

MechCircuit: Augmenting Laser-Cut Objects with Integrated Electronics, Mechanical Structures and Magnets

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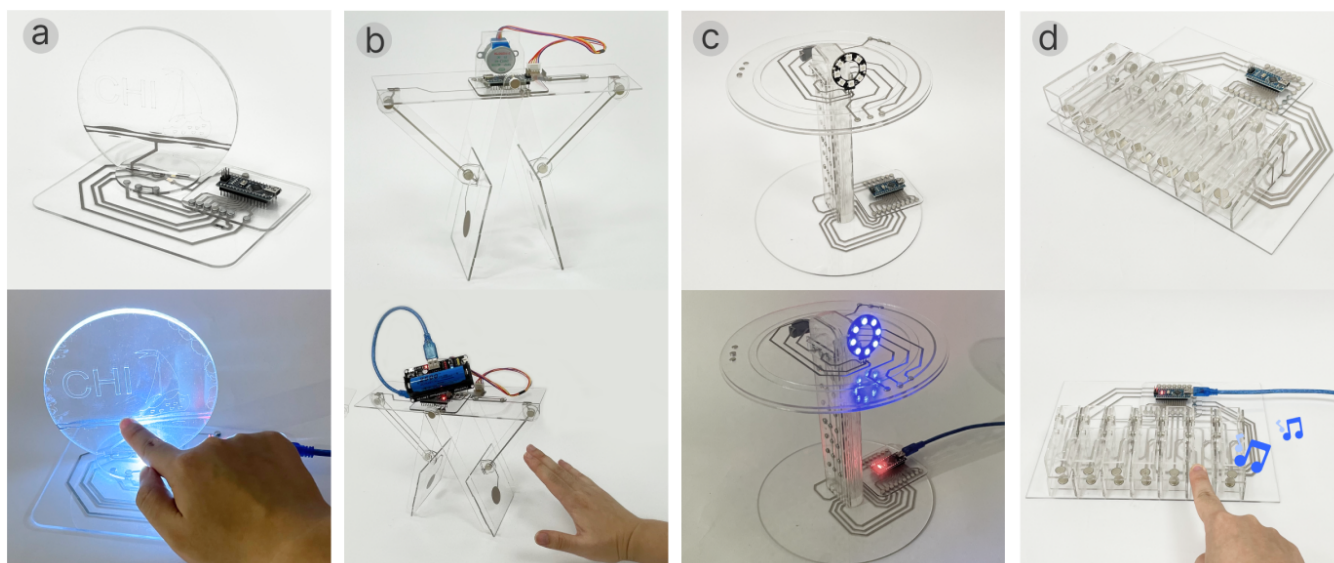


Figure 1: Interactive prototypes produced by students in the workshop: a) rotatable-switch-controlled lamps; (b) walking robot; (c) liftable table lamp; (d) piano

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ABSTRACT

Laser cutting revolutionizes the creation of personal-fabricated prototypes. These objects can have transformable properties by adopting different materials and be interactive by integrating electronic circuits. However, circuits in laser-cut objects always have limited movements, which refrains laser cutting from achieving interactive prototypes with more complex movable functions like mechanisms. We propose MECHCIRCUIT, a design and fabrication pipeline for making mechanical-electronical objects with laser cutting. We leverage the neodymium magnet's natures of magnetism and conductivity to integrate electronics and mechanical structure joints into prototypes. We conduct the evaluation to explore technological parameters and assess the practical feasibility of the fabrication pipeline. And we organized a user-observing workshop for non-expert users. Through the outcoming prototypes, the result demonstrates the feasibility of MECHCIRCUIT as a useful and inspiring prototyping method.

CCS CONCEPTS

• **Human-centered computing** → **Interaction devices**.

KEYWORDS

Prototyping; Movable electronics; Digital fabrication;

ACM Reference Format:

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1 INTRODUCTION

In Human-Computer Interaction (HCI) field, laser cutting is widely used in prototyping as a rapid fabrication technique. Laser cutting can be used to cut flat plates and then assemble them as 3D objects [1, 28, 42, 49]. By adopting different materials or stacking these materials in multi-layers, these objects can have inflatable [48] and flexible [3, 7, 34] structures. Besides, to make interactive prototypes, researchers have explored integrating electronic circuits in laser cutting, contributing to new interaction possibilities such as touch and proximity sensing [17], temperature detection, and image capture [26].

While electronics are integrated into laser-cutting prototypes, most structures for integrating electronics are not transformable in these prototypes, which confines these structures to appearance construction without actual functions. To support transformability, some studies integrate circuits into foldable structures [33, 47]. In these studies, electronic circuits can respond to bending or stretching folded structures. However, these foldable structures can not provide more complex movements like mechanical motions (e.g., rotary, linear). Though researchers have explored creating mechanisms through laser cutting [22, 43], these mechanisms are still separated from electronic circuits in these works.

To integrate electronic circuits with mechanical function structures, we propose MECHCIRCUIT, a design and fabrication technique for laser cutting interactive prototypes with electronic circuits and mechanical structures. We leverage the neodymium magnet's natures of magnetism and conductivity to achieve mechanical-electronical functions. MECHCIRCUIT embeds neodymium magnets in the laser-cut components, which can magnetically attach together to perform mechanical functions and maintain conducting electricity during mechanical movements. In the design and fabrication pipeline of MECHCIRCUIT: (1) users use our software tool to combine magnet-based mechanical structure joints and electronic circuits and export files that contain planar components for laser cutting; (2) users spray conductive ink directly on these components to produce the circuit paths and embed magnets and electronic components into these sprayed electronic circuits; (3) users snap and assemble planar components to achieve the prototype. To validate the performance of MECHCIRCUIT, we conduct the evaluation to determine technological parameters and demonstrate the practical feasibility of the fabrication pipeline. Finally, to evaluate the applicability of MECHCIRCUIT, we organize a workshop, in which we recruit 8 participants to create interactive prototypes with our pipeline.

MECHCIRCUIT enables non-expert users in the mechanical and electronic fields to design and fabricate interactive prototypes with electronic circuits and mechanical structures. Users can achieve mechanical functions like rotary and linear without employing traditional mechanical parts. Meanwhile, rather than involving complicated operations including wiring, soldering, and gluing in conventional electronic circuits, MECHCIRCUIT applies magnetism and laser-cut slots to connect electronic components (e.g., Arduino nano board [2], sensors, buttons), which makes connection quicker and convenient and replacement of the specific components much easier. In addition, MECHCIRCUIT is accessible to a wide audience for using the standard laser cutting machine and consumer-level materials.

The contributions of this paper include:

- an accessible fabrication pipeline leveraging neodymium magnets to integrate mechanical structures and electronic circuits in interactive laser-cutting prototypes;
- an exploration of technological parameters and an evaluation of the practical feasibility of the fabrication pipeline;
- a set of exemplary cases created in a workshop for displaying the applicability of MECHCIRCUIT.

2 RELATED WORK

2.1 Personal Fabrication in HCI

More recently, personal fabrication tools such as laser cutters and 3D printers have made fabricating objects more accessible. Researchers have explored converting static fabricated artifacts into simple mechanisms that allow for certain degrees of movement, including joints [6, 22, 43] linkages [12, 21], hinges [30, 41], and metamaterials [15, 34, 38]. For example, LaserStacker [43] used a laser cutter to weld multi-layer acrylic sheets, enabling the rapid creation of 3D objects with rotating joints such as scissors. Lami-Fold [22] supported a variety of features for sliding, rotating, and

hinge mechanisms by stacking and laminating. Ion et al. [16] integrated metamaterial textures into 3D printed objects which allow the resulting objects to be grasped, pushed, or stood on. In addition, previous research has also presented dynamic objects by selectively ablating multi-material sheets [7], recursively combining mechanical components [29], and creating 3D inflatable objects [48].

Other works embed electrical functions in prototypes to make them interactive. It can be achieved by generating electrical circuits, for example, spraying conductive ink [31, 45], inkjet printing [19, 20, 52], inserting conductive plastic [5, 13, 18, 23, 36, 37, 40], and paste conductive material on the surface [26, 47]. CircWood [17] is a new method to produce various sensors and electrical circuits by partially carbonizing the wood surface with a laser cutter. Swaminathan et al. [40] formed low resistance conductors by laser etching and fiber printing between layers of carbon-fiber composite. ProtoSpray [11] explored the use of conductive PLA as a base electrode for electroluminescence and produced freeform displays on various surfaces. LASEC [9] combined laser cutting of parametric patterns for stretchability with ablation for custom circuits realizing circuits on cut patterns.

Currently, shapes, structures and circuits are often separately designed when designers make prototypes. These separated designs lead to mistakes in the final combination, which cause the failure to anticipate results. Besides, The traditional connection between electronic components and circuits requires wires, soldering, gluing and other operations, leading to inconvenient connections between electronic components and digitally fabrication objects. A suitable solution for connecting the traditional electronic circuit and the new digital fabrication is needed.

2.2 Interactive Objects with Transformable Structures

With a growing interest in interactive prototypes, novel solutions are required to integrate electronic circuits and transformable structures. HCI researchers have contributed pipelines to make exploring different design patterns that these fabrication techniques and mechanisms afford accessibly.

FoldTronics [47] is a 2D-cutting-based fabrication technique that allows the place the electronic components and circuitry onto a thin sheet with a honeycomb structure. While this method allows for rapidly prototyping interactive devices, it can only be folded flat or spread along one axis. Some mechanisms are implemented using particular materials. For example, Wang et al. [44] have produced a three-way switch by screen printing conductive traces on a PLA material, which lights up different colors of LEDs when connected to different pins. Due to the elasticity of the PLA material, the user can bend the pins of the three-way switch to control the circuit as needed. ElectroDermis [27] is a way of making wearable electronic bandages in which rigid circuit boards and electrical components are wired together using stretchable copper wiring to make the produced electronic devices flexible. Foldios [33] enables unique combinations of foldable geometries and printed electronics by printing thin-film circuits on lightweight paper crafts, which could capture shape-changing input. For example, when the user lifts the head of an interactive paper cow with fold-sensing controls, an external speaker plays a “moo” sound. Similarly, Sensing Kirigami

[54] uses carbon-coated paper (organic paper coated with carbon fiber) for folding and bending sensing. However, most of these approaches rely on the properties of the material to achieve the mechanism. The transformable structures created in this way cannot support more movement modes, such as rotational motion and linear motion.

The MECHCIRCUIT system seeks to extend this related work, it integrates transformable structures with more movement modes and electronic circuits that can be customized and reliably created through our fabrication pipeline for interactive movable prototypes.

2.3 Interaction with Magnetic Materials

In HCI, magnets have been widely used for haptic interaction [4, 46, 51] and functional physical input [39, 50]. Zheng et al. [53] think that structures using the magnetism of magnets require fewer parts and are simpler in construction than conventional mechanical fabrication approaches. GaussBricks [25] investigates elastic textures afforded by a chain of static magnets; including clicking, bending, stretching, and squeezing. This allows users who have limited mechanical knowledge to easily fabricate prototypes with mechanical movement. Besides, magnetic fields can be used as data input. For example, Lamello [35] utilizes a microphone to read input by parsing the audio signal generated by 3D printed tines. GaussBricks [25] uses Hall sensors to detect the position of a magnet and present the position information on a screen. Outside of the HCI domain, researchers have produced materials by combining conductive and magnetic materials which are both conductive and magnetic. Examples include Magnetic Liquid Metal [10], which is produced by adding magnetic materials to liquid metal, or flexible paper [24], which is made by mixing graphene and iron. Such combined materials have proved wide applications in industry and consumer electronics [8]. However, the preparation of these materials requires expert knowledge and specific equipment. Therefore they are not suitable for personal fabrication.

Our work uses commercially available neodymium magnets. These magnets are both magnetic and conductive and can be used to create circuits with magnetic properties. By integrating a movable structure with more mechanical movement and electronic circuitry by neodymium magnets, users can customize and reliably fabricate interactive prototypes.

3 BASIS OF MECHCIRCUIT

In this section, we present MECHCIRCUIT, a fabrication method that realizes mechanical-electronic functions directly. For our method, we employ laser cutting and PMMA to produce the structures, and magnets and conductive silver ink to form the electronic circuits. We would detail (1) the basic integration principle of mechanical structure and circuit principle in MECHCIRCUIT, and (2) several basic structures created aimed to inspire users to create unique structures.

3.1 Basic Integration Principle

Figure 2 is an integration structure case for demonstrating how we can integrate mechanical structures with electronic circuits by laser-cut PMMA layers and magnets.

Using conductive magnets. We bridge mechanical structures and electronic circuits with neodymium magnets, which are the strongest type of permanent magnet available commercially, and achieve high conductivity (Figure 3) with the plate of nickel and copper (Figure 2a). Magnetism enables different components to attach to form mechanical structures and be transformable. As shown in Figure 2c, component X attaches to component Y and it can slide up and down. Conductivity makes magnets connect electronic circuits (Figure 2b). In our case, the LED of component X would light up all the time for the vertical distance of magnets in component Y is smaller than these magnets' diameter.

Creating circuit paths on structures. To refrain from being dependent on producing electronic circuits and structures, we create circuit paths directly on the surface of the structures. Specifically, the surface is laser-cut to reserve electronic circuit paths, which would be sprayed with conductive silver ink later.

Creating slots on structures. To form the electronic circuit right on the surface of structures, magnets and electronic components should be embedded in these structures as well. To embed magnets and different components, we design three types of slots: magnet slots (Figure 2d2), electronic pin slots (Figure 2d3), and electronic chip slots (Figure 2d1). A magnet slot is a hole for sticking magnets while an electronic pin slot is for sticking pins of electronic components. The inner wall of these two types of slots is covered with conductive ink. In our case, the button battery used the electronic pins, which are embedded in the electronic pin slots. An electronic chip slot is used to embed electronic components in the chip package form. Half the inner wall of this type of slot is covered with conductive ink for the chip package always requires connecting on both ends. In our case, the chip LED is embedded in an electronic chip slot.

3.2 Basic Mechanical-Electronic Function Structure

We propose a set of basic mechanical structural units to inspire users to create unique and more complex structures (figure 4). These basic mechanical-electronic function structures include infinite rotation structure, linear motion structure, pressing structure, polar rotation structure, and rotation linear conversion structure. The introduction of each structure is following:

(1) Infinite rotation structure. This structure connects two components by their magnets that attract each other, which allows two components to rotate infinitely and the circuit will maintain conduction when the structure rotates.

(2) Linear motion structure. In this structure, the upper component is sliding in the groove of the lower one, which achieves linear motion. The upper component has one magnet and connects to the lower component, which has three magnets in line. These magnets enable the upper component to fix every time it moves a certain distance, and the circuit will remain unobstructed at each fixed position.

(3) Pressing structure. In this structure, the upper component covers the lower component, and both are embedded with magnets that repel each other. This structure achieves the function of button that could be pressed and automatically bounce back. The circuit

could conduct current when the button is pressed down and two magnets come into contact.

(4) Finite rotation structure. A central magnet and a circle of surrounding magnets are embedded in both two components of this structure, which achieves the polar rotation function. In this basic structure, the components would fix every 36 degrees, and the current would be conducted in every fixed position.

(5) Rotation linear conversion structure. In this structure, the circular component is a rotating part embedded with a circle of magnets while the linear moving component is embedded with magnets in line. The circular component rotates and can drive the linear moving component to achieve linear motion. Similarly, the linear moving component moves linearly and can drive the circular part to rotate. In this basic structure, the circuit will maintain conduction.

4 FABRICATION PIPELINE

In this section, we describe how in one pass can users achieve mechanical-electronic functions of the interactive object by using MECHCIRCUIT fabrication pipeline (Figure 5). We illustrate all steps in the example of making a rotatable-switch-controlled lamp. This example is used to introduce pipeline, and details of MECHCIRCUIT in our workshop (figure 7), which would be demonstrated specifically later.

4.1 Designing

Our fabrication pipeline aims to support users who are non-expert in mechanical structures and electronic circuits fields to create interactive prototypes. The design software enables users to design mechanical structures, and directly applies electronic circuits to these structures. As illustrated in Figure 6, a user performs the following steps:

4.1.1 Import Files. Users can import files created in advance (Figure 6a).

4.1.2 Add Slots of Electronic Components and Magnets. Users use software to select and add required electronic components and mechanical structure joints on the PMMA layers (Figure 6b), as well as move these electronic components and mechanical joints. After determining the position, magnets slots and components slots will be generated automatically, which relieves users from positioning magnets and slots for frequently used components. It should be noted that since laser cutting employs the lens to converge the laser beam, the kerf is slope. In our software, this slope kerf is considered and compensated to hold magnets and components. Specifically, after users determine the magnet diameter, the generated magnet slot will be minus 0.22mm as the compensation. This kerf compensation parameter was obtained through iterative testing and it can fix a magnet tight without using glue. The evaluation of the compensation parameter is shown in 5.1. The software will also automatically generate a separate PMMA board for the Arduino at the end, which will make the replacement of the Arduino more convenient (Figure 6d). Moreover, to facilitate the customized creation of mechanical structure joints, we provide three ways to create magnet slots: i) create one single magnet (corresponding to the infinite rotation structure), ii) create magnets in line (corresponding to the linear

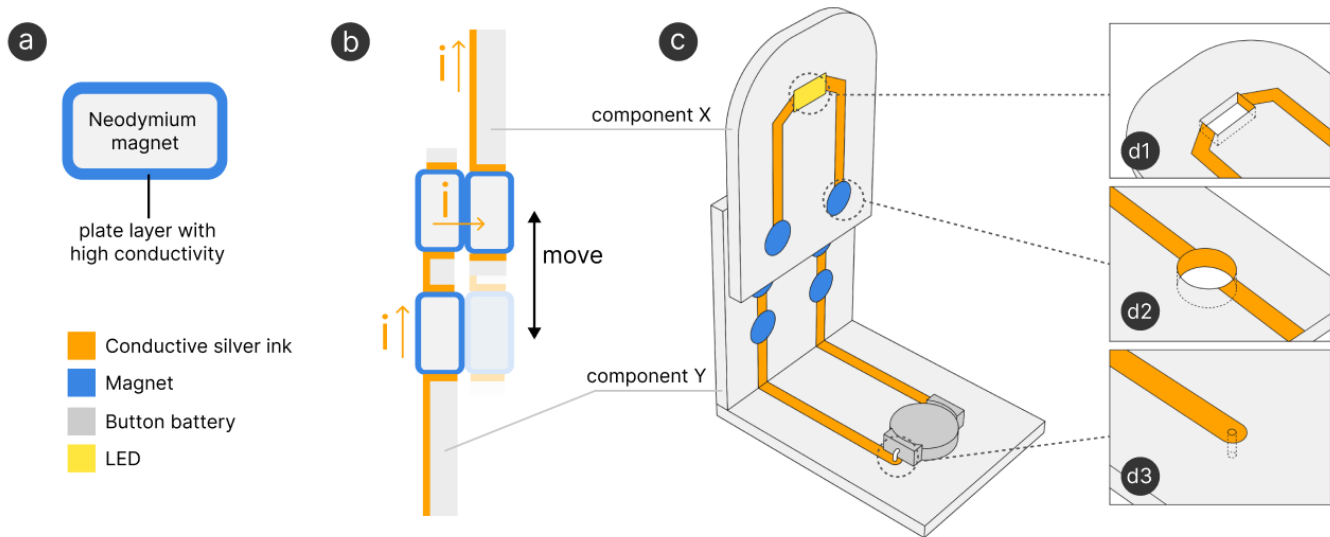


Figure 2: (a) Sectional view of neodymium magnet; (b) magnets connect electronic circuits; (c) an integration structure case; (d) three types of slots



Figure 3: A resistance test on neodymium magnets: we conducted several tests on 15 neodymium magnets with a diameter of 5mm and a thickness of 3mm, and the results showed that the resistance of the 15 neodymium magnets was 1.4Ω

motion structure), and iii) create a circle of magnets (corresponding to the finite rotation structure).

4.1.3 Apply Circuits Directly to Structures. After adding the electronic components and mechanical structure joints, users can connect generated slots to form specific circuits in our software (Figure 6c).

4.1.4 Generate and Export Laser Cutting File. After completing the design in the software, users can generate the laser cutting file. In this file, the cutting path for slots (which correspond to electronic components and mechanical structures) and the cutting

path for electronic circuits will be stored in two different layers. Dividing layers are used to set different laser cutting configurations. Specifically, the slot path (black lines) should be cut through the PMMA layer, while the circuit path (red lines) only needs to be cut through the paper membrane, which covers PMMA (see Figure 6d).

4.2 Laser Cutting

In this paper, we use a commercial laser cutting machine to cut commercially accessible PMMA (a 2.0mm thick transparent acrylic layer with the paper membrane covers on top). In detail, the laser cutting machine (RS-1390) is from HONG XIN LASER TECH. To achieve two different cutting requirements (slots path and circuits path) mentioned above, we use two cutting capacity configurations. For creating slots, we cut the PMMA board through (machine capacity 50%, the internal capacity of software 70%, cutting speed 100mm/s). While for producing the circuit paths, we use laser cutting engraving PMMA (machine capacity 50%, the internal capacity of software 10%, cutting speed 100mm/s).

4.3 Spray Conductive Silver Ink

After finishing laser cutting, users should remove PMMA in the slots and tear off the paper membrane of the circuit paths to get components (Figure 5c1). These components then should be sprayed with conductive silver ink. In specific, conductive ink should cover all the slot and circuit paths. Notably, to avoid the short circuit, slots of chip package electronics components should be half-covered in the middle with sticky tape before spraying. In this paper, we use commercial conductive silver ink (from Shenzhen Jingche Technology), which is easy to access. With the ink can bottom about 10 centimeters high from and 45 degrees to the PMMA, we spray back and forth two times for each spraying process. The sprayed conductive silver ink on the PMMA will solidify within about 15

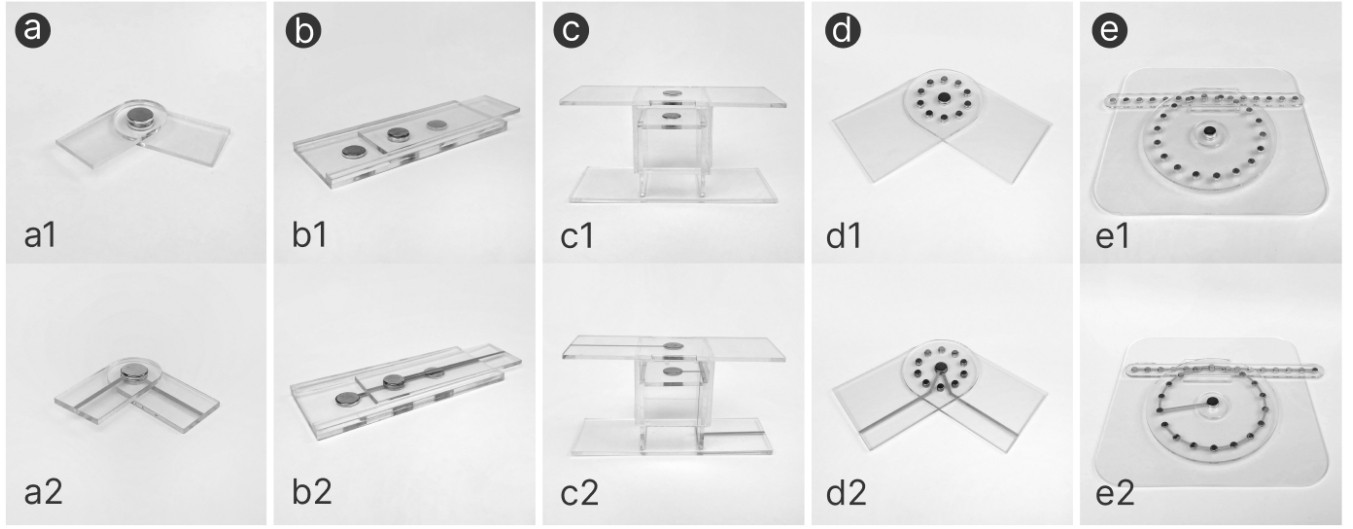


Figure 4: Basic mechanical structural units: (a) a1:infinite rotation structure; a2: infinite rotation structure with circuit; (b) b1:linear motion structure; b2:linear motion structure with circuit(c) c1:pressing structure; c2:pressing structure with circuit; (d) d1:Finite rotation structure; d2:Finite rotation structure with circuit; (e) e1:Rotation linear conversion structure; e2:Rotation linear conversion structure with circuit

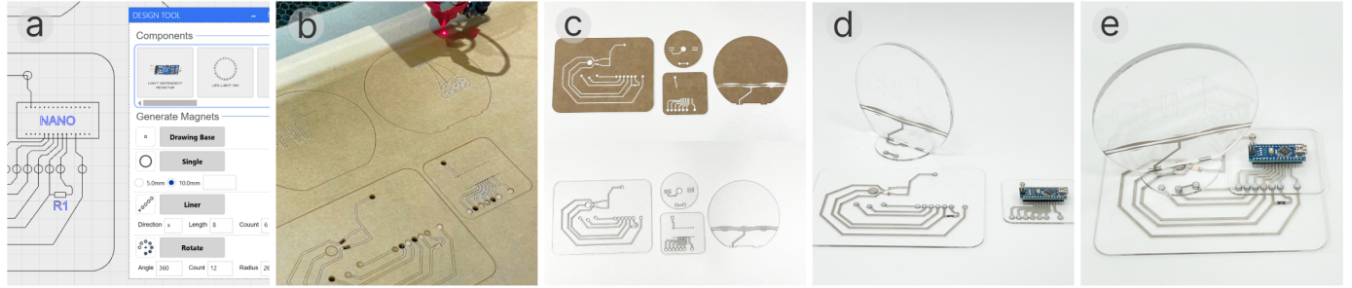


Figure 5: Example of MechCircuit pipeline: (a) design laser cutting sketch in our software; (b) cut out the components by using the laser cutting machine; (c) spray conductive silver ink on the components; (d) embed magnets and electronic components into the components; (e) snap and assemble all the components together

minutes at room temperature of 25°C. In the actual operation, we suggest using the blow dryer to accelerate the solidification process. With the dryer keep blowing back and forth at 50°C, the silver ink will solidify within 2 minutes. We assess this solidification method by repeating it 10 times and the results show that these conductive paths have the same performance as the air-solidifying one. To guarantee the stability of the circuits, we sprayed and solidify the silver ink three times (See 5.1 for the evaluation of different times), which takes about 8 minutes with the blow dryer. After completing the spraying operation, users can tear off the remaining paper membrane on the surface of the PMMA (Figure 5c).

4.4 Embedded Magnets and Electronic Components

After finishing spraying the ink, users should embed electronic components and magnets into the corresponding slots of the PMMA

board. As mentioned in Section 3.1, we design three types of slots for embedding magnets and different components (Figure 7a, b, c). To support magnet orientation, in the actual magnets embedding process, we hold magnets that stick together just like holding a pen, in which the magnets are in the same magnetic direction. Holding the magnet-made pen by the tip of it can help users guide into slots easily. Meanwhile, we suggest users embed electronic components first before magnets, for electronic components are easier to be attracted by magnetism than magnets. We embed the magnets into slots in the sequence from bottom to top and every magnet should be pressed tight before inserting the next one. In this paper, we use magnets with a thickness of 3mm, which is thicker than the PMMA board. By doing this, the magnet can protrude from the PMMA board surface, which enables two PMMA components to have direct contact. To guarantee this equal protrusion length of magnets, the table with the flat platform is used. Magnets are pressed from the top kerf side of the PMMA until they are against the flat platform

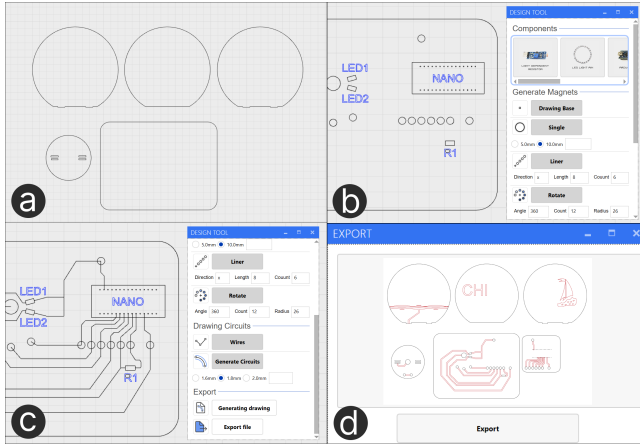


Figure 6: Design software process: (a) Import files; (b) add slots of electronic components and magnets; (c) apply circuits directly to structures; (d) generate and export laser cutting file

during the embedding process. Our practical operation suggests that, by doing this, scattered magnets (Figure 7a) as well as magnets in the row (Figure 7e) can be firmly touched to the corresponding PMMA boards after snapping.

4.5 Snapping and Assembling

Finally, users need to attach all the PMMA components together by magnetic attraction (Figure 7e). to form the final object. To assemble two mutually perpendicular PMMA components, a plug-in is used (Figure 7d).

5 EVALUATION

5.1 Evaluation of MECHCIRCUIT Performance

To determine the technical parameters of the pipeline, we deployed assessments as the reference for choosing the specific parameters of the conductive path and the slot compensation. Besides, to demonstrate the practical feasibility of our fabrication pipeline, we made the empirical evaluation of the MECHCIRCUIT performance, which consists of electrical connection quality and magnetically-connected structure stability. All of these evaluations were performed using the same materials and methods as described in section 4.2. The summary of the evaluations is shown in Table 1.

5.1.1 Determining Fabrication Details of Conductive Path. In this section, to determine the parameter of the conductive path, the path resistance with different spray times and different widths was assessed. For choosing the spray time, we produced thirty conductive paths that were 100 mm long and 2 mm wide. These paths were equally divided into six groups. Over different groups of paths, we spray conductive ink 1 to 6 times. After the ink solidified, we measure the resistance at the ends of each conductive path. As shown in Figure 8a, the average resistance of the conductive path decreased from 53.95 Ω to 3.2 Ω and stay stable. We finally chose to spray the conductive ink 3 times for creating the path, for the least manual operations while having low and stable resistance.

For determining the path width, we cut eleven paths with a width ranging from 1.0 mm to 3.0 mm and a length of 10 cm on a piece of PMMA (Figure 8b) and spray conductive ink three times on each path. We repeated creating the PMMA piece three times. Overall, these three samples showed the same result that the resistance of the path was negatively correlated with its width. In our pipeline, we chose 2.0 mm as the width for the paths being expected to have low resistance and small width.

5.1.2 Determining Compensation for Slots. For our pilot exploration of compensation, we used the force gauge to measure the force needed to push magnets and electronic components out of the slots. To acquire the compensation parameter for 10 mm diameter magnets, slots with diameters of 9.70 mm to 9.90 mm were cut on PMMA. Every 0.02 mm was set as one group and 11 groups in total, and each group had 10 samples. We first embedded the magnet through the top kerf side and flattened it on PMMA, then placed the PMMA board perpendicular to the ground. Then we used the force gauge to push the magnet till it popped out from the top kerf side, recording the peak of force from the beginning until the magnet was out. It should be noted that we pushed the magnet at the bottom kerf side for the force was smaller than pushing at the top kerf side. As shown in Figure 9, the force is positively correlated with the slot diameter and the average force separating the two magnets is 6.50 N (see details in Section 5.1.5). We expected the slot diameter enables magnets to be embedded easily as well as the force pushing the magnet out of the slots to be greater than the force separating the two magnets. After the evaluation, we finally chose 9.78 mm as the slot diameter. In addition, we deployed the same method to electronic components including chip resistance and LED to determine the compensation parameter, which was 0.22 mm too. In conclusion, the size of the slot was offset 0.11 mm for the corresponding magnets and electronic components. With our software, the compensation was considered and users did not need to modify the slot size manually. All the compensation parameters used in this paper were based on the specific laser cutting machine and PMMA material.

5.1.3 Quality of the Electrical Connection While Moving. To investigate whether the connection quality is independent of the mechanical movement, we tested the electric connection of the circuit for five basic mechanical-electronical function structures. As shown in Figure 10a, it is a frame with four infinitely rotating structures. The frame was embedded with a 3V battery and a chip LED to form a complete circuit. We repeatedly pushed and pulled on the frame, recording the voltage values at both ends of the LED every 1 second over 2 minutes in total. For the linear motion structure, the finite rotation structure, and the rotation linear conversion structure, we pushed the magnet once per second and recorded the voltage values. For the pressing structure, we pressed once per second and recorded the data at the same time. Each structure has 120 valid data. We analyzed the data of five basic mechanical-electronical function structures. The standard deviation was reported for each structure in Table 2. The results showed that the circuit remained stable during the movement of the structure.

5.1.4 Quality of the Electrical Connection for Slot Embedded with Magnets. To assess the electrical connection for slots embedded

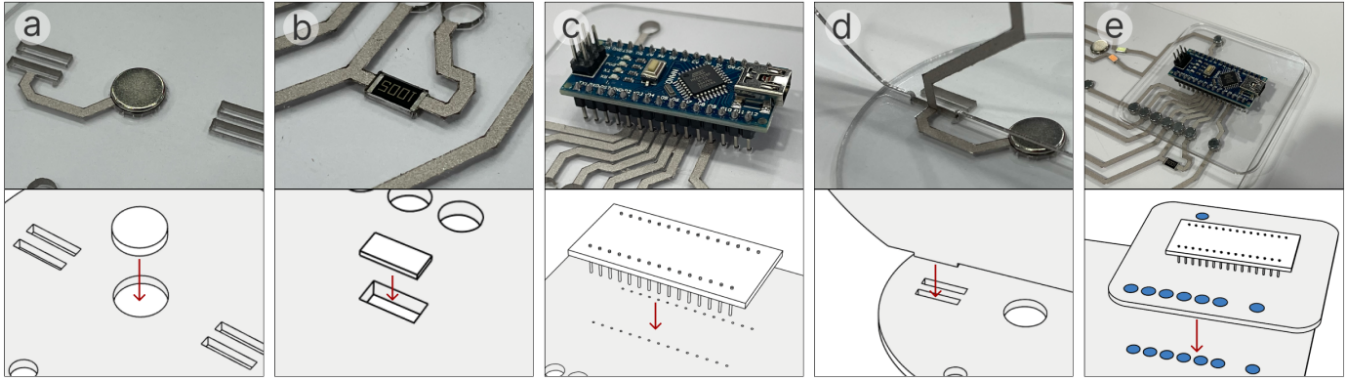


Figure 7: Fabrication details: (a) slots for magnets; (b) electronic chip slots; (c) electronic pin slots; (d) a plug-in is used to assemble two mutually perpendicular PMMA components; (e) assemble all the PMMA components together by magnetic attraction

Table 1: Evaluation Summary

Evaluation	Goals	Tasks
Determination of Technological Parameters	Determining fabrication details of conductive path	Measure resistances for different times of spraying and different widths of path.
	Determining compensation of slot	Measure the threshold force of pulling out magnets in different size of slots.
Evaluation of Practical Feasibility	Quality of the electrical connection while moving	Measure the voltage during the movement of five basic units.
	Quality of the electrical connection for slot embedded magnets	Measure the resistance of slots embedded with magnets after repeated use.
	Stability of magnetic-connected structures	Measurement of vertical and horizontal tension strength of magnetic-connected structures.

Table 2: Summary of the average value, standard deviation and range (maximal delta from mean) for the voltage of five basic mechanical-electronical function structures

Basic structures	M	SD	Range Δ
Infinite rotation structure	3.086	0.270	[-0.034 , 0.076]
Linear motion structure	3.103	0.067	[-0.097 , 0.103]
Pressing structure	3.052	0.069	[-0.148 , 0.082]
Finite rotation structure	3.038	0.082	[-0.182 , 0.088]
Rotation linear conversion structure	3.074	0.070	[-0.126 , 0.084]

with magnets, we produced PMMA components that were embedded with magnets (10 mm diameter) connected by a conductive path. We linked two PMMA components together to form a joint (Figure 10b). Firstly, we measure the resistance between point A and point B (value a), and point C and point D (value b). Secondly, we continuously rotated the joint for 3 seconds and then measured the resistance between point A and point D (value c). Finally, we subtracted value a and value b from value c to obtain the resistance of the joint, which is the sum of the resistance of two magnets and two slots. For one joint, we repeated the operation 20 times and calculated the average value, standard deviation, and range. Eight different joints were tested by the same method (Table 3). The

results showed that the resistance of one joint kept stable after repeated use. And the resistance of a joint averaged 0.67Ω (SD=0.04).

5.1.5 Stability of Magnetic-connected Structures. To validate the stability of the magnetic-connected structures, we conducted the tension tests on a pair of magnets. These tests demonstrated the force needed to separate a pair of magnets from the vertical direction and from the horizontal direction. For the vertical force measurement, we respectively attach two connected magnets to the force gauge and a platform. Then we separated these magnets steadily with the force gauge perpendicular to the platform. We repeat the separating process 10 times and the peak of the force

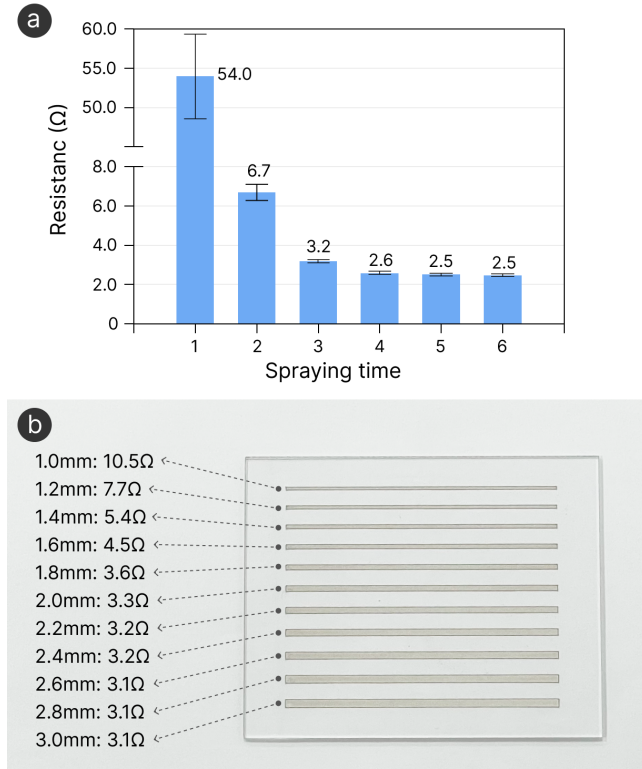


Figure 8: (a) resistances with different times of spraying; (b) resistances with different widths of path

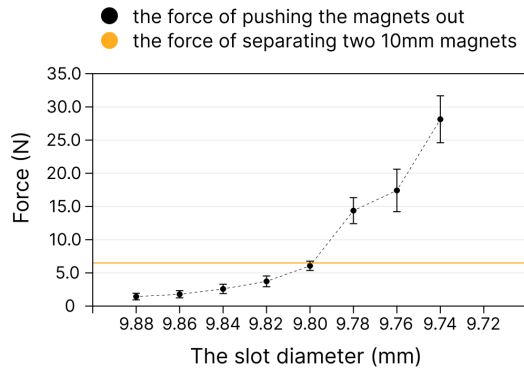


Figure 9: The relation between the slot diameter and the needed force for pushing the magnet out (for the magnet of 10 mm diameter)

of every process was recorded. The results suggested that for magnets of 10 mm diameter, the average peak force for separating was 6.50 N (SD=0.23), while for magnets of 5 mm diameter was 2.33 N (SD=0.08). For the horizontal direction, similarly, the two connected magnets were attached to the force gauge and the platform. And in this measurement, we took apart these two magnets steadily with the force gauge parallel to the platform and repeated the measuring

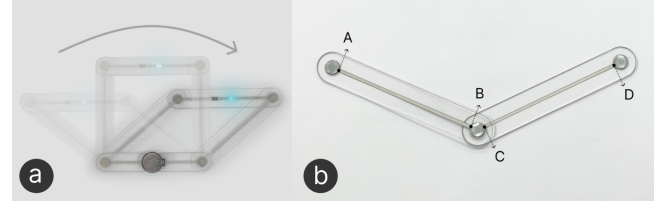


Figure 10: (a) The test of the Infinite rotation structure; (b) the joint formed by two PMMA components

Table 3: Summary of the average value, standard deviation and range (maximal delta from mean) for resistance of slot embedded with magnet

Joint ID	M	SD	RangeΔ
1	0.71	0.05	[-0.11 , 0.09]
2	0.70	0.06	[-0.10 , 0.10]
3	0.61	0.05	[-0.11 , 0.09]
4	0.65	0.05	[-0.05 , 0.05]
5	0.64	0.07	[-0.04 , 0.16]
6	0.62	0.04	[-0.02 , 0.08]
7	0.67	0.05	[-0.07 , 0.03]
8	0.72	0.07	[-0.12 , 0.08]

process 10 times. The results demonstrated that for magnets of 10 mm diameter, the average force for separating was 3.10 N (SD=0.04) and for magnets of 5 mm diameter was 1.14 N (SD=0.02).

5.2 User Study

In this section, we aim at exploring our novel prototyping method to allow designers to incorporate the solution of electronics bonded to mechanical structures into their designs. To evaluate how MECH-CIRCUIT meets our objectives in practice, we held a workshop focusing on the designers' experience of using the pipeline and their perceptions of the method.

5.2.1 Participants and Procedure. When we were satisfied with the stability and usability of our pipeline, we deployed it in the context of a workshop. The two-day long workshop, which was held in the art department of a large public university, required participants to have knowledge of electronics and mechanics (e.g. have attended relevant courses or have at least one operational experience) but are not experts. Through offline recruitment and selection, eight (3 female, 5 male) Masters in Design participated in the workshop. As shown in Table 4, they had an average of 4 years (SD=1.32) of experience in product design and had various degrees of electronic knowledge, mechanical knowledge, and laser cutting knowledge.

The workshop is divided into two sessions and lasts for two days. Students are told to work in pairs to design and fabricate an interactive device by our pipelines (Group information is shown in Table 4.).

In the first session, we first organized an information meeting, present ourselves and explain to them the project goals and the procedure. We then showed our fabrication pipeline and made an example of the rotatable-switch-controlled lamps used for the

Table 4: Demographics of workshop participants. Novice: do not know much about knowledge and have not much operational experience. Advanced Beginner: know a little about knowledge and have little operational experience. Competent: know much about knowledge and have much operational experience.

ID	Gender	Product Design Experience	Electronic Knowledge	Mechanical Knowledge	Laser Cutting Knowledge	Group
P1	Female	5 years	Novice	Novice	Advanced Beginner	Group 1
P2	Male	5 years	Novice	Novice	Advanced Beginner	Group 1
P3	Male	5 years	Competent	Advanced Beginner	Competent	Group 2
P4	Male	2 years	Novice	Novice	Novice	Group 2
P5	Female	3 years	Advanced Beginner	Novice	Advanced Beginner	Group 3
P6	Male	2 years	Competent	Advanced Beginner	Novice	Group 3
P7	Female	5 years	Novice	Novice	Advanced Beginner	Group 4
P8	Male	5 years	Competent	Advanced Beginner	Advanced Beginner	Group 4

demonstration. Finally, we discussed with the students to make sure they all understood the process.

The design brief of the second session required students to build prototypes using Arduino control boards, sensors, conductive silver ink, and PMMA board. Prototype devices need to have interactive inputs (e.g. touch, voice control) and interactive outputs (e.g. lights, movement). There is no design theme and students are allowed to create freely. If they have any questions during the fabrication process they can get help from the researchers aside. Two researchers observed and record the difficulties students meet. Individual students documented projects with photographs and notes which were shared with the research team. At the end of this session, students filled out a questionnaire reporting on their experience with workflow. Subsequently, a one-to-one semi-structured interview was conducted with the students, in which we asked them mainly about their attitudes towards the novel pipeline, the scenarios in which they might use it, and their expectations of it.

5.2.2 Design Cases. We present four design cases, the first of which was used in the first session to present an example of our fabrication pipeline, and the next three are the outputs of the designers participating in the workshop.

Rotatable-Switch-Controlled Lamp. We used pipeline to create a rotatable-switch-controlled lamp to demonstrate to the students in the first session. The lamp consists of three parts: the Arduino expansion board, the base, and the PMMA stand. The Arduino expansion board and the base are wired together with magnets (Figure 11a). The base has a two-way switch, a chip resistor, and two chip LEDs with two different colors. The PMMA stand is engraved with a pattern, where the wave pattern is sprayed with conductive ink (Figure 11b). The conductive pattern and the chip resistor form a capacitive sensor. When the user touches the wave pattern on the PMMA stand, the LED lights up. In addition, the two-way switch offers two choice of LED determined by the position of the attached magnets: when the PMMA stand is rotated to the left, the pink LED will light up (Figure 11c), and when it is rotated to the right, the blue LED will light up (Figure 11d).

Star Button. The first group of students is novices in electronic circuits. They designed a button with simple circuits inspired by the pressed structures we provided (Figure 12). This button has two pairs of magnets on both sides with attractions. When the

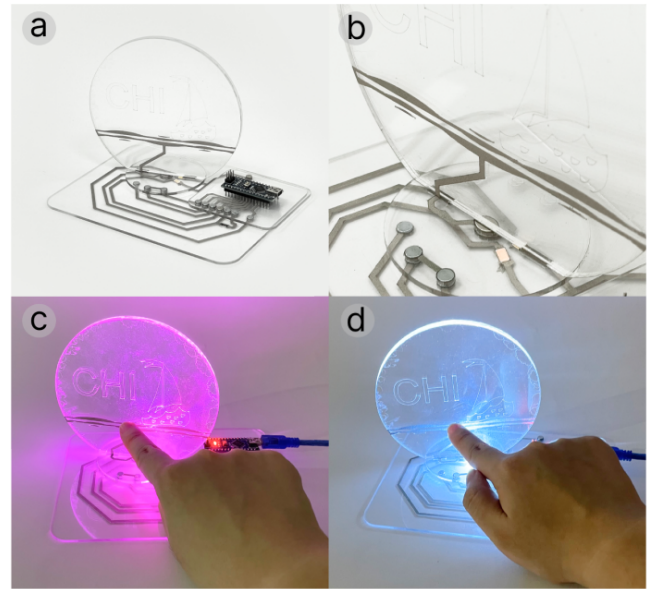


Figure 11: (a) Rotatable-switch-controlled lamps; (b) the wave pattern is a capacitive sensor; (c) on one side the pink LED will light up; (d) on the other side the blue LED will light up

user presses it and release the hand, the button will back to its original state because of the attraction. The device is powered by a battery and has a chip LED. They designed the circuit in the shape of a cloud and put a star inside the button. When pressing the star button, the two repulsive magnets touch each other, and a chip LED is connected to light up.

Walking Robot. Since mechanical structures are provided in our concept, these structures could be used to transmit the movement of the motor, which has the potential to build robot prototypes. Here, group 2 demonstrated a walking robot that chases the proximate hand (Figure 13a). This robot used a step motor to shift its gravity center, enabling itself to move forward. They used the basic structure of infinite rotation to accomplish the movement of the robot. Combining chip resistors, they sprayed two big electrodes to detect the proximity of the hand (Figure 13b). Two electrodes

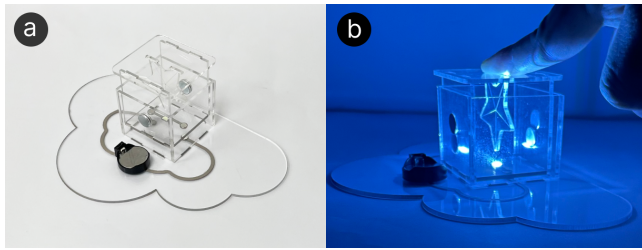


Figure 12: (a) Star Button; (b) the light on when pressing the button

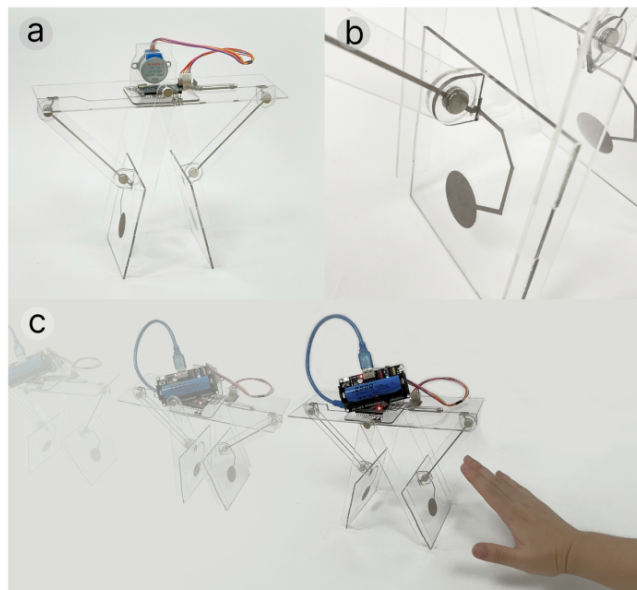


Figure 13: (a) Walking Robot; (b) capacitive sensors on foot; (c) the robot would walk towards the hand

were on the two sides of the robot respectively. When one hand approaches one side, the robot would walk towards it until this hand disappears or gets out of detective distance (Figure 13c).

This example shows how MECHCIRCUIT could serve as one low-cost prototyping way for creating mechanical motion robots. Meanwhile, compared with installing conventional revolving shafts, MECHCIRCUIT could integrate magnets into PMMA boards by laser cutting, which reduces weight and lowers producing cost of the robot prototype.

Liftable Table Lamp. Students in the group 3 designed a lamp with a discontinuous rotation structure and Linear structure (Figure 14a). The light was composed of two parts: base, slide switch column, and switch cover. The slide switch column was stacked with multiple layers of PMMA boards; the switch cover was a discontinuous rotating structure consisting of two layers of PMMA boards with LEDs and batteries. In addition, the switch cover and the slide switch column compose a linear structure that could move up and down. This interactive lamp has two adjustment modes. First, the user could slide the switch cover on the slide switch column to

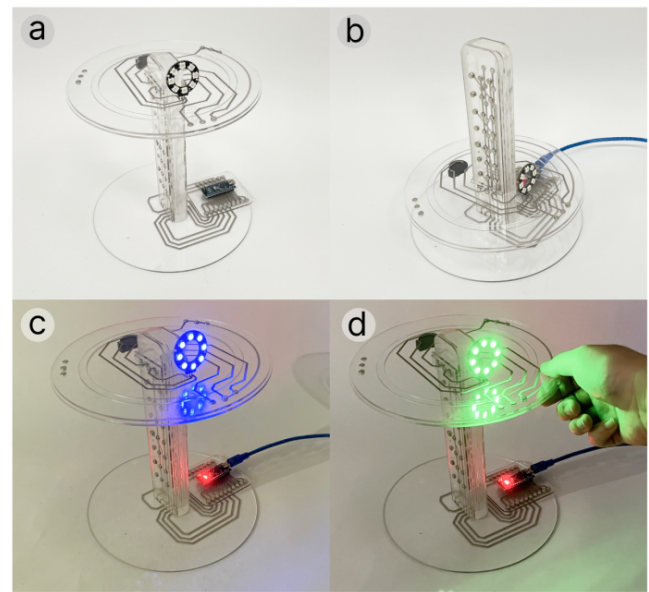


Figure 14: (a) Liftable Table Lamp; (b) the light is turned off when the switch cover slides to the bottom; (c) move the switch cover upward can turn on the light; (d) rotate the switch cover to control the color of the light

control the brightness of the light. The light is turned off when the switch cover slides to the bottom (Figure 14b); it is the brightest at the top (Figure 14c). Last, the user could also rotate the switch cover to control the color of the light (Figure 14d). The Arduino board, LEDs, and batteries were attached to the lamp by magnets, allowing easily replaced components if needed, changing a switch cover with a different shape.

Piano. Group 4 prototyped an interactive piano using seven press structures (Figure 15a). By assembling two repulsive magnets on the bottom of the keys and the base to build an automatic rebound press structure, which can simulate the movement modes and press feedback of piano keys. Continuous rotation structures were used for the joint part of these seven keys. The control panel monitored the status of each key (Figure 15b). When the user presses the button, the two repulsive magnets touch each other, at this time the circuit is connected, and then the music is played (Figure 15c). This electronic piano design case shows that MECHCIRCUIT can design and fabricate more interactive device prototypes by integrating rich inputs and outputs.

5.2.3 Designer Feedback. In this sub-section, we report the observation of researchers and the feedback of students on the pipeline. Next, we report our observations from three aspects.

Insights from Novice. When designing cases, we observed that our basic mechanical structural units were useful to users who were novices in mechanical and electrical structures. They regarded units as templates and added these mechanical-electronic structures quickly to their design sketches. This inspired us to extend more

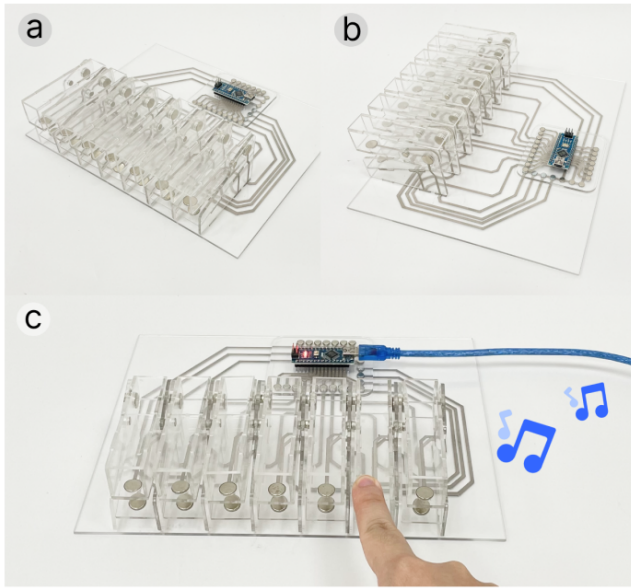


Figure 15: (a) Frontal view of piano; (b) rear view of piano; (c) presses the button and the music is played

units to suit the diverse needs of designers in the future. The participant who was not familiar with laser cutting (P6) mentioned the software function of exporting files for the laser cutting machine was helpful. He said: “I can focus on my structures and circuits.” A novice (P1) operated incorrectly when spraying conductive silver ink. She sprayed vertically, which caused the PMMA to be covered with too much conductive silver ink, but this had little effect on the usability of the final product. With our pipeline, novices of electrical circuits tended to take the conductive ink path as an important part of the product form. P1 said: “I care about the aesthetics of the circuit, it is exposed on the surface, so that is part of my design.” But novices of circuits were more likely to encounter difficulties in electrical connection. For example, P7 repeatedly discussed the electrical current with her partner to check the circuit connection. We believe that automatic circuit generation and circuit error reporting functions should be added to the software to support novice circuit designers in the future.

Efficiency. When using the software, more than half of the participants gave positive feedback on automatic slot generation, which can help users create magnet-involved circuits more efficiently. P6 said: “The corresponding slots will emerge after I place the electronic components, this is great.” MECHCIRCUIT relieved the consideration of movable components holding structures, which may require modeling and 3D printing. Specifically, P6 said: “We don’t have to think how to integrate mechanical structures into the prototype form, because they are already part of it.” With our method of holding connected magnets like a pen, participants can guide magnets into slots easily without confusing the magnet orientation. But when shifting to another PMMA board, some participants (P1, P4, P5) mentioned that they need to think about the orientation

for a second. In addition, we found that after completing their designs, students in group 2 and group 4 compared the electronic circuits in the software with their design sketches to ensure that there were no discrepancies. Similarly, P3 suggested developing a 3D view instead of the current wireframe in the software, which would make the circuit and structure design clearer. One student (P4) reported difficulty in tearing the paper membrane off. But it should be noted that tearing paper was much easier after using a blow dryer, for the membrane stickiness will decrease after being heated. In general, they can successfully distinguish between the different poles by attraction and repulsion. For the convenience of designers, it is necessary to mark the magnetic poles in the future.

Attitude towards the pipeline. Students reported almost no difficulties understanding the pipeline. All students were able to implement their design ideas and thought the method was quick to fabricate prototypes. Almost all students found mechanism and circuit design in MECHCIRCUIT easier than traditional methods, especially when producing mechanical structures with movable parts. For example, P8 said: “This method is an ‘upgrade’ and it is better and more fun than the previous method.” Similarly, P1 described this approach as like playing block toy. The majority of students were willing to utilize this method to make prototypes again. Students also commented that this integrated fabrication method allowed them to consider both the circuit and structure in the immersion and ideation stages of their design work, which inspired them to fabricate interactive devices new or different.

6 DISCUSSION, LIMITATION AND FUTURE WORK

While MECHCIRCUIT integrates electronic circuits, mechanical structures, and magnets in interactive laser-cut objects, it currently has limitations that must be considered in the fabrication process. As follows, we discuss these limitations and provide possible future solutions. Meanwhile, we give an outlook on the potential of MECHCIRCUIT as a new design and fabrication technique.

6.1 Magnets Integration in Prototype

In this paper, magnets are used to make multiple components attached together. The magnetic connection makes MECHCIRCUIT detachable and replaceable. Take the Rotatable-Switch-Controlled Lamp in 5.2.2 as an example, the patterned lamp is magnetically attached to the base, which enables users to replace the lamp part with another one without changing the base. Due to the magnetic connection, the MECHCIRCUIT prototype can be disassembled under heavy force, although all the cases provided in this paper have not been disassembled during movements. Since the connection strength relates to the magnetic force, magnets with greater magnetic force can be used to create prototypes that need greater load-bearing capacity. To attain greater force, the electromagnet is also a potential method, for the magnetism of the specific-size magnet can increase by raising the current. Additionally, the magnitude and presence of the magnetic force of the electromagnet are controllable, which may enrich the interaction and mechanisms of prototypes.

MECHCIRCUIT incorporates magnets into mechanical structures as well as electronic circuits. On the one hand, compared to separately using traditional mechanical and electronic parts, MECHCIRCUIT integrates form with functions. Take Lifiable Table Lamp in the 5.2 section as an example, the structure of the slide switch column serves as the form of the lamp. At the same time, this column functions as the switch for brightness control. On the other hand, magnets have the potential to enrich interactions in the mechanisms. In the future, by distributing magnets of different forces [32], MECHCIRCUIT could further provide haptic feedback in mechanical structures like sliding and rotating.

6.2 Electronic Circuit Path Connection and Power Efficiency

In this paper, MECHCIRCUIT uses magnets and conductive silver ink to produce electronic circuit paths to connect electronic components. Magnets conveniently connect the circuit and the mechanical structure by magnetic attraction, and the sprayed conductive silver ink replaces the traditional wire. This magnetic connection method relieves complicated operations such as gluing and soldering. However, magnets and conductive silver ink also put forward new requirements for circuit connection stability and power use efficiency.

In our circuit paths, magnets and electronic components are fixed tight with the slot compensation. In this paper, we make an evaluation to determine the specific compensation parameter. However, the compensation parameter will need to be adjusted when using different thickness layers or materials. Previous researches suggest that scalable structures like the spring can be produced with 2D laser cutting configurations [55]. To support a larger range of compensation, in the future, we expect to create some scalable structures around the slots to fix magnets and electronic components.

Meanwhile, we spray silver ink to produce the conductive circuit paths. Compared with traditional copper wire, these circuit paths have higher resistance. Notably, our evaluation demonstrates that the resistance of the circuit path is small (100mm length and 2mm width about 3 ohms). This resistance has limited influence on applying analog sensors like temperature sensors to the low-power project (e.g. using Arduino to supply power) with our pipeline, for these sensors are not required to have great precision in creating product prototypes. However, the circuit resistance limits the use of higher-power appliances and dissipates more heat than traditional electronic circuits. In the future, we can explore conductive ink with lower resistance or use copper tape with laser cutting to reduce power loss.

In addition, the magnets and the sprayed circuit paths are directly exposed, which has potential risks in the higher-power equipment. To prevent exposed conductive circuits from being touched or accidentally short-circuited, covering the outmost layer of these circuits with an extra PMMA board could be a further solution [14].

6.3 Prototyping process with manual operations

With laser cutting technology, our fabrication pipeline can be used to produce interactive prototypes and fulfill the design iteration. To

reduce prototyping costs, our pipeline is a semi-automatic and semi-manual process, employing common materials like magnets and PMMA and the commercial laser cutting machine, and requiring spraying conductive paths. A future augmented laser-cutting device could further reduce handcrafting steps, researchers leverage fabrication devices to apply silver ink and place different components [31]. Specifically, we could use laser cutting to coat the PMMA with silver ink and then burn the paper membrane of the PMMA. In addition, components are magnetically connected to build these prototypes. This magnetic connection enables users to manually assemble and replace specific parts easily. In the user study, one group of participants (P5, P6) found the lamp base component was not big enough to bear the column and the cover, so they replace the base after assembling the lamp.

7 CONCLUSION

This paper has presented MECHCIRCUIT, a design and fabrication pipeline that utilizes the neodymium magnet's natures of magnetism and conductivity to achieve mechanical-electronical functions in laser-cutting interactive prototypes. We further deploy a series of evaluations to determine the technical parameters and demonstrate the practical feasibility of our fabrication pipeline. Besides, we organize a workshop with 8 participants to confirm the creative utility of interactive prototypes.

We are convinced that MECHCIRCUIT can help users create prototypes with mechanical structures and electronic circuits using simple materials like PMMA, magnets, and silver ink. Meanwhile, our pipeline relieves complex operations such as wiring and soldering and makes the connection easier and replaceable. Furthermore, we expect that MECHCIRCUIT can be used in the product design iteration for a wide audience using the standard laser cutting technology.

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