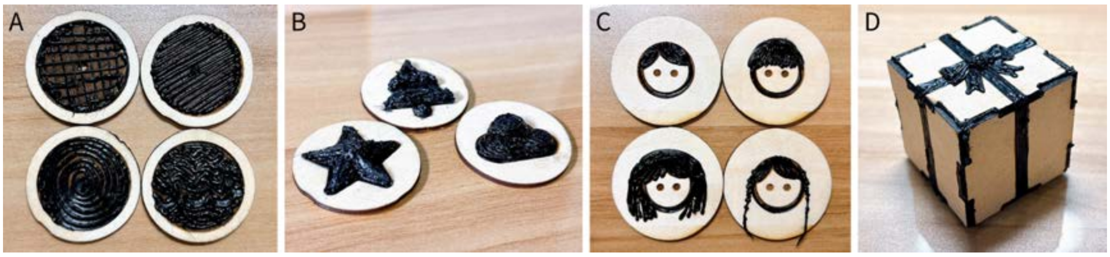

Figure 4.11 Unique advantages of using 3D pen manually: A: Creation of varied textures on circuit surfaces. B: Flexible Construction of 3D shapes. C:Easy real-time modifications and additions. D: Use of conductive filament as an adhesive in 3D structures.

Prototype III is developed to demonstrate the unique advantages and innovations brought by the manual process of using a 3D pen. In the following Part 1 to 4, different set of samples are created to showcase each of these benefits.

4.6.1 Part 1: Creation of Varied Textures on Circuit Surfaces

Design

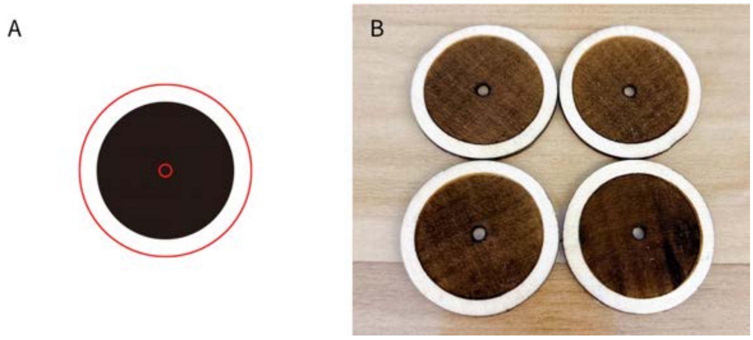

Figure 4.12 Design of Prototype III Part 1. A: Laser Cutting Design.(red lines for cutting, black areas for engraving). B: Samples after laser cutting.

The pattern is created using the Design Tool (Section 3.4). Its base shape is a 35mm circle, with a 28mm solid circle as the circuit pattern inside. A 2.5mm hole is cut in the center.

A 2.5mm MDF board is used as the substrate material, and a total of four pieces are cut.

Process

Using 3D pen with conductive filament to fill the pattern traces with different drawing paths, to create samples with different surface textures. The created textures include: grid, linear, spiral, and wavy patterns.

Results

The result is shown in Figure 4.13. Although all circuits remain flat, the surfaces exhibit different textures, providing distinct visual and tactile experiences. The textured surfaces could offer potential applications in tactile interfaces, where users can distinguish circuit areas by touch.

Figure 4.13 The circuit surface displays grid, linear, spiral, and wavy textures.

Moreover, the 2.5mm hole is designed to serve as an interface. After the interactive circuit samples are completed, users can simply place the wire through the hole from the back and extrude some conductive filament using the 3D pen to make the connection, as shown in Figure 4.14.

Figure 4.14 The 2.5mm hole serves as an interface for easy wire connections using a 3D pen after completing the circuit samples.

4.6.2 Part 2: Flexible Construction of 3D Shapes

Design

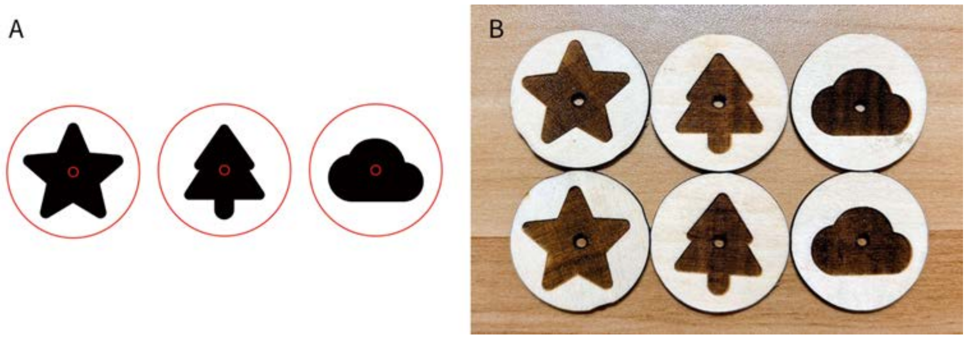

Figure 4.15 Design of Prototype III Part 2. A: Laser Cutting Design.(red lines for cutting, black areas for engraving). B: Samples after laser cutting.

The pattern is created using the Design Tool (Section 3.4). Its base shape is a 35mm circle, with a pattern of star, tree, and cloud inside. A 2.5mm hole is cut in the center.

A 2.5mm MDF board is used as the substrate material, and two pieces of each pattern are cut.

Process

Using a 3D pen with conductive filament, for each pattern, one sample is created by filling the pattern traces with a single layer of filament for the 2D version, and another sample is created by layering multiple filaments to form the 3D version.

Results

The result is shown in Figure 4.16. In the 3D samples, various shapes are created: the center of the star shape is raised to form a peak, the tree shape has leaves and a trunk with varying heights to create layered depth, and the cloud shape has a smoothly curved raised surface. Compared to 2D samples, 3D samples provides a richer tactile experience.

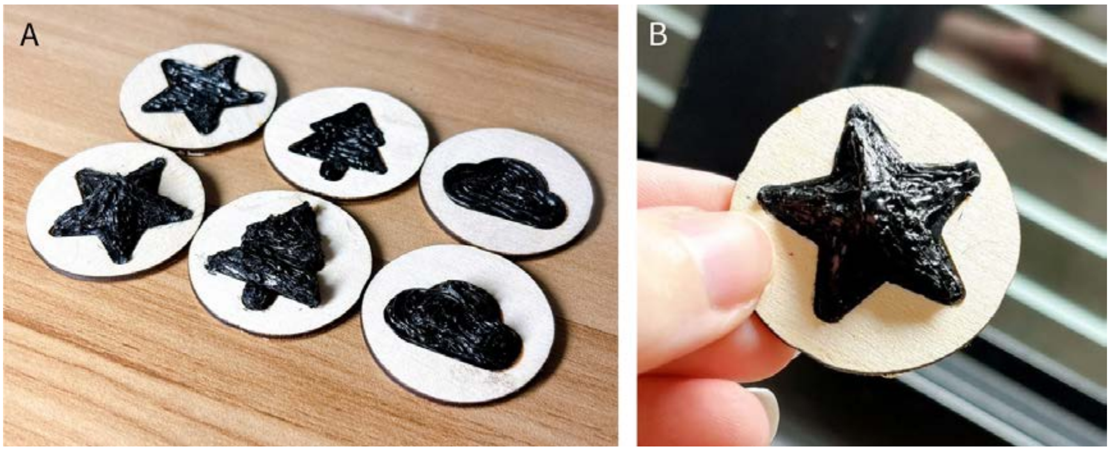

Figure 4.16 A: The top row are 2D samples; the bottom row are 3D samples. B: Star-shaped 3D sample is raised at center, forming a peak.

4.6.3 Part 3: Easy Real-Time Modifications and Additions

Design

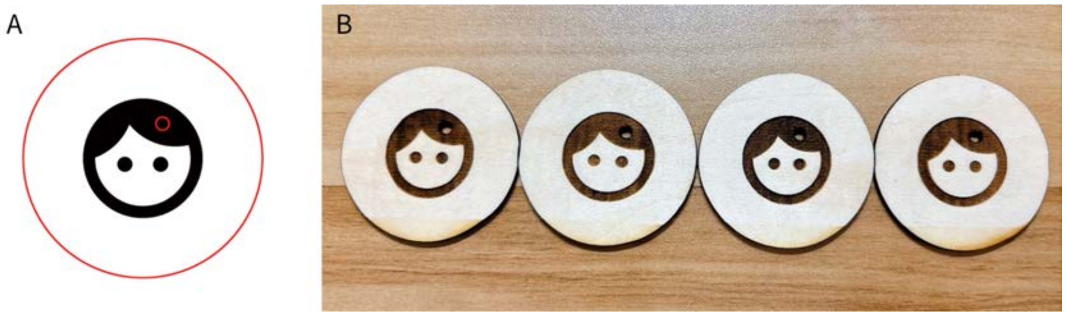

Figure 4.17 Design of Prototype III Part 3. A: Laser Cutting Design.(red lines for cutting, black areas for engraving). B: Samples after laser cutting.

The pattern is created using the Design Tool (Section 3.4). Its base shape is a 45mm circle, with a pattern of face inside. A 2.5mm hole is cut in the pattern.

A 2.5mm MDF board is used as the substrate material, and a total of four pieces are cut.

Process

Using 3D pen with conductive filament to draw the patterns, making free modifications and additions to the existing design.

Results

Figure 4.18 Different hairstyles are added to the same face design in each sample.

The result is shown in Figure 4.18. Different hairstyle are added to the original face design in each samples.

Although the original design is the same and the circuit trace has already been engraved using laser cutting, modifications and additions can still be freely made during the circuit-drawing process with a 3D pen. This flexibility allows users to express their creativity.

4.6.4 Part 4: Use of Conductive Filament as an Adhesive in 3D Structures

Design

The base shape is a 60mm-sided cube structure, with ribbon-shaped circuit patterns on each face, intersecting at the top and bottom surfaces. The top surface has a bow pattern in the center, creating a gift box design.

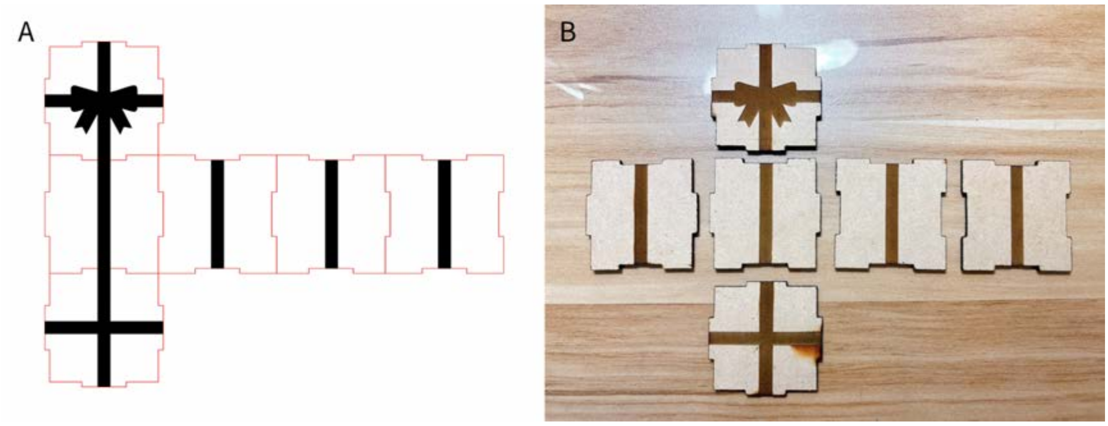

Figure 4.19 Design of Prototype III Part 4. A: Laser Cutting Design.(red lines for cutting, black areas for engraving). B: Samples after laser cutting.

Process

Using a 3D pen, each face is connected with conductive filament to form the 3D structure, as shown in Figure 4.20. The pattern traces are also filled with conductive filament across each face to connect the interactive circuits of the entire 3D structure.

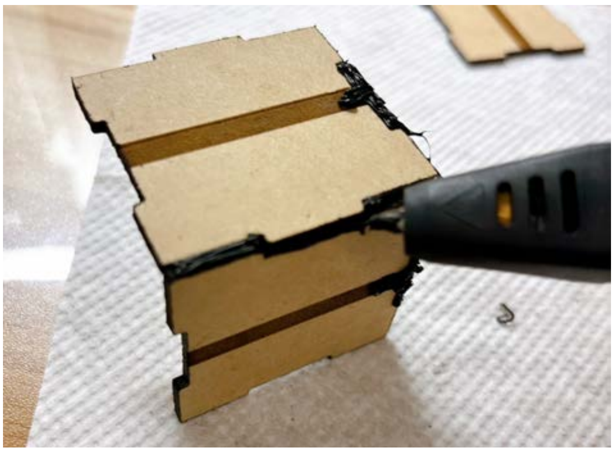

Figure 4.20 Connecting each face with 3D pen and conductive filament.

Results

Figure 4.21 A 3D structure is form with 3D pen and conductive filament.

The result is shown in Figure 4.21. A 3D structure is formed using a 3D pen and conductive filament, without the need for any glue. The conductive filament used as an adhesive between the substrate faces, constructing the 3D structure. It also connect the circuits across multiple faces, creating a complete circuit within the 3D structure.

4.6.5 Conclusion

The four unique advantages of using a 3D pen manually have been shown above. These benefits are easier to achieve manually than with fully automated or digital processes. They include creating a richer tactile experience, flexible 3D shapes, and more control during the process. The hands-on approach also allows for more customizable and personalized designs.

Chapter 5
Evaluation and Discussion

5.1. Workshop I: Creating a Simple Touch Sensor

- Date and Time: October 12th (Sat)–13th (Sun), 2024, 11:00–17:00
- Location: Tokyo Port City Takeshiba, Tokyo Metropolitan Industrial Trade Center Hamamatsucho Hall 3F Exhibition Room
- Participants: Open to the public; attendees of KMD Forum 2024 -Voyage-, mostly KMD students
- Purpose:
  - To test the "Fabrication" and "Integration" stages of the fabrication workflow.
  - To observe how participants use the 3D pen, their reactions during the process, and the difficulties they encounter.
  - To collect feedback for improving the process.
  - To gather ideas for potential use cases or applications.

5.1.1 Overview

The workshop introduces the process and tools for creating interactive circuits. Participants will create a simple touch sensor that lights up an LED using a 3D pen, conductive filament, and pre-laser-cut pieces with circuit pattern traces.

5.1.2 Tools and Materials

The following tools and materials are prepared for the workshop:

Figure 5.1 The participant is using the 3D pen and conductive filament to trace along the engraved circuit pattern.

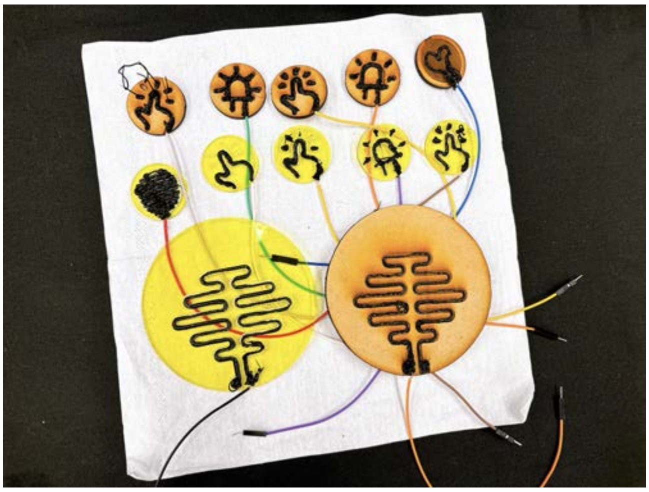

Figure 5.2 The results of participants in Workshop I.

- 3D pen
- Conductive filament
- Silicone jumper wires, wire cutter, and wire stripper
- Laser-cut substrate (acrylic and wood) with various laser-engraved circuit patterns
- Pre-programmed LED output module connected to an Arduino board

5.1.3 Procedure

1. The participant selects a pre-laser-cut piece with their preferred pattern and material.
2. The participant uses the 3D pen and conductive filament to trace along the engraved pattern and connect the wire, with the insulation stripped off from the connecting end.
3. The participant connect the other end of wire to the Arduino board.

4. To test functionality, the participant touches the interactive circuit, causing the LEDs on the output module to light up and allowing them to experience the functionality of a simple touch sensor.

5.1.4 Feedback and Insights

A total of 12 participants (labeled as Participant A to L), all with a certain level of design or creative background, attended the workshop and completed the post-workshop questionnaire.

The questionnaire includes the following questions:

- Section (1): Usability and Effectiveness of the Process (Likert Scale Questions with five levels ranging from "1–Strongly Disagree" to "5–Strongly Agree")
  - Do you think it is easy to use a 3D pen and conductive filament to create interactive circuits?
  - Do you think the design of the process helped you successfully complete the circuit?
- Section (2): Applicability of the Method (Likert Scale Questions with five levels ranging from "1–Strongly Disagree" to "5–Strongly Agree")
  - Do you think this method enables you to integrate electronic interactive technology into creative designs?
  - Do you think this method is suitable for individuals in creative fields?
  - After the workshop, are you willing to apply this method in your future creations?
- Section (3): Suggestions and Feedback (Optional, Open-Ended Questions)
  - How was your overall experience during the workshop? Is there anything that could be improved?
  - Do you have any thoughts or suggestions regarding the application scenarios of the method or its potential future expansions?

– Do you have any additional comments or suggestions?

Participants' opinions on the usability and effectiveness of the process are shown in Figure 5.3. More than half of the participants thought using the 3D pen was easy, while a small number of participants thought it was difficult. Most participants felt that the design of the process can help to successfully complete the circuit.

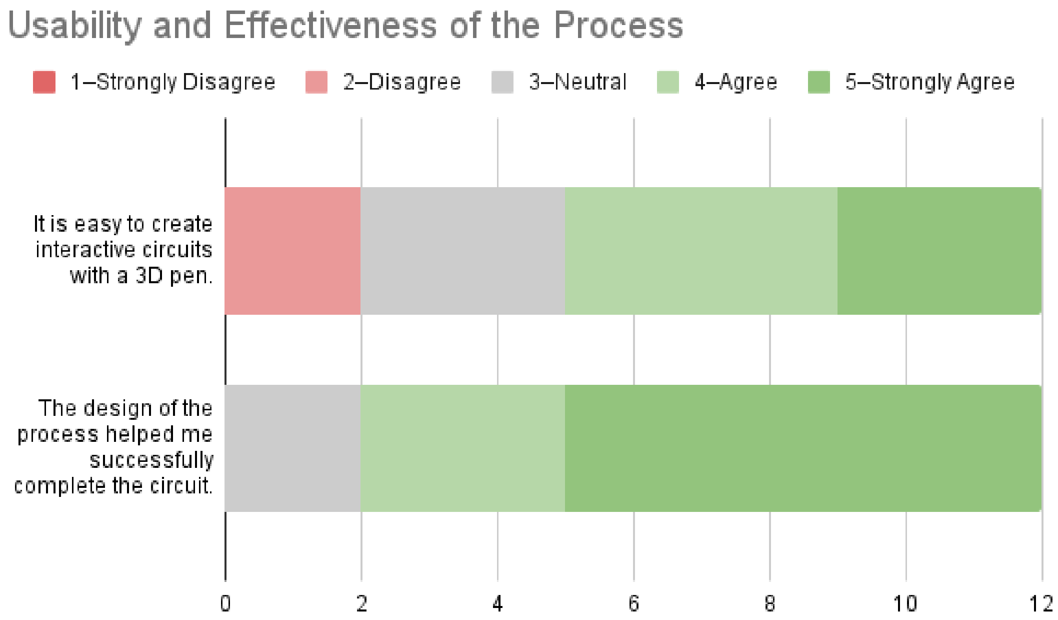

Figure 5.3 Participants' opinions on usability and effectiveness of the process in Workshop I.

Participants' opinions on applicability of the method are shown in Figure 5.4. Almost all the participants think this method enables them to integrate electronic interactive technology into creative designs. Moreover, all participants think they are willing to apply this method in their future creations after the workshop.

This shows that the workshop successfully demonstrated part of the fabrication process and got positive feedback from the participants. It also suggests that they find this method valuable and are willing to use the method in the future.

Furthermore, nearly all the participants think this method is suitable for designers or creators, though participant E disagrees. It suggests that further improvement may needed to make the method more inclusive or accessible for users.

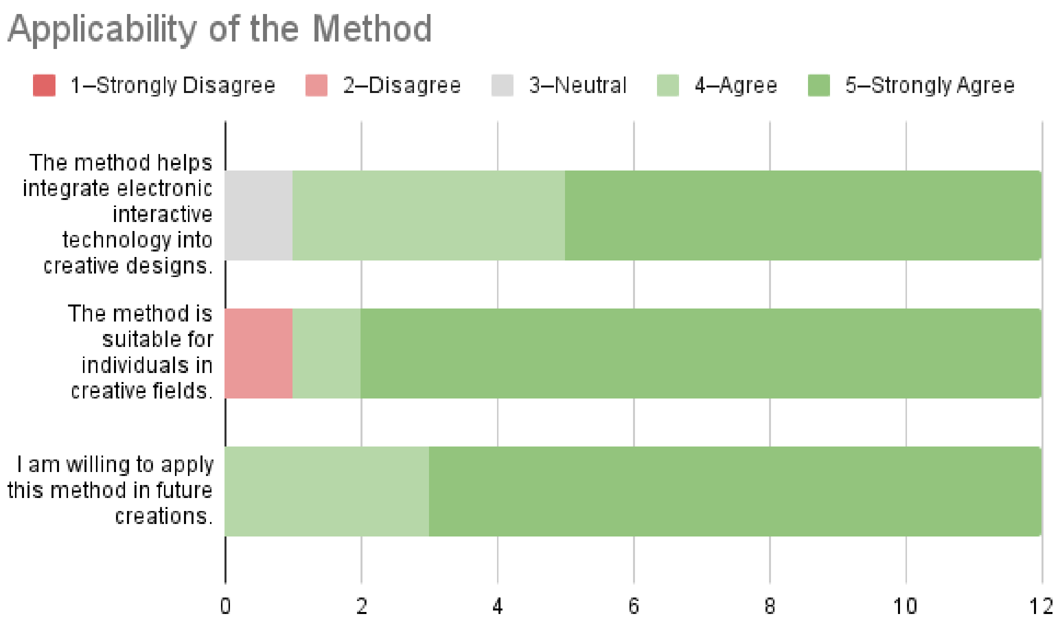

Figure 5.4 Participants' opinions on applicability of the method in Workshop I.

In the open-ended responses of the "Suggestions and Feedback" section, several participants shared their thoughts on the workshop experience and potential areas for improvement:

- Participant A and F mentioned that the 3D pen was somewhat difficult to control. Participant A suggested, "The pattern design should not be too small to match the capability of the 3D pen."
- Participant J also mentioned, "Maybe the boards can be bigger for practice." It indicates that smaller base and engraved patterns make it more difficult for users to trace along.
- Participant H suggested providing more use cases, such as practical applications in daily life, "to help people better visualize how this method can

be applied."

- Participant I said, "The concept is simple and interesting. I would like to know more applications."
- Participant J and L felt that the process was very fun.

Additionally, participants shared ideas about the application scenarios and the potential future expansions of the fabrication process:

- Participant A suggested improvements for the pattern design: "It would be great to design a series of patterns with specific meanings so they can be applied in suitable scenarios. Also, allowing users to customize patterns would make it more flexible!"
- Participant B thought this technology could be applied to the manufacturing of electronic components in factory production lines.
- Participant F thought it would be interesting to use this for creating interactive designs, while Participant G suggested it could be used to produce various installation art pieces and interactive products.
- Participant H suggested applying this method to store-bought or self-3D-printed figurine to create lighting or sound effects, saying, "I would like to make a small glowing figurine for my desk."
- Participant I thought the method was suitable for children and could be featured in science magazines for kids. In contrast, Participant J believed elderly people would enjoy the process.
- Participant L felt the process should include more explanations about the principles of the interactive circuit, such as, "How does pressing the filament make the circuit work?"

5.1.5 Observations and Reflections

By observing how participants used the 3D pen, I noticed that even though every participants was using it for the first time, there were differences in the quality and speed. For participants who produced high-quality results, I observed that they tended to keep the pen tip close to the baseboard and moving it slowly along the engraved pattern. In contrast, users who held the pen tip too far from the baseboard or moved it too quickly often failed to press the filament onto the baseboard and had to restart, making the process feel difficult. Therefore, to help users get the technique more quickly, instructions on how to use the 3D pen should be explained in the method.

Some participants tended to not follow the engraved patterns while drawing the circuits, instead creating their own designs. Additionally, some participants even drew 3D patterns on the base. This shows that participants are eager to express their creativity during the process and are not limited to 2D patterns. Therefore, it implies that customization features are highly expected by the users.

5.1.6 Conclusions

The workshop successfully demonstrated how the 3D pen and conductive filament can be used to create interactive circuits. It also provides insights into participants' reactions to the process. Feedback collected shows both the strengths and areas for improvement.

All participants successfully completed the interactive circuits. This suggests that the method offers a feasibility approach to circuit creation. Additionally, participants expressed a willingness to apply the approach in future projects, indicating its potential to inspire innovation. Participants also provided suggestions for the method and the potential applications.

Overall, the workshop validated the feasibility of the fabrication process and provided feedback for future enhancements.

5.2. Workshop II: User Testing of the Entire Fabrication Workflow

- Date and Time: October 12th (Sat) and 13th (Sun), 2024, with sessions held between 14:00 to 20:00, each lasting approximately one hour.

- Location: Keio University Hiyoshi Campus Collaboration Complex 3F Hacking Studio and S03 Discussion Room
- Participants: KMD students
- Purpose:
  - To test all stages of the fabrication workflow: “Design,” “Fabrication,” and “Integration.”
  - To observe how participants use the Design Tool.
  - To collect feedback for improvment.
  - To gather ideas for potential use cases or applications.

5.2.1 Overview

In this workshop, participants will create an interactive circuit application. The Design Tool (as shown in Section 3.4.3) is introduced, distinguishing this workshop from the previous one. With the Design Tool, participants can customize their circuit pattern designs. They then use a 3D pen and conductive filament to fabricate the interactive circuit. Finally, the circuits are connected to the preset physical computing system to complete functionality.

5.2.2 Tools and Materials

The following tools and materials are prepared for the workshop (as shown in Figure 5.5):

- 3D pen
- Conductive filament
- Silicone jumper wires, wire cutter, and wire stripper
- Substrates of various materials and colors (e.g., acrylic sheets, MDF boards)
- LED output module connected to a pre-programmed Arduino board
- Interchangeable LEDs in various colors

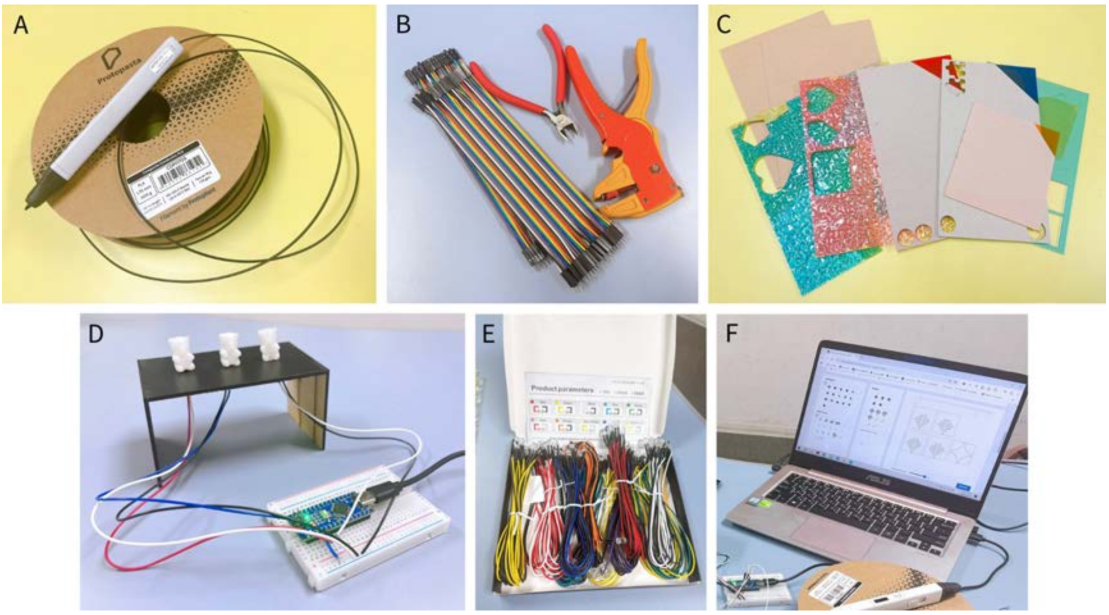

Figure 5.5 Tools and Materials Used in Workshop II. A: 3D pen and conductive filament. B: Silicone jumper wires, wire cutter, and wire stripper. C: Substrates of various materials and colors. D: LED output module connected to a pre-programmed Arduino board. E: Interchangeable LEDs in various colors. F: Laptop for using the Design Tool.

- Laptop for using the Design Tool (Participants may also use their own laptops).

5.2.3 Procedure

1. The participant designs the base shape and circuit pattern using the Design Tool.
2. The participant selects a preferred substrate.
3. The substrate is laser cut according to the participant's design.
4. The participant uses the 3D pen and conductive filament to trace along the engraved pattern trace and connect the wire, with the insulation stripped off from the connecting end.
5. The participant selects their preferred LED color to interchange the LED on the output module.
6. The participant connects the other end of the wire to the Arduino board, completing the functionality.
7. To test functionality, the participant gives touch input to the interactive circuit, causing the LEDs on the output module to light up.

5.2.4 Feedback and Insights

A total of 9 participants (labeled as Participant A to I), all with a certain level of design or creative background, attended the workshop and completed the post-workshop questionnaire.

The questionnaire includes the following questions:

- Section (1): Usability and Effectiveness of the Process (Likert Scale Questions with seven levels ranging from "1–Strongly Disagree" to "7–Strongly Agree")
  - Do you think it is easy to add or search for the desired circuit pattern using the Design Tool?

Figure 5.6 The results of participants in Workshop II.

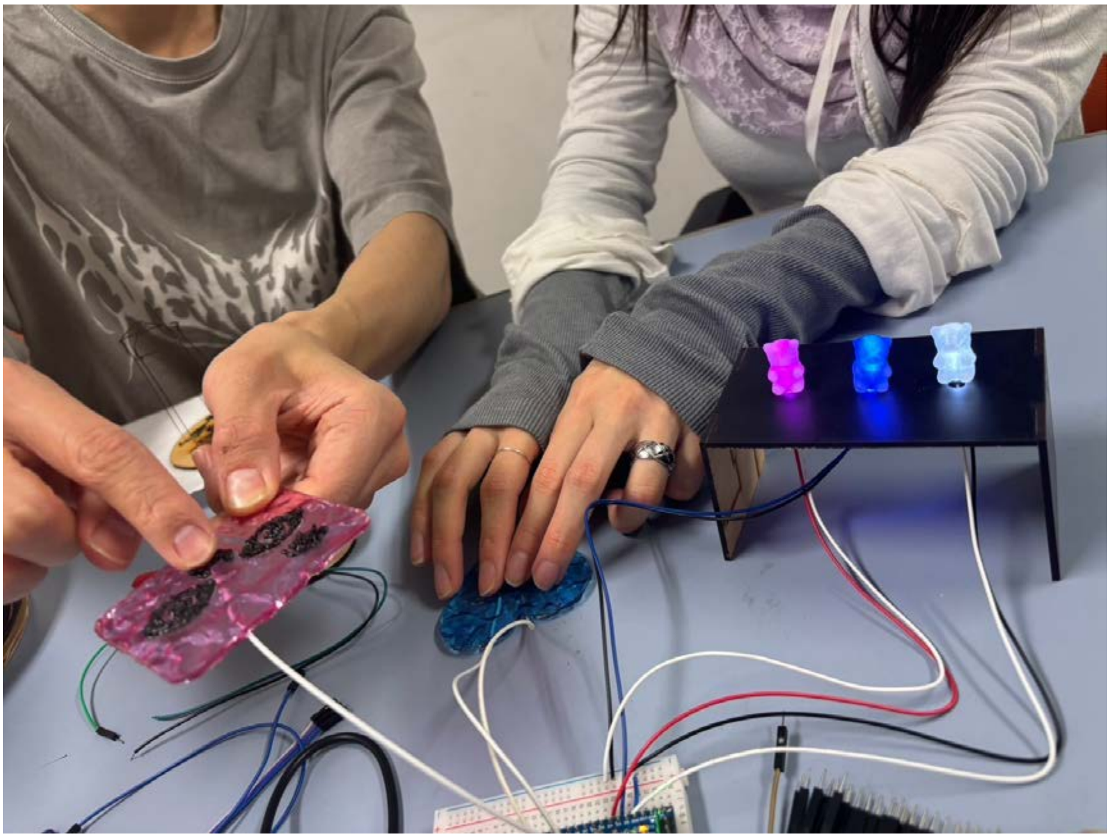

Figure 5.7 Participants tried the functionality of lighting up the LEDs after completing the interactive circuits and connecting them to the output module.

  - Do you think it is easy to edit circuits pattern using the Design Tool?
  - Do you think the templates provided by the Design Tool were helpful?
  - Do you think it is easy to draw interactive circuits using the 3D pen?

- Section (2): Applicability of the Method (Likert Scale Questions with seven levels ranging from "1–Strongly Disagree" to "7–Strongly Agree")
  - Do you think this method enables you to integrate electronic interactive technology into creative designs?
  - Do you think this method is suitable for individuals in creative fields?
  - After the workshop, are you willing to apply this method in your future creations?

- Section (3): Suggestions and Feedback (Optional, Open-Ended Questions)
  - How was your overall experience during the workshop? Is there anything that could be improved?
  - Do you have any thoughts or suggestions regarding the fabrication process of the interactive circuit?
  - Do you have any thoughts or suggestions regarding the Design Tool?
  - Do you have any thoughts or suggestions regarding the application scenarios of the method or its potential future expansions?
  - Do you have any additional comments or suggestions?

Participants' opinions on usability and effectiveness of the process are shown in Figure 5.8.

The first three questions focused on analyzing the features of the Design Tool, including the functions: adding or searching for the desired circuit pattern, editing circuit patterns, and using templates. Participants provided positive feedback, with average scores of 6.56, 5.89, and 6.67, respectively. This suggests that the Design Tool offers a good user experience. However, the score for "editing circuit patterns" was relatively lower. Improvements could potentially be made by adding features such as multiple editing (transforming multiple targets at once), snapping to grid when transforming, and so on.

The average score for the question about the ease of drawing interactive circuits with the 3D pen was 5.22. Although most participants found it easy, two selected the neutral option, indicating that using the 3D pen is not necessarily easy for everyone. Participants mentioned that the difficulty with the 3D pen is caused by the challenge of making modifications after the filament cools and hardens quickly. If the drawing doesn't turn out well, they must peel off or cut the filament and start over. One participant suggested that heat tools, such as wood burning tools, could help reshape the filament after it cools. Another participant used a heat gun to reheat the filament and smooth the surface of the interactive circuit, and was able to achieve some success. Therefore, incorporating these tools could improve the process in the future.

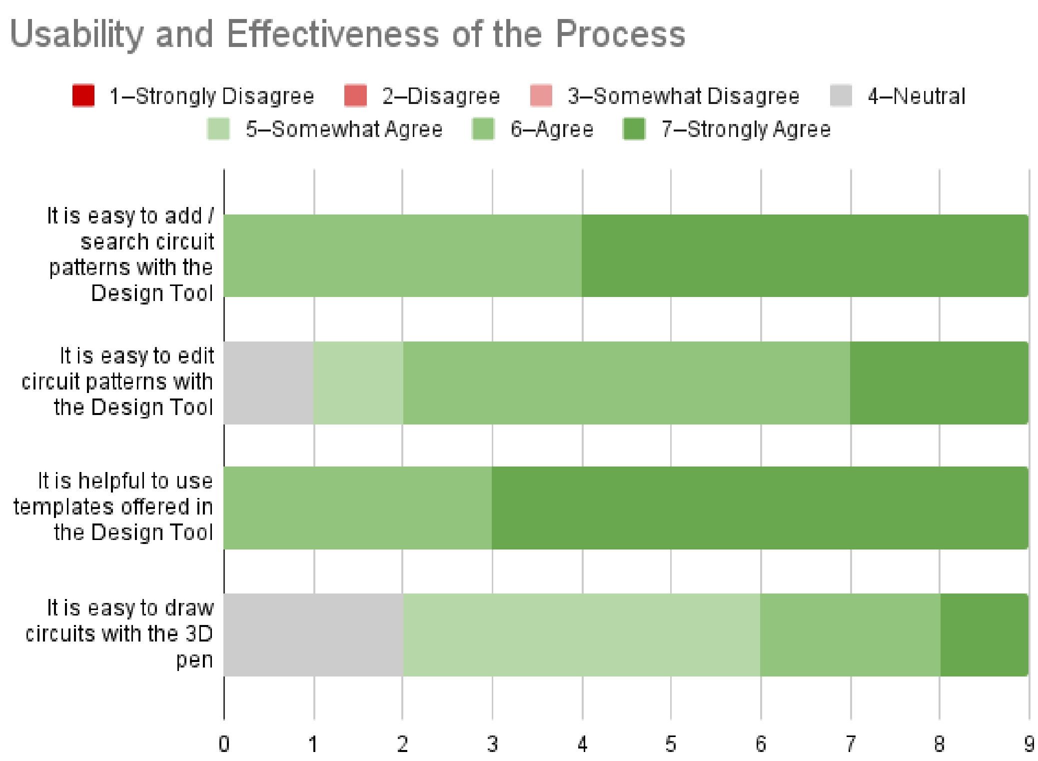

Figure 5.8 Participants' opinions on usability and effectiveness of the process in Workshop II.

Participants' opinions on applicability of the method are shown in Figure 5.9. All participants agreed that the method enables them to integrate electronic interactive technology into creative design, that it is suitable for individuals in creative fields, and that they are willing to apply this method in their future creations. The average scores for these questions were 6.33, 6.56, and 6.33, respectively. These questions were similar to the previous workshop but received more positive responses this time. This indicates that the introduction of the Design Tool has improved the usability and accessibility and enhanced users' creativity and inspiring stronger motivation to use it for creating interactive creative applications.

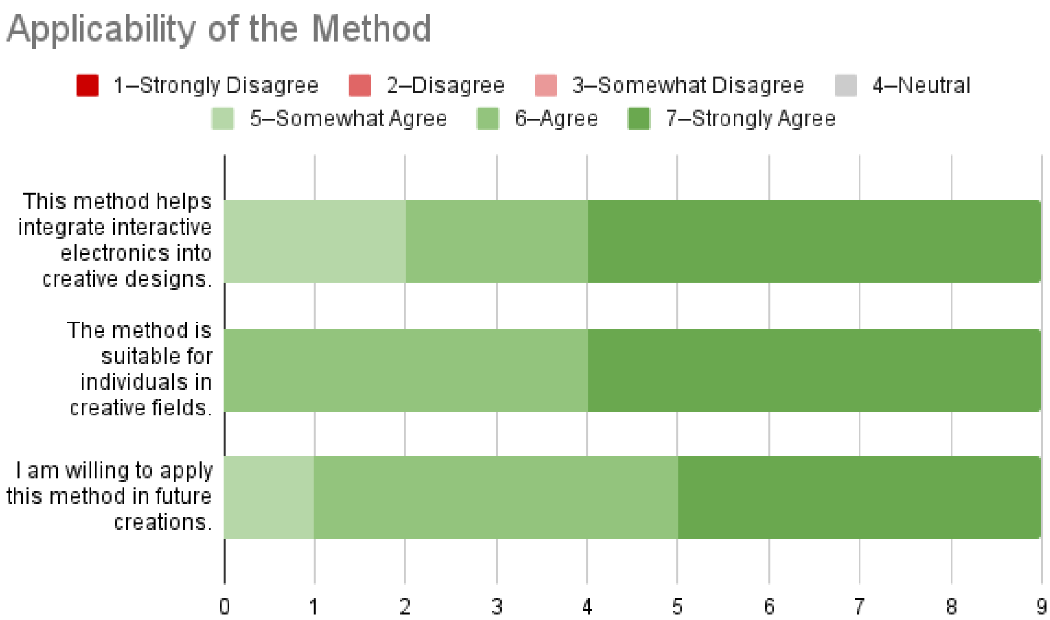

Figure 5.9 Participants' opinions on applicability of the method in Workshop II.

In the "Suggestions and Feedback" section, participants generally shared positive feedback about their experience:

- Participants B, D, E, H, and I all described the experience as "very fun" or "interesting."
- Participants shared their perspectives from a non-engineering background.

Participant D said, "Even without a background in technology, it was great that I could complete a project easily." Participant I said, "I felt that I could adapt towards a subject that I did not have much knowledge of. It was really informative and hands-on."

- Participants B and F mentioned difficulty controlling the 3D pen. Participant B said, "Some of my images are quite small, and I find it difficult to use the 3D pen for detailed work." Participant F said, "The material keeps coming out after I release the button, which makes my work less desirable."
- On the other hand, Participant H shared their positive adaptation: "It took some time to get used to using the pen, but after a while, I found it really fun and easy to use. Also, I found some playful ways of using 3D pens like sketching it like a pencil or using hands to shape the circuit. It's really fun to explore different ways of using a 3D pen!"
- Participant I also shared their positive experimentation: "The 3D pen part was really fun and interesting, and I liked the use of different techniques in creating different textures and shapes. I was trying to create a circular shape to represent an eye and realized that I could do so if I attempted to mold the filament while it was slightly warm."

Regarding the design of the Design Tool and fabrication process of interactive circuits, participants shared their thoughts:

- Regarding to the Design Tool, Participant C said, "The process of designing on the platform was very enjoyable and user-friendly! Having templates and patterns prepared in advance made designing easier." Participant H suggested, "I think it would be helpful to have a video tutorial just to show how the process goes from start to finish, or videos that show how to use 3D pens." Additionally, Participant H highlighted the usefulness of templates: "I'm not from an engineering background, so it's hard for me to imagine how I can utilize these circuits. The examples of the 3D light box was helpful."
- Regarding to customization, Participant D said, "I enjoyed being able to customize the design freely, including the circuit pattern, LED colors, and

wire colors." Participant I said, "I liked that it was customizable as it allows for creativity and your personality to show through the design. When I thought of circuits, I did not know that it could involve a creative process."

- Participant H suggested further improvements: "I think integrating generative AI to generate desired patterns could make the design process easier."

Additionally, participants shared additional improvement they would like:

- Participants A and H both want to build 3D structures. Participant H said, "I can start to imagine the many ways you can use 3D pens to make 3D circuits, not just on a 2D plane, which makes this so incredibly fun." Participant I added, "Currently, mine still looks very 2D, but I feel it would be fun to make something very sculptural!"
- Participants C and E both suggested they would like more filament colors available.

Furthermore, participants shared ideas for potential applications:

- Participant A suggested that the method can be used in interactive artworks and fashion fields.
- Participant D shared, "I would like to create something interactive in my living spaces, like a chair that lights up when you sit on it."
- Participant E mentioned, "I want to make interactive toys for little babies or cats to play with."
- Participant I proposed, "It would be fun to make an interactive light display with more complex light systems."

5.2.5 Observations and Reflections

After introducing the Design Tool, data showed that participants' overall experience improved, and they provided positive feedback on the newly added features, such as adding and editing base and circuit patterns, as well as applying templates. Participants also showcased their creativity by designing various interactive circuits. For example:

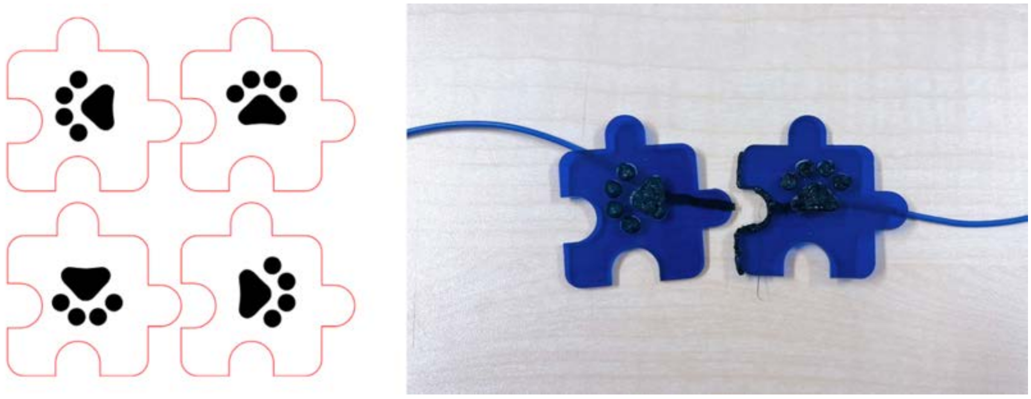

Figure 5.10 Puzzle-shaped interactive circuits designed by the participants.

Figure 5.11 Face-like design interactive circuits designed by the participants.

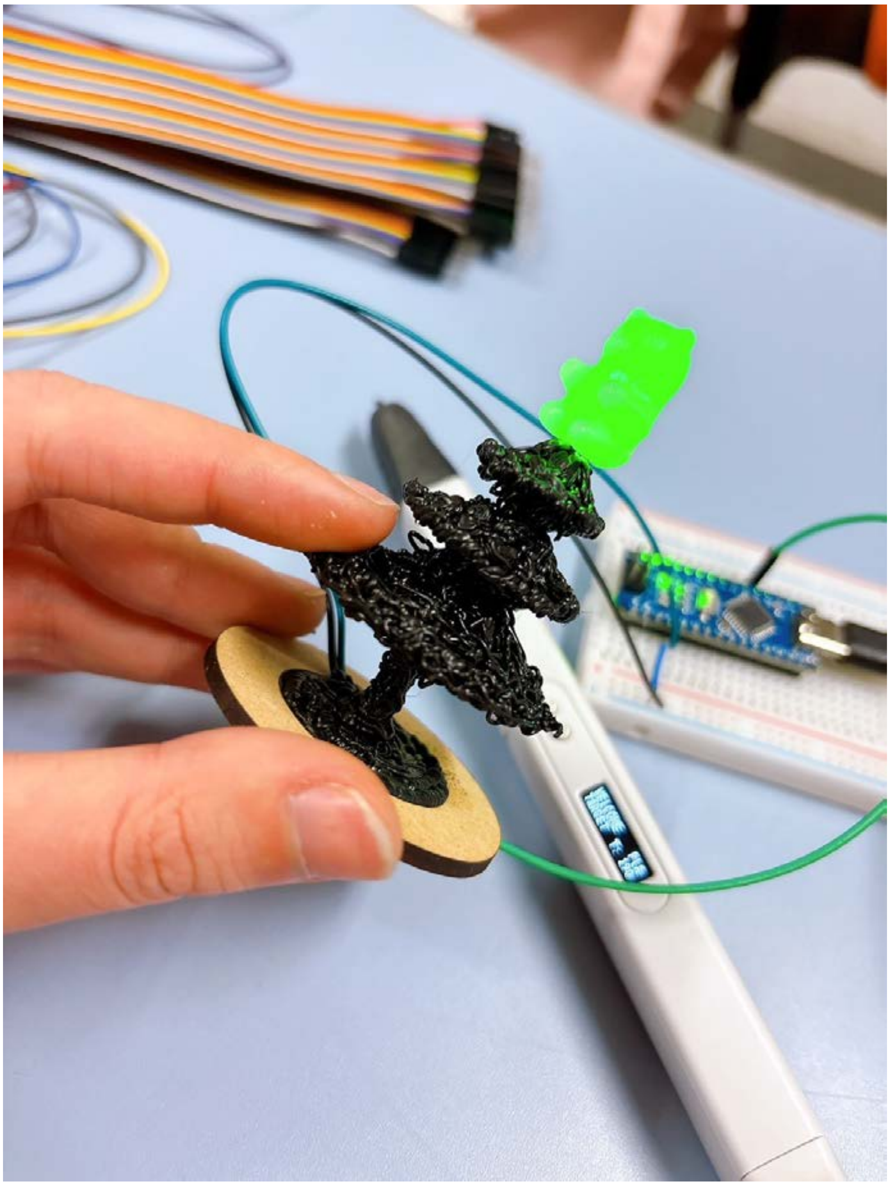

Figure 5.12 Interactive circuit with a 3D structure, incorporating the output module's LED, designed by the participant.

- Participant A designed puzzle-shaped bases and extended conductive filament to the edges of the puzzle pieces. When the pieces are connected, an expanded circuit is formed (see Figure 5.10).

- Participant H and Participant I used the provided patterns to create different face designs, and added raised 3D shapes in areas like the eyes (see Figures 5.11).

- Participant E created a 3D Christmas tree shape on top of a base, further incorporating the output module's LED into the design and placing it at the top of the tree (see Figure 5.12).

Since the Design Tool provided over 2,000 circuit patterns, participants found it engaging and enjoyable to explore. Some participants suggested additional features, such as the ability to upload custom patterns or generate designs using generative AI. Furthermore, several participants attempted to create 3D designs and proposed that the Design Tool include enhanced support for 3D design functionality.

Regarding the provided output module, participants found it fun and satisfying to quickly complete the functionality and found the customization options (such as choosing the wire and LED colors) interesting. These findings indicate that the customization features meet users' needs and enhance the experience.

However, the difficulty in controlling the 3D pen remains a challenge. Several improvement suggestions were gathered from the participants:

- Introducing heat tools, such as wood-burning tools or a heat gun, to reheat and reshape the filament after it cools for easier adjustment for interactive circuits.

- Introducing techniques for using 3D pen, such as using 3D pens like a pencil or shaping the circuit with hands, as Participant E suggested.

- Adding video tutorials to show how to use 3D pens, as well as the entire fabrication process.

These insights from participants offer valuable guidance for improvement. Implementing these changes in the future could further enhance the user experience.

5.2.6 Conclusions

Workshop II provided valuable insights into the usability and potential improvements of the fabrication process and the Design Tool. Participants engaged with the Design Tool's new features and appreciated the customization function, which enhanced their creative experience and design flexibility.

However, challenges with controlling the 3D pen were still existed, along with suggestions for improvement. Participants also expressed interest in expanding the Design Tool capabilities, such as greater flexibility in circuit pattern design and enhanced support for 3D designs, to facilitate both 2D and 3D creations.

Overall, the feedback indicates that the fabrication process Design Tool successfully encourages creativity and has potential for future applications.

5.3. Discussion

5.3.1 Feasibility of Creating Interactive Circuits with a 3D Pen and Conductive Filament for Creative Individuals

The feasibility of creating interactive circuits with a 3D pen and conductive filament was demonstrated through these two workshops.

The participants in both workshops all had varying levels of design backgrounds. All participants successfully completed the fabrication process. Once their circuits were integrated with the preset physical computing system, they achieved interactive functionality.

The preset physical computing system provided in the workshop was simple, and with basic knowledge and provided diagram, participants could build it themselves. This allows for the creation of simple interactive circuits that achieve basic electronic functionality, with the potential for further development into more advanced features.

5.3.2 Differences Between the Two Workshops and the Insights

The first workshop focused on the "Fabrication" and "Integration" stages of the fabrication workflow but did not include the "Design" stage. Participants were provided with pre-defined base materials and fixed circuit patterns. During observations, participants generally used the 3D pen in a structured and constrained manner. While some attempted to create 3D structures, most remained limited to the given patterns. Although the workshop involved hands-on fabrication, it did not fully explore the creative potential of the manual process.

In contrast, the second workshop covered all stages of the fabrication workflow: "Design," "Fabrication," and "Integration." By introducing the Design Tool, participants were given the freedom to design their own circuit patterns. Observations revealed that participants began experimenting with different ways of using the 3D pen. Some constructed 3D structures, while others explored diverse pen strokes, textures, or extended their designs beyond the laser-cut traces, leading to more diverse outcomes.

These findings suggest that the customization process of the Design Tool stimulated participants' creativity, encouraging deeper exploration and engagement. This integration of digital design and hands-on fabrication process enhance the overall experience.

5.3.3 Benefits of Hands-on Process and Customization in the Process

As suggested, the hands-on process offers several unique advantages: it enables the creation of varied textures on circuit surfaces, flexible construction of 3D shapes, easy real-time modifications and additions, and the use of conductive filament as an adhesive in 3D structures.

These behaviors were observed in Workshop II and were reflected in the participants' final design outcomes. Additionally, based on feedback from the questionnaires, interviews, and observations, the following benefits of incorporating hands-on process and customization into interactive circuit fabrication can be identified:

Enhance Creativity: Customization allowed participants to explore unique designs by arranging and combining different patterns, showcasing their personal aesthetic. In the hands-on process, participants used distinct 3D pen techniques to draw the circuits, creating different textures. Some participants even created 3D structures.

Enhance Flexibility: The customization process enabled flexible modifications, allowing participants to add and edit their designs freely. The hands-on use of the 3D pen also provided opportunities for real-time adjustments and additions on any stage of the process, in contrast to fully digital fabrication.

Enhance User Engagement: Unlike fully digital methods such as 3D printing, which require minimal user interaction, the workshops demonstrated high levels of engagement. In the first workshop, participants worked on their circuits for an average of 15 minutes. In the second workshop, where design process was further introduced, the engagement time ranged from 30 minutes to 1 hour. Although it is possible to finish in a shorter time, participants chose to invest more time in refining their creations, leading to a deeper connection between the participants and their creations. In interviews, most participants mentioned that they found the process fun and enjoyable.

Chapter 6
Conclusion

6.1. Summary

In this research, a fabrication process for creating interactive circuits is proposed. The process begins with designing circuit patterns and engraving them onto a substrate using a laser cutter. Then, a 3D pen and conductive filament are used to trace the engraved patterns and create the circuit.

Proof-of-concept prototypes were developed to demonstrate the feasibility of this approach. By utilizing capacitance changes as capacitive touch sensors and LEDs as output, two interactive application prototypes were created. These prototypes were demonstrated at the Tokyo Maker Faire and KMD Forum. Four sets of sample prototypes were also developed to demonstrate the unique advantages of using a 3D pen for hands-on fabrication.

A Design Tool was also developed to further support this process, enabling users to customize circuit patterns.

Two workshops were conducted to evaluate the approach and gather user feedback. The first workshop simplified the process by providing pre-laser-cut pieces. The second workshop tested all stages of the workflow. The results from the workshops demonstrated the usability and potential of the proposed approach, with feedback offering valuable insights for future improvements.

6.2. Limitations and Future Work

Several limitations were identified that could be addressed for future improvement and expansion.

One area for enhancement is the variety of input mechanisms. Currently, the interactive circuit applications function as touch sensors, but they could be expanded to include other types of inputs, such as temperature sensing or water level detection, to increase their functionality.

Another potential improvement is the expansion of output modules. By incorporating a wider range of electronic components, such as buzzers or vibration motors, the system could support a broader array of applications.

Participants also expressed interest in 3D circuit design, as the current Design Tool focuses primarily on 2D designs. Future development could explore methods to enable 3D circuit creation, offering more complex and innovative design possibilities.

Exploring alternative substrate materials is another avenue for improvement. For example, flexible materials like silicone could support adaptable circuit designs using flexible conductive filaments, while heat-resistant materials such as ceramics could enable circuits for high-temperature environments, such as temperature-sensing applications.

Finally, developing additional prototypes is also important. These prototypes can showcase diverse use cases, demonstrate the versatility of the approach, and inspire creativity among users.

In conclusion, while there are some limitations, addressing these areas in future development will further enhance the approach and explore additional possibilities for hands-on fabrication process.

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Appendices

A. Source Code and Deployed Website of the Design Tool

The following links provide access to the source code and deployed website for the Design Tool:

- **Source Code**

  The GitHub repository can be accessed at:

  `https://github.com/yunjuwang/interactive-circuit-design-tool`

- **Deployed Website**

  The Design Tool is available at:

  `https://yunjuwang.github.io/interactive-circuit-design-tool/`

  (Not supported on Safari browser.)

B. Arduino Code for Capacitive Touch Sensing in Physical Computing System

```
#define THRES 50
#define SAMPLES 20

#define SERIAL_DEBUG

#define LED1 2
#define LED2 3
```

```
#define LED3 4
#define LED4 5

typedef struct touchPad{
  int pin;
  int unpValue;
  int value;
  char state=0, prevState=0;
  char toggleState=0;
};

touchPad touchPad1, touchPad2, touchPad3, touchPad4;

void setup() {
  /* Set A0 pull-up resistor, used to charge internal capacitor */
  pinMode(A0, INPUT_PULLUP);
  analogRead(A0);

  pinMode(LED1, OUTPUT);
  digitalWrite(LED1, 0);
  pinMode(LED2, OUTPUT);
  digitalWrite(LED2, 0);
  pinMode(LED3, OUTPUT);
  digitalWrite(LED3, 0);
  pinMode(LED4, OUTPUT);
  digitalWrite(LED4, 0);

  /* Initialize sensors */
  touchPadInit(&touchPad1, A1);
  touchPadInit(&touchPad2, A2);
  touchPadInit(&touchPad3, A3);
  touchPadInit(&touchPad4, A4);

#ifdef SERIAL_DEBUG
  Serial.begin(57600);
#endif
```

```
}

void loop() {
  /* Scan sensors */
  touchPadScan(&touchPad1);
  touchPadScan(&touchPad2);
  touchPadScan(&touchPad3);
  touchPadScan(&touchPad4);

  /* Use sensors reding to control LEDs */
  digitalWrite(LED1, touchPad1.state);
  digitalWrite(LED2, touchPad2.state);
  digitalWrite(LED3, touchPad3.state);
  digitalWrite(LED4, touchPad4.state);

  delay(10);

#ifdef SERIAL_DEBUG
  Serial.print(touchPad1.value);
  Serial.print(",");
  Serial.print(touchPad2.value);
  Serial.print(",");
  Serial.print(touchPad3.value);
  Serial.print(",");
  Serial.println(touchPad4.value);
#endif
}

void touchPadInit(touchPad *pad, int pin){
  pad->pin=pin;
  pad->unpValue = (sampleB(pin) - sampleA(pin));
  DIDR0 |= 1;
  DIDR0 |= 1<<(pin-A0);
}

int sampleA(int sensePin){
```

```
  /* Sample capacitor is charged to VCC
   * via A0 pull-up resistor, touch pad
   * is discharged by pulling pin low
   */
  ADMUX = 0b01000000;
  pinMode(sensePin, OUTPUT);
  digitalWrite(sensePin, 0);

  pinMode(sensePin, INPUT);
  ADMUX = 0b01000000 | sensePin-A0;

  ADCSRA |= 1<<ADSC;
  while((ADCSRA & (1<<ADSC)) != 0);

  return ADC;
}

int sampleB(int sensePin){
  /* Sample capacitor is discharged by selecting
   * GND as ADC input, touch pad is charged to VCC
   * via pin pull-up resistor
   */
  ADMUX = 0b01001111;
  pinMode(sensePin, INPUT_PULLUP);

  pinMode(sensePin, INPUT);
  ADMUX = 0b01000000 | sensePin-A0;

  ADCSRA |= 1<<ADSC;
  while((ADCSRA & (1<<ADSC)) != 0);

  return ADC;
}

void touchPadScan(touchPad *pad){
  static float A, B;
```

```
  A=0;
  B=0;

  /* Get some readings from sensor and calculate average */
  for(int i=0; i<SAMPLES; i++){
    A += sampleA(pad->pin);
    B += sampleB(pad->pin);
  }

  A /= SAMPLES;
  B /= SAMPLES;

  pad->value = (B - A);

  /* Member unpValue is a running average of the unpressed readings.
   * A sudden change in sensor reading is interpreted as a touch
   */
  if(pad->value > (pad->unpValue + THRES))
    pad->state=1;
  else{
    pad->state=0;
    pad->unpValue=((float)pad->unpValue*0.9)+((float)pad->value*0.1);
  }

  if(pad->state == 1 && pad->prevState == 0)
    pad->toggleState = !pad->toggleState;

  pad->prevState = pad->state;
}
```