Duco: Autonomous Large-Scale Direct-Circuit-Writing (DCW) on Vertical Everyday Surfaces Using A Scalable Hanging Plotter

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Human environments are filled with large open spaces that are separated by structures like walls, facades, glass windows, etc. Most often, these structures are largely passive offering little to no interactivity. In this paper, we present Duco, a large-scale electronics fabrication robot that enables room-scale & building-scale circuitry to add interactivity to vertical everyday surfaces. Duco negates the need for any human intervention by leveraging a hanging robotic system that automatically sketches multi-layered circuity to enable novel large-scale interfaces. The key idea behind Duco is that it achieves single-layer or multi-layer circuit fabrication on 2D surfaces as well as 2D cutouts that can be assembled into 3D objects by loading various functional inks (*e.g.*, conductive, dielectric, or cleaning) to the wall-hanging drawing robot, as well as employing an optional laser cutting head as a cutting tool. Our technical evaluation shows that Duco's mechanical system works reliably on various surface materials with a wide range of roughness and surface morphologies. The system achieves superior mechanical tolerances (0.1mm XY axis resolution and 1mm smallest feature size). We demonstrate our system with five application examples, including an interactive piano, an IoT coffee maker controller, an FM energy-harvester printed on a large glass window, a human-scale touch sensor and a 3D interactive lamp.

CCS Concepts: • **Human-centered computing → Ubiquitous and mobile computing systems and tools**.

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1 INTRODUCTION

To date, advances in fabrication methods for electronics have emphasized packing the most functionality into the smallest form factors. Such optimizations have paved the way for the fabrication of devices with increasing complexity and diversity of form factors (*e.g.,* mobile phones, activity trackers, etc.). However, little has been done to enable the digital fabrication of electronics with large surface areas. On the other hand, large vertical surfaces are ubiquitous and abundant in our daily lives (*e.g.,* walls, windows, fences), functioning mainly as space dividers or infrastructure coverage. They exist everywhere and take up substantial spaces, yet are used mostly for structural purposes without interactivity. Many interactive art installations and research projects [50, 62, 67] have recently attracted great attention by demonstrating practical uses for adding additional functional layers with arbitrary designs by taking advantage of these existing large and vertical surfaces.

Existing circuit fabrication methodologies, such as printed electronics (*e.g.,* inkjet printing, 3D printing, etc.), have demonstrated the advantages of providing low cost, highly accessible digital electronic fabrication methods. We have seen advances that increase the level of customization in the printed electronic process [54], serve a broader spectrum of users [6], and extend the number of everyday surfaces and objects to which printed electronics can be applied [12]. Notably, *Inkjet-printed circuits* pioneered an easy, fast, and cheap digital fabrication method for prototyping functional electronic devices [22]. In addition, many other inkjet-based advances have resulted in a wider variety of sensors [11], displays [39] and other interactive objects [38].

However, there are no such digital fabrication tools to prototype large-scale circuits. Among the current systems for fabricating large-scale circuits, the challenge lies in the need for human efforts (*e.g.,* preparing and aligning stencils, manually painting or spraying the functional materials, removing the stencils), making it laborious and extremely difficult for large-scale fabrication (*e.g.,* large amount of human efforts and time, material waste left on stencils, non-reusable stencils for different designs, poor manual consistency and repeatability of circuits) [62, 67]. It is also noteworthy that even to prepare the stencils, most of the existing machines are still taking up much of the plane space (*e.g.,* CNC routers used in [50], laser cutters used in [62]). The vertical spaces have not made the best use as direct fabrication workspaces so far.

To advance the field of recasting large-scale everyday vertical surfaces as smart surfaces which can be highly beneficial to the three previously identified circuit fabrication domains relying on large surface areas (*e.g.,* human-scale sensing, energy harvesting, 3D interactive artifact), a digital fabrication system that can meet the following four criteria is needed: 1) to greatly reduce the amount of human intervention required during the fabrication process without requiring any stencils, 2) exhibit superior circuit fabrication performance by paying attention to resolution, accuracy, repeatability, 3) support circuit fabrication with a diverse selection of tools on versatile vertical everyday surfaces and 4) take advantage of utilizing vertical spaces as main fabrication sites.

With these considerations, we propose Duco, a direct circuit writing (DCW) system for creating high-fidelity large-scale electronics. Duco supports three types of tools: a drawing pen/brush equipped with conductive, dielectric, and cleaning inks to additively draw circuits on top of the vertical surfaces, a laser cutting head for subtractively making 2D cutouts on large surfaces, and a UV LED head to automatically cure inks that are printed. Duco is able to effortlessly switch between different inks using a custom rotary tool changing mechanism.

To validate the proposed system for circuit fabrication on versatile substrates with a wide range of visual and surface features (*e.g.,* surface roughness, topology), we demonstrate applying Duco to six vertical everyday surfaces (wall paint, wall paper, wood, glass, acrylic, and ceramic). Duco enables the DCW method to fabricate circuits directly onto target vertical surfaces, eliminating the need for manual transfer or pasting steps. The main contributions of this paper are:

- the hardware design (mechanical and electrical design) of the Duco system;
- a comprehensive tool library including a pen/brush with three compatible inks (conductive, dielectric, and erasing) to draw functional circuits and a laser cutting head to make 2D cutouts;
- a custom interface to design and guide the fabrication process of Duco;
- a detailed online repository showcasing Duco's design, assembly and operation to extend its accessibility and replicability;
- five illustrative application examples to demonstrate how the Duco system can be used to create large-scale interactive surfaces.

Table 1. Comparison of different electronics fabrication methods.

Fabrication Methods	Scale (> A4)	Human Intervention (<1 hr)	No Stencils/Mold	No E-waste	Multi-material
Silicon casting [33,60,63]	✗	✗	✗	✓	✓
Screen printing [28,36,61,64,66]	✗	✗	✗	✗	✓
Chemical etching [14]	✗	✗	✓	✗	✗
3D printing [47,51,57]	✗	✓	✓	✓	✓
Inkjet printing [6,22,24,38]	✗	✓	✓	✓	✓
Aerosol spraying [62,67]	✓	✗	✗	✓	✗
Hand drawing [44,46]	✓	✗	✓	✓	✗
DUCO	✓	✓	✓	✓	✓

2 RELATED WORK

2.1 Fabrication Methods for Prototyping Electronics

Over the past few decades, HCI researchers have made extensive efforts for prototyping electronics. Some approaches demonstrate utilizing 3D printing [47, 51, 57], vinyl/laser cutting [13, 19, 29, 35, 65], or inkjet printing [6, 22, 24, 38]. Others bridge fabrication techniques including chemical etching [14], screen printing [28, 36, 61, 64, 66], silicon mold casting [33, 60, 63], spraying [62, 67], and free hand drawing [44, 46]. After thoroughly investigating the existing circuit manufacturing methods, we creted a comparison Table 1 to highlight several key benefits of the Duco system. While previous research has made great efforts to digitally fabricate circuits, our work is utilizing an autonomous robotic system to develop circuits beyond the conventional scale and negate manual labor at the same time also paying attention to other key features, such as accuracy, waste of materials, and support wide range of surfaces.

Another group of studies relevant to our approach pertains to the field of printed electronics. One of the earliest examples is *Instant Inkjet Circuits* which introduces using commodity inkjet printers for rapid prototyping of functional devices [22]. Based on the accessibility and noble design spaces, researchers have applied this technique to fabricate various sensors [11, 23, 37, 54], antennas [27], displays [39], mobile device touch screen extensions [21], and actuators [38]. However, most of the prior work is limited in terms of printing substrate selections and printing dimensions. These two issues hinder the potential to deploy printed electronics onto a wider range of objects and scales. Recently, *Silver Tape* and *Soft Inkjet Circuits* have demonstrated techniques to print or transfer functional circuitry onto a variety of substrates, yet both are still limited by inkjet printer size [6, 24]. *ObjectSkin* presents a hydro-transfer method for relatively large electronic fabrication beyond inkjet printer size by using a bigger water tank for the transfer step [12]. However, the manual dipping step makes it challenging for an accurate and consistent layout of the printed pattern to be transferred, and the printing size of this method is still limited by the tank size. Our Duco system addresses the limitations of printing size and substrate selections by leveraging a hanging wall robot that moves the drawing platform along with multiple tools and substrates.

2.2 Large-scale Interactive Surfaces

An increasing number of works have demonstrated the fabrication of large-scale interactive surfaces. *Wall++* introduces a technique to construct a capacitive sensing wall by brushing conductive nickel paint onto the wall surfaces [67]. *Sprayable* demonstrates a spraying technique to prototype large-scale sensors and displays [62]. However, also discussed by these two pioneered works, current fabrication methods heavily involve human interventions for preparing, aligning and removing stencils. In addition to manual efforts, people will not only need extra tools to prepare stencils (*e.g.,* vinyl or laser cutters), they will also leave a large amount of material waste on stencils which is typically even more than the material needed for the circuit itself. The stencils will then need to be remade for each new design. These typical weaknesses for methods involving stencils are worsened when developing large-scale circuits with versatile designs. Similar to 3D or inkjet printers that negate most of the human effort after initial setup, we employ a robotic system to autonomously draw circuits directly onto the surfaces without the use of stencils for room-scale applications and beyond.

2.3 Drawing Platforms for Vertical Surfaces

Several industrial manufacturing machines provide autonomous large-scale circuit fabrication with high resolution, but they are expensive, bulky and can not directly fabricate computational circuits on existing surfaces [20]. While not originally designed for circuit fabrication, when we thoroughly investigated the existing digital fabrication tools that can directly fabricate large-scale circuits on targeting surfaces, some drawing machines show similar design criteria. Popular examples include *JEDAR* [16], *WallPen* [56] and *Botsy* [4]; however, all these machines are still bound to the axes dimension with quite expensive machine cost (*e.g.,* WallPen E1 for over $30000, Botsy for $2500). *Scribit* [7] and a DIY example *Polargraph* [41] are less expensive and compact machines which can facilitate drawing on a scalable area based on a mechanism using flexible timing belts to guide the movement. Also, there are different types of wall-climbing robots [18, 25, 32, 43], but none of these machines are designed to fabricate circuits. Our work has taken inspiration from these machines while adding more hardware and software functionality to deploy the machines for the purpose of circuit drawing.

3 DUCO WORKFLOW OVERVIEW

Our system for large-scale circuit drawing involves five steps: (1) sketching a circuit pattern, (2) setting up the system, (3) selecting tools and substrates, (4) drawing the pattern by operating the system, and (5) wiring up the circuits.

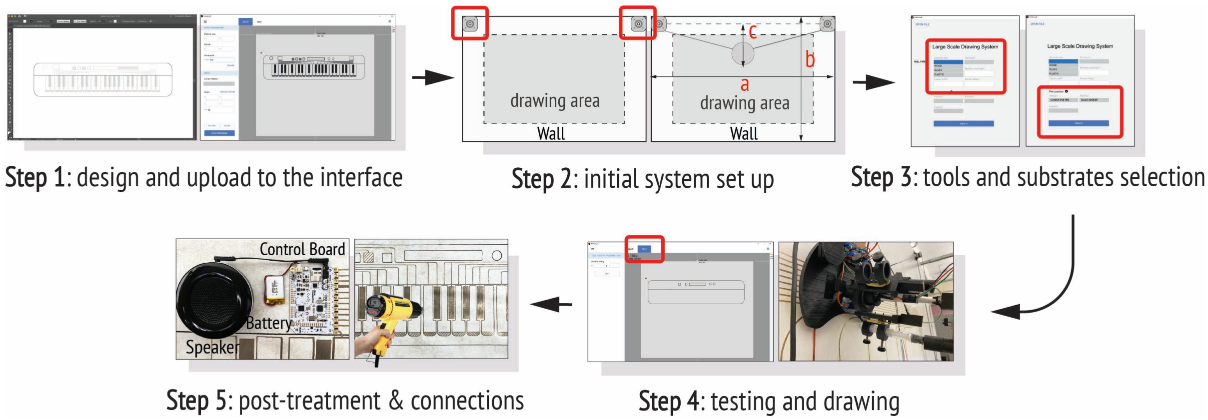

Fig. 1. Demonstration of the fabrication pipeline from designing the pattern, defining the drawing parameters, selecting tools and substrates, to setting up the hardware system, and finishing up the drawing tasks.

3.1 Creating the Digital Design

The first step for drawing a functional circuit is to develop the circuit graphic design. Any 2D vector graphic design software, such as Adobe Illustrator or Sketch can be utilized for this step. We can also use professional circuit design software (*e.g.,* KiCad), which allows users to export each circuit design layer as separate SVG files. Once the circuit design is completed, users can uploaded it to our interface. Our user interface can also automatically identify a solid pattern (*e.g.,* square, rectangular pattern), where users can self-define the drawing tool width in our interface, so the solid pattern will get filled up automatically. To prepare design files for multi-layer circuit fabrication, a user can export each layer as a separate SVG file while keep the same drawing location on canvas.

3.2 Initial System Setup

After exporting the graphic patterns, the next step is to set up the system. The anchors with stepper motors are supposed to be fixed onto the drawing substrate. Then, dimensional parameters need to be collected, labeled as a, b and c in Figure 1 step 2, given that they are required by the interface. For the next step, selected tools will need to be mounted on the central platform.

3.3 Drawing Tools and Substrate Selection

Our system provides three options for tools: (1) a drawing pen/brush, loaded with conductive, dielectric, or cleaning inks, (2) a laser cutting head as the cutting tool that can make 2D cutouts, and (3) a UV LED head to automatically cure the inks. For the substrate selection, users are allowed to select one substrate from our library. Each substrate is tested and encoded with its optimal operating parameters.

3.4 Preliminary System Testings and Drawing

Once the tools and the target substrate are selected, a series of preliminary tests should be conducted to ensure the system performs correctly. First, a drawing position test will be executed, where users are requested to move the drawing tool to a specific location on canvas. Second, a tool pressure test is recommended to achieve the optimal pressure for the drawing tools. Additionally, if a multi-layer task is specified, tool switching mechanisms will also be tested after which the drawing is ready to start and will finish with no labor involved.

3.5 Connection and Post-process

Finally, after the drawing task is completed, we need to cure the inks before connecting the electronic components. The sintering process for the Dycotec DM-SIJ-3200 [30] silver nanoparticle ink requires a temperature as low as 100°C, and the curing process for the NEA 121 [42] dielectric ink takes only 30s under ultraviolet light. Users can also implement one of the three connection methods for mounting electronic components: conductive paste (Bare Paint [40]) and conductive epoxy adhesive (MG Chemicals 8331 [9]) for permanent and robust connections and liquid metal (EGaIn) for temporary connections.

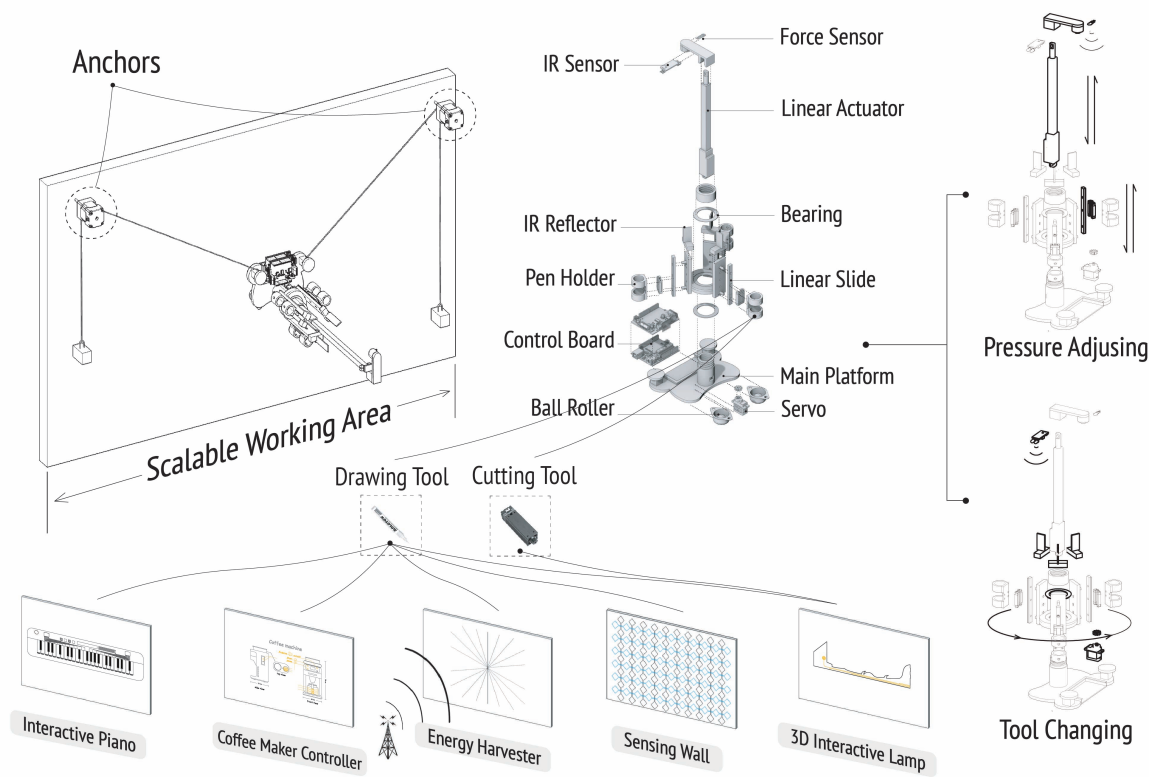

Fig. 2. Demonstration of the hardware design: Top-left: Overview of the system. Middle: The explosion view of the drawing platform. Top-right: Two highlighted functions designed for circuit fabrication. Bottom: Highlighting drawing tools and cutting tool with associated applications.

4 DUCO FABRICATION SYSTEM

4.1 Design Principles

Similar to most of the existing digital fabrication systems (*e.g.,* 3D printer, CNC router or inkjet printer), which do not require users' attention after the jobs have been uploaded to the system, for prototyping large-scale circuits, we take the negation of human efforts as the key feature to not only save the user's time, but also enable fabrication with much higher precision than manual labor while assuring user's safety for circuit deployment at vantage points that are difficult to reach (*e.g.,* bridge, building). Overall, in order to ensure our system for large-scale circuit fabrication with a high level of drawing performance on everyday surfaces, we set five criteria for hardware design.

(1) *A compact, autonomous system:* To enable large-scale circuit drawing with minimum human intervention, our system should be an autonomous platform that can support large and adjustable moving areas as well as maintain compactness to be easily set up.
(2) *Low-cost and easy to use:* To support a broad spectrum of users, we expect our system to be low-cost, made from off-the-shelf parts, and easy to use.
(3) *High-precision performance:* Drawing functional circuits requires precision. To prevent defects (*e.g.,* open circuits or shorts), we require the system movement to be smooth and precise.
(4) *Versatility of connecting tools and inks:* Drawing functional circuits also requires applying more than one ink (*e.g., conductive and dielectric*). Our system should be able to carry multiple tools and switch from one to another accurately to support multi-material deposition.
(5) *Robustness to support everyday surfaces:* To facilitate drawing circuits on a wide range of everyday surfaces, our system should be able to adjust itself to a variety of surface conditions including geometries and textures. This involves keeping the tool in proper contact with the substrate, and yields the need for constant contact control which requires a mechanism that is responsible for pressing the tools gently against rough surfaces or surfaces with complex geometries.

4.2 Hardware Design

As shown in Figure 2, our drawing platform is comprised of several mounting slots and a functional arm. Two anchors along with the stepper motors are together set on the target vertical drawing surface and connected to the central drawing platform. The system enables high motion resolution through the help of stepper motors which drive the GT2 timing belts to move the drawing platform. Weights are added to tighten the belts, but can also be replaced by a winder mechanism for a more compact system design. For the control board, an Arduino Uno is used to receive commands via the serial port from the user's PC.

We have also tested different moving modes for the system. By driving the system at a high speed (*e.g.,* higher than 20 cm/s), we can more rapidly prototype circuits. To achieve optimal resolution and quality for the circuits, we can enable microstepping mode, but this mode inevitably sacrifices operating time.

Tightened belts driven by stepper motors are enabling a stable and robust system design but are essentially constrained to move on a relatively fixed 2D plane because of the tension in the ropes, which makes it impractical and challenging to handle concave or convex textures. To facilitate the fabrication of circuits on versatile surfaces, we employ a combination of pressure sensor and linear actuator to actively adapt to surface changes on the target surface material. To further reduce the amount of human intervention, we also added a tool switching module to enable the possibility of using more than one ink or tool within a task.

It is also noteworthy that Duco is highly maker friendly: all components are either directly purchased or 3D printed by an FDM 3D printer. All the details are collected and further discussed in our online repository.

4.2.1 Inks and Tools: With the goal of fabricating circuits directly on target substrates, we have identified several existing tools that are suitable for our purposes: Inkjet-printing head, extruding nozzle, and commodity pens. After our investigation and also inspired by many existing circuitry drawing works [5, 46, 52], we selected our main drawing tool to be the commodity pen. We selected commodity pens based on the following five aspects: (1) The drawing tool needs to be low-cost. The heavily used pen in this work is a 4mm MOLOTOW painting marker [31] which is only $4.8 each. (2) These pens can be easily loaded with different functional inks. Also thanks to the low-cost manner of the empty marker, we can simply have a set of markers loaded with conductive, dielectric, erasing or even other functional inks. (3) Pens are light-weight. For our hanging system, adding too much weight onto the drawing platform can cause the platform to tilt or lean to one side. (4) It is easy to draw traces with different widths by utilizing different pen diameters. (5) It is simple to mount, replace, and control pens. Both inkjet printing head, and nozzle extruder require extra wiring and more complex control logic. Drawing pens only require a linear actuator to push the pen along a linear slide, and use a rubber band to constantly retract the pen back. Due to the above advantages, we chose pens as our tool of choice for fabricating large-scale circuits. We identified Dycotec DM-SIJ-3200 and NEA 121 as our conductive and dielectric inks. We also investigated several solvents that can be used as cleaning inks to correct or erase the circuits.

4.2.2 Tool Switch Mechanism: We build an automatic tool switching mechanism to further lower the need for human intervention. The stepper motors are locked to their positions during the tool switching. Both of these designs improve our drawing quality and accuracy.

Our automatic switching tool module design is highlighted in Figure 2. We fabricated a central carriage composed of three slots. Each slot is equipped with a linear slide and pen holder. This configuration can hold three different tools concurrently. If the number of concurrent tools required increases, it is possible to simply add more slots. The tool slots rotate in and out of the primary drawing position on command. To achieve this, the carriage rotates by using a continuous servo. The IR sensor will receive the reflected signal from the reflector that we mounted on the top of each slot and send the command to the controller to stop the platform at current position. We have also tested other low-cost sensor options, (*e.g.,* encoder, RGB sensor) and eventually chose IR sensor which allows the pen to rotate from an arbitrary angle, but we agree other sensors might also work.

4.2.3 Contact Force Sensing: Smooth circuit drawing on surfaces with different geometries and textures can be challenging. Adapting to these changes is necessary for drawing on a broad range of daily objects. We expect our system to be able to fulfill tasks smoothly and automatically even on surfaces with some roughness or various topology. Also, in order to ensure the drawing tool is held against the drawing surface with consistent force, a contact pressure control system is developed. The pressure control system is tuned to push the drawing pen against the target surface with proper amount of force which creates consistent trace drawings with precise width while preventing the tool from scratching or catching on the drawing surface.

Our implementation of the pressure control loop involves two simple components, a force sensitive resistor (FSR), and a linear actuator. The FSR detects the pressure of the pen applied against the drawing surface and transmits this data to the control board. The control board then commands the linear actuator to retract back or push forward the pen according to the detected pressure data.

In practice, deadlock may occur when a pressure range is not reachable. This situation implies the surface roughness or topology level is outside of the acceptable range. The platform performs reliable and quick contact feedback control when being operated on surfaces that fall within our calibrated range.

5 DUCO INTERFACE

To enable a smooth drawing workflow, we developed a user-friendly interface based on the Processing–open source integrated development environment. Our interface assists three tasks: hardware setup configuration, machine testing, and task running.

5.1 Basic Settings & Configuration

Users begin the machine configuration process by defining the dimensions for the machine movement (dark-grey area shown in Figure 3 a2) or the target drawing area (light-grey area shown in Figure 3 a2) in the text field. Our interface provides both options: users can self-define the size of a drawing area or use the default drawing area

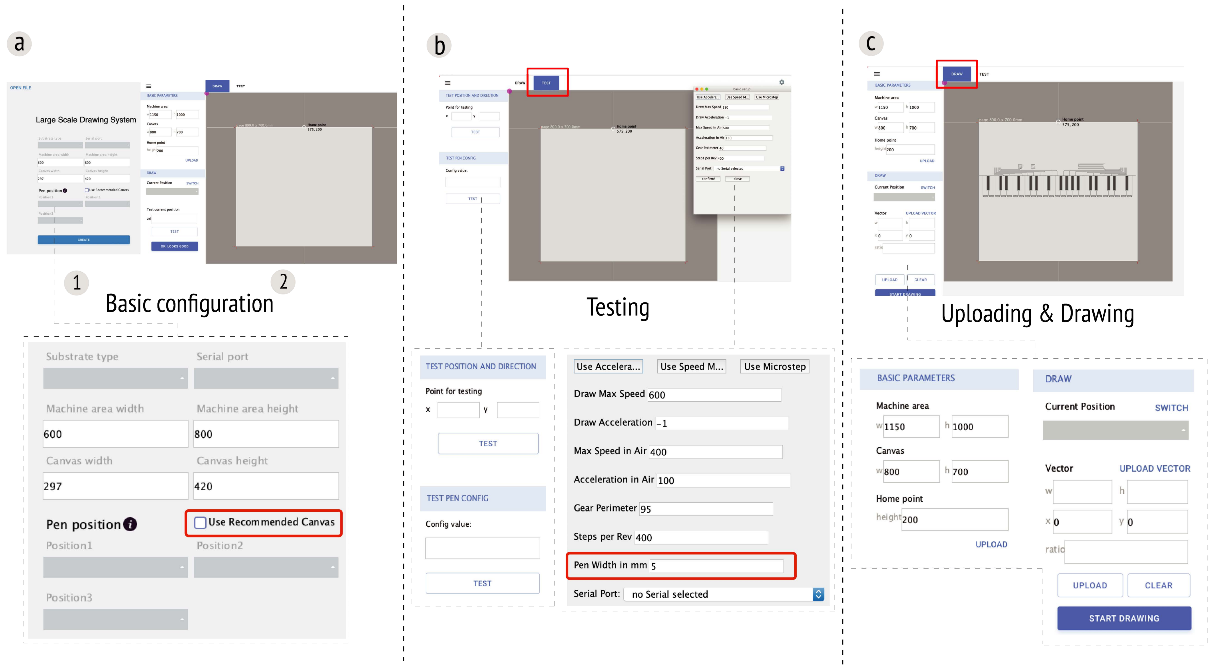

Fig. 3. User interface walkthrough: (a) enter the parameters for the machine setup and define the drawing area size; (b) test machine behaviors (e.g., switching a tool or changing the movement speed); and (c) upload a circuit design file and start operating the system.

recommended by the interface by clicking the checkbox highlighted in Figure 3 a in red. Once the dimensions are determined, users select which surface they will use for the task. We have provided a drawing substrates library that will generate default optimal parameters for several pre-defined substrates. Then, users move to the next panel to finalize the machine setup (Figure 3 a2) where users can adjust configuration parameters.

5.2 Tool & Motion Test

After completing the configuration step, users move to the test mode to conduct two preliminary tests (Figure 3 b). First, users choose which tool to use and rotate the system until the tool is positioned to the drawing spot. Then, users should adjust the selected tool to make sure it is under a proper pressure against the target substrate. Second, users need to test the machine movement, by either directly clicking on the canvas or entering the destination X & Y coordinates to test the movement.

5.3 Upload & Task Running

With the machine configuration and basic testing completed, the machine is ready to execute a task. Now, users need to upload a desired circuit pattern in a SVG format to the interface (Figure 3 c). Once the design file is uploaded, users can set drawing location either by directly dragging the file around on the canvas or entering its exact X & Y coordinates. Finally, users are ready to start the machine operation with the ability to stop or resume the drawing at any time.

5.4 Multi-layer Fabrication

To draw a multi-layered circuit, users need to ensure additional layers are placed at the exact same location as the base layer in the design file. When users upload files to the interface, new layers will be aligned with the base layer by default. In most cases, new layers will require new tools, so it is necessary to repeat the previous steps (5.1-5.3) for the new tools.

5.5 Advanced Settings

Our interface allows users to change fundamental machine parameters such as speed, acceleration, or stepper gear perimeter (Figure 3 b). These parameters are especially useful when exploring a new drawing surface that is not included in our current library. It is possible to obtain dramatically different drawing performance by tuning these parameters. Taking acceleration and speed as example, if high acceleration and speed are selected together, the platform will finish the task very rapidly, saving implementation time but inevitably affecting the drawing quality of the circuitry. Also, we allow the users to self-define the pen tip width, highlighted in Figure 3 b in red, which is much helpful when users export SVG files from professional circuit design software (*e.g.,* KiCad). So users can directly upload the files to Duco interface, and the system will automatically identify the widths of different traces and fill up the traces with different numbers of moving paths based on the pen tip width they entered.

6 DRAWING TOOLS EVALUATION

In order to better understand the performance of our circuit drawing robotic system, we carried out a series of tests. These tests included general resolution and accuracy tests as well as electrical and mechanical tests for the drawing tools and substrates. Each test is corresponding to one key criteria of Duco. We believe these test results validate the circuit drawing capabilities of the system. Additionally, these tests establish a procedure for evaluating new drawing tools and substrates.

6.1 Resolution, Accuracy and Speed Testings

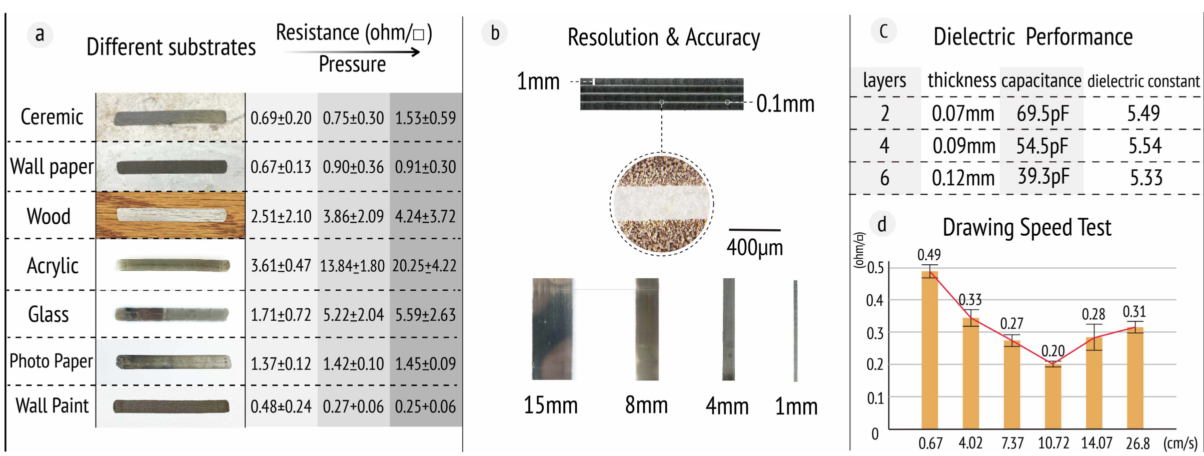

Fig. 4. (a) Resistance evaluation for the conductive ink on different substrates. (b) Resolution and accuracy testings. (c) Characterization of the dielectric ink. (d) Drawing speed testing.

6.1.1 Resolution Testing. To test the drawing resolution of our system, we examine the thinnest line width that Duco can achieve as well as the smallest gap achievable between two lines. Figure 4b shows that the smallest line gap that we can achieve is 0.1mm. We have carried out a series of tests by drawing four lines in a group with line to line gap of 10mm, 5mm, 1mm, 0.5mm, 0.4mm, 0.3mm, 0.2mm till 0.1mm which is the minimal gap that we were still able to observe consistent drawing results without any line intersections. The tests are done on acrylic sheet with a trace length of 5cm, and has been repeated for 5 groups with 4 lines in a group. At the bottom of Figure 4b, we show the thinnest line width that we achieve is 1mm. It is clear for this drawing system that line width will be directly determined by the pen tip width. We have also tested 15mm, 8mm, and 4mm lines to demonstrate the possibility of directly drawing conductive traces in different widths. It is important to note that wider drawing tips can dramatically reduce the drawing time for solid patterns compared to using thinner tips to draw multiple paths.

6.1.2 Accuracy Testing. Additionally, we demonstrated the system's accuracy tests for drawing both single layer and multi-layer circuits on acrylic sheet. For single layer accuracy testing, we first used a 4mm pen to draw a ground truth pattern with a length of 5cm and repeated the pattern for 10 times with a 2cm center-to-center deviation in our graphic design. We then measured the real center-to-center differences and compare with 2cm, which we achieved 2.05cm real deviation in average, which represents 2.5% error. We also repeated this test 3 times, and achieved similar results of 2.04cm and 2.02cm deviations on average. For the multi-layer accuracy testing, we tried to determine how well two layers can be aligned after the system automatically switches the pen. We mounted two pens with different colors, conducted a task which involved switching the tool and drawing a dot. Over 15 trials we achieved an average of 1.2 ±0.7mm distance between the centers of two consecutive dots.

6.1.3 Drawing Speed Testing. Duco platform is similar to 3D printer that the speed can have both pros (*e.g.,* save fabrication time) and cons (*e.g.,* lower the quality of the print) to the system. The printing speed for Duco will also play an essential role in evaluating its performance. As indicated in Figure 4 d, we have carried out the speed testing with an attention to how different drawing speeds can cause the variations of resistance. Among the tests, We used a single line pattern as our testing pattern, with a dimension of 7cm long and 2mm wide. This pattern has been repeated 10 times for each speed, and we have tested multiple speeds ranging from 0.67 cm/s to 26.8 cm/s. According to the results, all the traces have reliably shown conductivity within an acceptable range, where 10.72 cm/s is the optimal drawing speed that exhibits the best electrical performance. Also, the testing results have shown that the slower drawing speed of 0.67 cm/s exhibits relatively poor electrical performance which we speculate when the system moves too slow, the pen tip also scratches the pattern.

6.2 Drawing Tool Testings

Along with the machine's drawing resolution, the electrical properties of the circuits are also a determining factor for the quality of large-scale electronics fabrication. We have evaluated three different conductive inks (SunChemical EMD 5730, Mitsubishi Paper Mills NBSIJ-MU0 and Dycotec DM-SIJ-3200), two dielectric inks (Dycotec DM-INI-7003 and NEA 121) as well as two different cleaning solvents (ethylglycol and ethanol) [24, 34]. Most of these inks have a viscosity from 1-200 cPs, which can be easily loaded into the commodity markers. We have also considered and tested *Circuit Scribe* and *Bare Paint*, which are micro-particle based materials and have a viscosity around 15000 cPs. Since the micro-particle based materials are not extrudable from the refillable markers and require pneumatic dispensing, we chose to omit these materials from our officially supported materials library for the sake of maintaining overall design simplicity.

6.2.1 Conductive Silver Pen. In order to support the drawing of circuits on a wide range of substrates as well as to minimize the post-treatment efforts, we selected Dycotec DM-SIJ-3200 as our conductive ink which can be cured at low temperature. We have mainly tested out resultant circuit conductivity on seven different substrates (

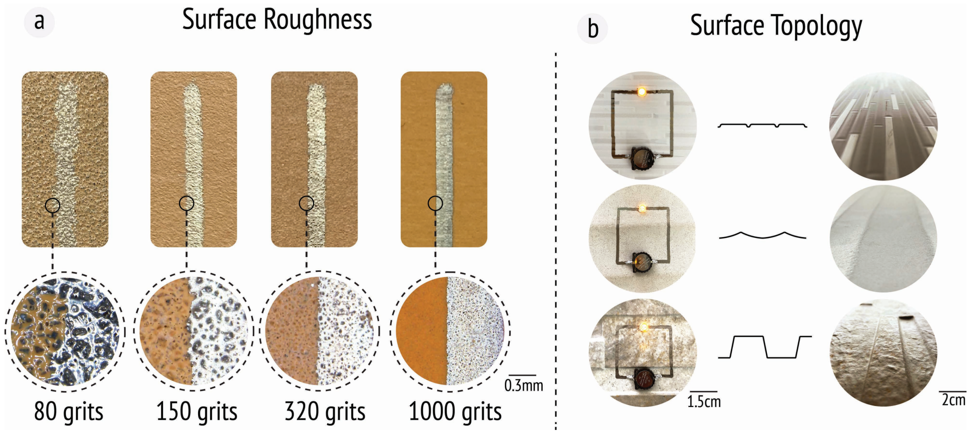

Fig. 5. Drawing quality evaluation on various surfaces with different roughness and topology.

ceramic, wall paper, wall paint, wood, acrylic, glass and photo paper), which exemplify most vertical surface materials encountered in our daily lives. We summarized the results in Figure 4 a. The 4mm by 40mm rectangular pattern was tested 15 times at a constant contact pressure. We reported the mean value and the standard deviation of the circuit's resistance measured by a four-probe setup. We observed very consistent values from each substrate, with relatively large variances for wood and glass substrates. These variances were likely caused by the uneven surface topology of wood and the poor surface adhesion of glass. For the pen contact pressure, we tested three different pressure settings. Surprisingly, we found that as pen contact pressure increases, circuit conductivity decreases for all the tested substrates. We speculate that after passing a certain amount of contact pressure, the pen tip begins to scratch away the patterns as it is drawing. In order to standardize the testing, all the samples are heat-sintered in an oven for 15 mins at 120°C. We failed to observe any conductivity for the wall paint substrates until we heat treated the wall paint again under 200°C for another 3 minutes.

6.2.2 Dielectric Pen. When choosing the dielectric ink for the system, the performance of the two inks we evaluated were very similar. Both inks can be quickly cured by a 3.3 V ultraviolet LED within 15 to 20 seconds. We ultimately chose the NEA 121 ink because of its more accessible price. In order to characterize the performance of our dielectric ink, we first drew a 10mm by 10mm silver square at the bottom and then 2, 4, and 6 layers of dielectric ink were drawn on top. We then connect the most top dielectric layer with a copper tape to measure the capacitance by using a LCR meter (Agilent, U1733C), and the results are presented in Figure 4 c.

6.2.3 Cleaning Pen. Drawing mistakes or accidental ink spreading can occur during the fabrication tasks. In order to allow the redrawing of circuits in the same area or the modification of existing designs, erasing will be necessary. Inspired by [24, 34], we have investigated 2 different solvents (ethylglycol and ethanol) as our cleaning inks. Unlike [24, 34], which utilized cleaning inks mainly dispensed onto photo paper, our work has introduced 7 materials as drawing substrates. However, not all substrates require special cleaning solvents to erase drawn traces. For example, due to low surface adhesion, the conductive traces on glass substrates are fairly easy to be erased even by using water. Conversely, the ink bonding on acrylic sheets is extremely strong and can not be removed by any of the solvents we investigated.

6.3 Substrate Testing

6.3.1 Surface Roughness. The majority of everyday vertical surfaces are to some degree patterned or textured. Researchers have made extensive efforts to fabricate circuitry on objects with different geometries [12], but the textures and patterns of these surfaces have barely been considered. In Figure 5 a, We have tested the drawing quality on four samples of sandpaper with 80, 150, 320, 1000 grits. We have used the 4mm pen to draw a 6cm long pattern on each sandpaper for 10 times and observed that the drawing quality is dramatically affected by surfaces with different levels of roughness. It was challenging to achieve smooth and consistent drawings on the 80 grits surfaces. For the smoothest 1000 grits surface, much sharper drawing edges were achieved.

6.3.2 Surface Topology. Besides surface roughness, target surface topology is also a major factor which needs to be considered when fabricating electronics on everyday vertical surfaces. In response to this design challenge, our circuit drawing system is equipped with a linear actuator and a pressure sensor, enabling the system to draw patterns across different surface heights. In Figure 5 b, we have shown experiments on ceramic tiles with three different surface patterns, with resistance of 65Ω, 80Ω and 134Ω from top to bottom respectively. These experiments determined how much height difference and how much transition angle between two adjacent surfaces the drawing system can handle. Based on the testing results, our circuit drawing system can handle roughly 1 to 4mm height differences, and 0-60° transition angles.

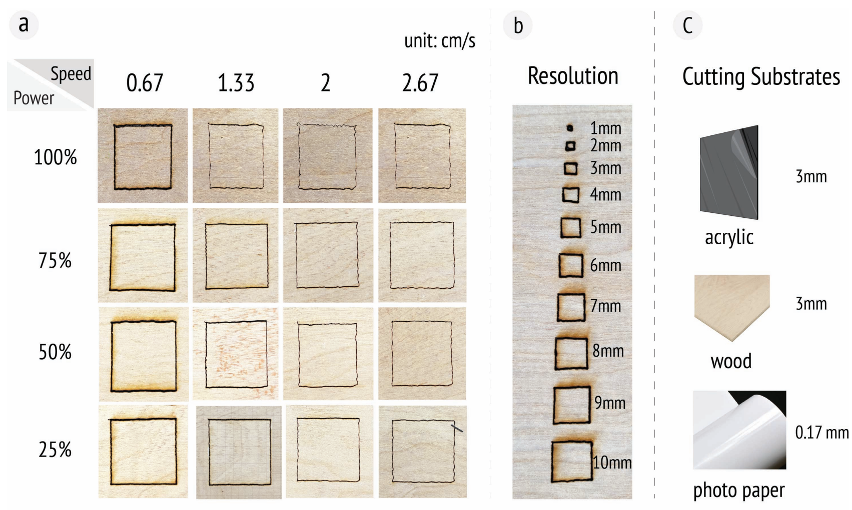

Fig. 6. laser cutting head testing: (a) Speed and power testing. (b) Resolution testing. (c) Substrates that laser cutting head can cut.

7 CUTTING TOOL EVALUATIONS

Several prior works have demonstrated using 2D planer printed electronics to prototype 3D interactive objects by cutting and folding the printed sheets [38, 68]. Likewise, we laser cut circuit printed sheets to fabricate real-world, large-scale interactive objects such as a standing lamp. The modular nature of our circuit drawing system gives means to the easy replacement of the drawing pen or brush with a laser cutting head to cut the substrates to make large-scale 3D interactive objects. With this goal in mind, we have tested a NEJE 5.5 watt laser cutting head [1] as our cutting tool. Figure 6 shows our test to evaluate the performance of this laser cutter head. We have summarized the testing results when under a combination of different power and speed settings (Figure 6 a). The cutting line quality is more sensitive when we switch from drawing tools to laser cutting head. Since the laser's focal point is much smaller than the pen tip, which is easier to be affected by platform vibrations. During the cutting test, we observed consistent cutting behavior even when the speed was increased beyond 1.33 cm/s. As the speed is increased, however, the cutting line quality is dramatically decreased. Additionally, the resolution testing results are shown in (Figure 6 b). The smallest square that we were able to successfully cut was 2mm by 2mm. We also tested the cutting of different materials, and achieved successful cutting through 3mm thick acrylic/wood pieces and 0.17mm thick photo paper.

On top of the technical evaluations for the laser cutter head, another key benefit of making the 2D cutouts in a vertical manner is saving the space for fabrication. Laser cutters have been extremely useful and widely available in maker environment or even beyond. They are playing an irreplaceable role in rapidly cutting sheet materials. However, one drawback for the laser cutting machine is that it occupies big space. For a conventional laser cutter we found in our institution, with a 27.5 inch by 19.5 inch cutting dimension, it takes up 47 inch by 34 inch plane space, while also capture vertical space with 37 inch in height. If aiming at obtaining the same working area, Duco will only take approximately $\frac{1}{8}$ of the volume. Especially if considering the horizontal space taken from the ground, Duco occupies almost none ground space by adapting a hanging fabrication platform.

8 OPEN SOURCE

In order to further extend and validate the accessibility of Duco for HCI researchers and makers, we documented Duco's design, assembly, and operation in our online repository: https://github.com/DUCO2020. We consider this documentation as an integral part of our demonstration. The documentation is prepared to invite a growing community of HCI researchers and DIY makers to build their own Duco to extend the proposed applications. We have also committed to maintaining Duco as an open-source project to facilitate other researchers' use of our system. We included detailed instructions for the following five aspects:

(1) Overall instructions for building and operating Duco.
(2) Hardware design: including a detailed bill of materials for the items we purchased from vendors, and 3D modeling files for the parts we self-machined.
(3) Platform assembly: detailed instructions on how to replicate our current design.
(4) Software: source code to operate Duco.
(5) User interface: a step by step set of instructions to use our interface.

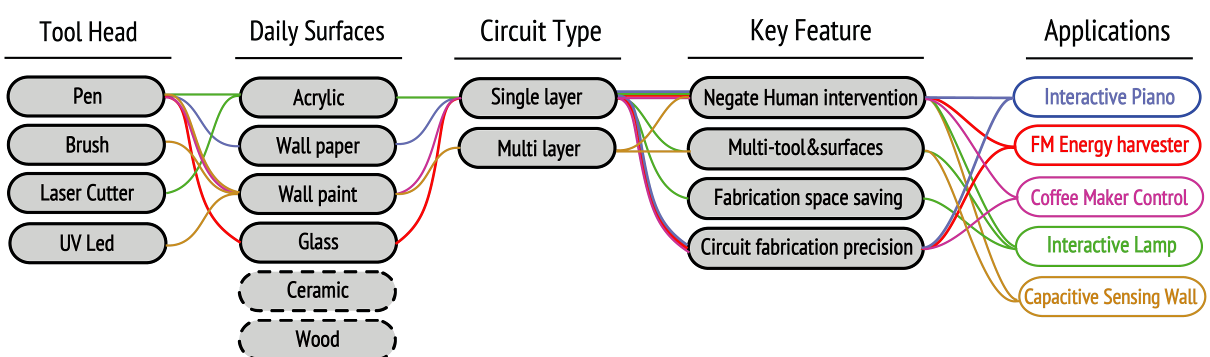

Fig. 7. Application Mapping Overview.

9 APPLICATIONS

We have showcased five application examples enabled by Duco system. These applications mainly cover three key circuit fabrication domains that are greatly favored by the enlargement of the functional surface areas or spaces: 1) human-scale sensing [59, 62, 67]; 2) energy harvesting [17]; and 3) 3D interactive artifact [38]. These five application examples are carefully chosen to highlight the advantages of using the Duco system: negating human intervention, supporting complex and accurate circuitry design, supporting multi-material/multi-tool and constructing circuits from 2D to 3D, from single-layer to multi-layer (Figure 7).

9.1 Interactive Piano

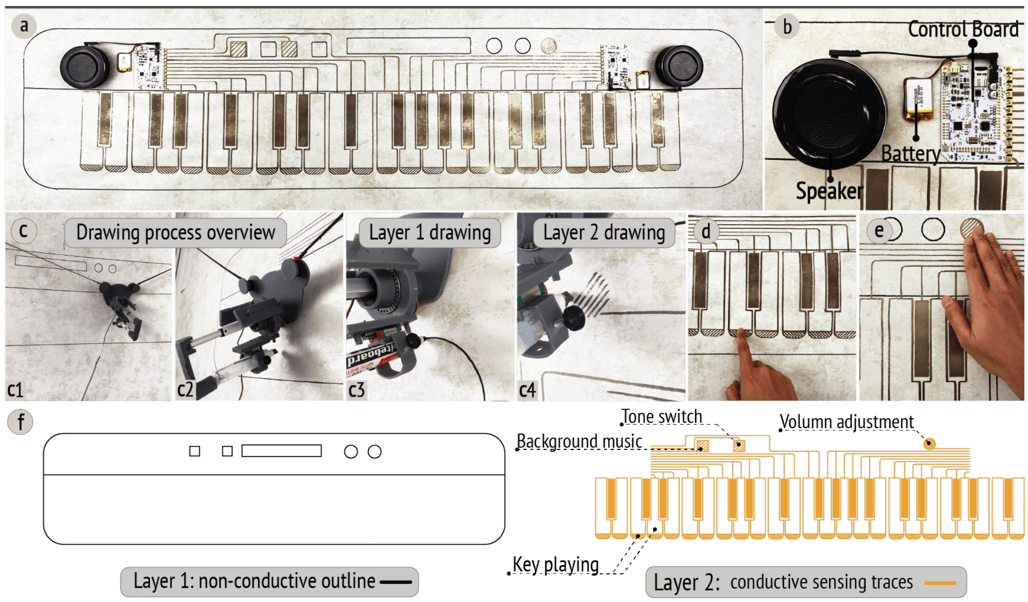

Fig. 8. Interactive Piano: (a) Overview of the system. (b) The control board, the battery and the portable speaker connections. (c) The drawing process overview. (d) Playing the capacitive keys. (e) Tuning the volume. (f) The schematics of two layers and their functions.

Many interactive panels, exhibitions, and art setups have demonstrated novel ways of embodied interactions, which are also favored by utilizing large interactive areas or spaces. Our inspiration came from well-known art installations [8, 10, 53]. Aiming at providing unconventional interactivity, in Figure 8, we present an untethered interactive piano with a size of 160cm by 32cm drawn on wall paper by using two separate pens, a normal black marker for non-functional outlines, and a conductive pen for the functional piano keys and connections. This application highlights the ability of Duco system in drawing complex but accurate circuitry patterns, which becomes very challenging to make by adopting the existing large-scale circuit fabrication method that relying on human inputs and stencils. When fabricating the interactive piano, we first used the 4mm black marker to draw the outline, and then switch to the 4 mm marker loaded with the conductive ink to draw the rest of the interactive patterns. The interactive piano exhibits multiple functions including white and black key playing, background music playing, tone switching, and volume adjusting. We wired up a pair of portable speakers, a 400 mAh Lithium battery and a Bare Conductive Touch Board [3] on each side of the printed piano.

9.2 Interactive Coffee Maker Control

As IoT devices become increasingly prevalent these days, more home appliances became "smart" that allow people to control or manipulate the functions remotely (*e.g.,* smart lighting system, temperature control, or button control). Here we showcase an interactive coffee maker controller (96cm by 68cm) drawn by Duco on our office's wall which is covered by blue wall paint. We used the black and conductive markers to draw the non-functional and functional patterns respectively. Then, we wired up the drawing to an ESP32 board by using the jumper wires and silver epoxy. Thanks to the end-user programming platform IFTTT [15] and Smarter Coffee Maker [48], we achieved demonstrating a remote controller including various functions of the coffee maker by creating different applets through the IFTTT (*e.g.,* start/pause the brewing, change the brewing strength or adjust the brewing size). As shown in Figure 9 c, we are controlling a coffee maker located in the community kitchen of our floor by using the control panel that we drew on the wall in our office. We believe this not only provides a novel and playful interaction with an IoT device remotely, but also demonstrates a vision to locate controls for multiple home IoT appliances to be centralised.

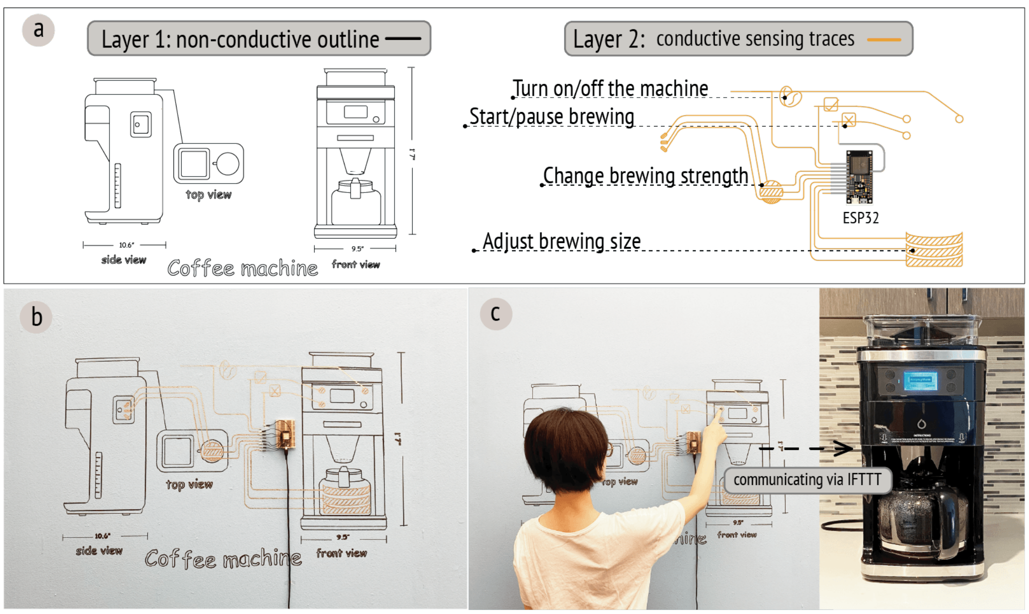

Fig. 9. Interactive Coffee Maker Control: (a) Demonstration the drawing and schematics of two layers and their functions. (b) The overview look of the coffee maker controller. (c) Brewing coffee remotely by using the controller.

9.3 Capacitive Sensing Wall

In order to augment the sensing capability on everyday surfaces, HCI researchers have manually painted or brushed conductive materials onto the wall surfaces to passively detect indoor human activity or gesture [62, 67]. While those techniques enable large-scale human activity sensing, the lack of autonomous fabrication tools hinders a possibility for further enlarging the sensing area. The capacitive sensing wall application features the strength of Duco's automation, scalable working area and support multi-tool tasks. After we upload a design file to the interface, Duco frees users' hand by taking a task of drawing the conductive layer(s) and the drawing/curing of the insulation layer automatically. The capacitive sensing wall is a 15 by 8 grid pattern inspired by *SmartSkin*

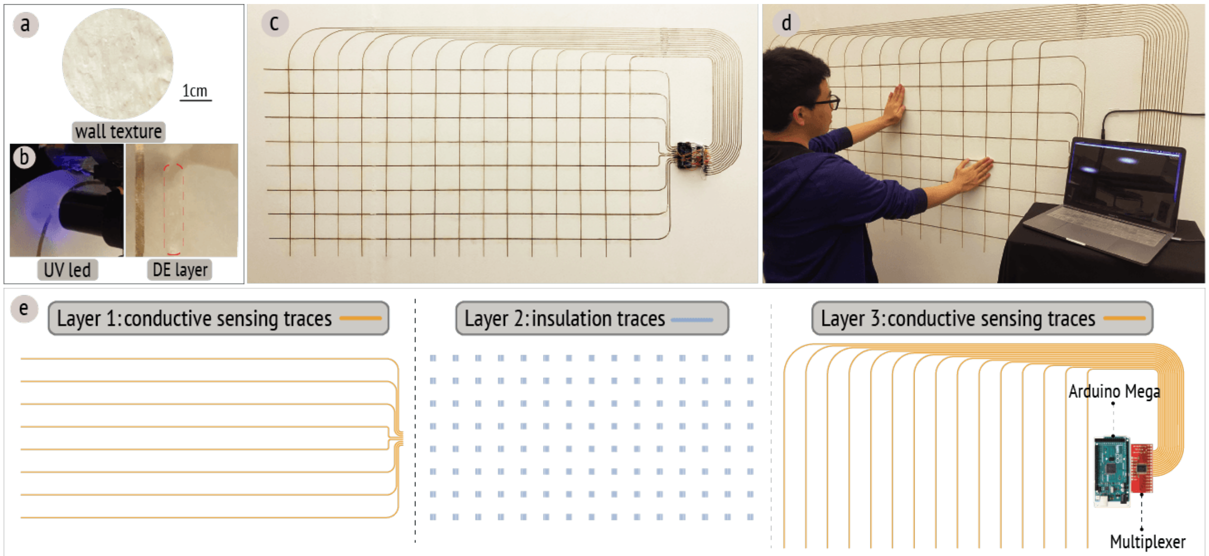

Fig. 10. Capacitive Sensing Wall: (a) Zoom-in look of the surface texture of wall. (b) Zoom-in look of UV curing and dielectric ink brushing. (c) Overview of the sensing wall. (d) Human touch is detected by the capacitive sensing wall. (e) Detailed schematic for each drawing layer.

with a dimension of 200cm by 110cm. It consists of two (top and bottom) conductive layers and an insulation layer in the middle [45], shown in Figure 10 (c,d). We highlighted the pen brush and UV LED to automatically draw and cure the dielectric ink in Figure 10 b. An Arduino Mega 2560 [2] and multiplexer [49] were used as the main hardware components to wire up the system.

9.4 FM Energy Harvester

Among most of the vertical separation materials, glass plays a special role. Unlike normal walls or wooden frames which functioning as space dividers, glass surfaces like windows must allow people to see through. Here, we design a wide-band, quasi-isotropic, kilometer-range FM energy harvester printed on a 120cm by 120cm glass sheet by utilizing the 4mm conductive marker, (Figure 11). Duco, as a digital fabrication system, features the capability of making drawings with high precision. Unlike other applications, energy harvester requires the patterns to meet the precise length, width or even the direction/location on a graph to achieve the desired RF characteristics (*e.g.*, all antennas we designed in the energy harvester pattern correspond to a specific wavelength, they are different in terms of length, width, location and pointing direction). The drawing results meet our simulation well which made it able to harvest energy from surrounding FM towers omnidirectionally. We purposely made the thin-trace design of this energy harvesting pattern to harvest energy and at the same time will not block the normal view through the glass. Radio frequency energy harvesters favor utilizing larger surface areas for harvesting more energy. We envision the possibilities of using our circuit drawing system to fabricate energy harvesters across the entire outside surface of a glass-covered building to harvest free energy from the ambient environment as a "printed battery" to support other activities within the building. Figure 11 f shows the printed energy harvester pattern wired up with a rectifier, a power management board with capacitors, and a blue-tooth module that we would like to power up. Also, Figure 11 c presents our field test, in which we successfully powered the bluetooth module with embedded thermometer and accelerometer. To our best

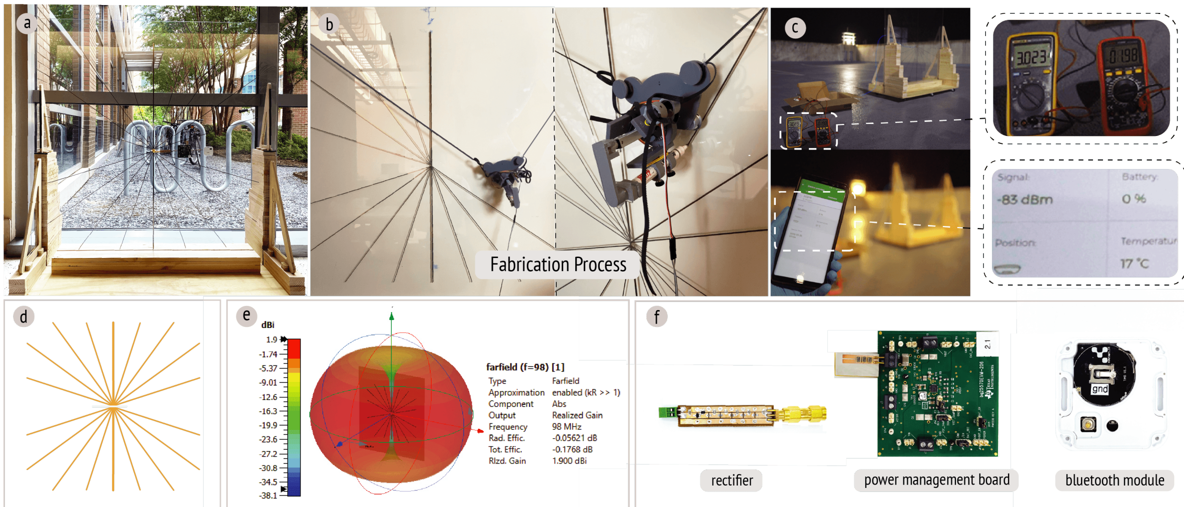

Fig. 11. Printed FM Energy Harvester on glass: (a) The front view of the printed FM energy harvester with components mounted. (b) The fabrication process for the energy harvester. (c) When the energy harvester is capturing energy and powering up a blue-tooth module with embedded temperature and location sensor. (d) The design for the energy harvester. (e) The simulation result of the FM energy harvester (f) A closer view of the electrical components: the rectifier, the power management board and the blue-tooth module.

knowledge, we are the first one utilizing low-cost autonomous platform to fabricate this energy harvester on glass, which can achieve a competitive power of around 200 μW in outdoor rooftop locations and 60 μW in indoor rooftop locations.

9.5 3D Interactive Lamp

Many daily objects can be assembled from multiple flat pieces (*e.g.,* desk, chair, lamp, shelf and etc.). Researchers have demonstrated embedding sensing capabilities into these objects, however, most of these interactive objects are limited by the existing fabrication machines, which are at the same time taking up plenty of plane spaces. We demonstrate a 110cm tall interactive lamp in Figure 12. We take the advantage of the vertical space as our main fabrication site. For the fabrication process, we firstly hang a 2mm thick black acrylic board with a dimension of 125cm by 60cm onto a wall by using double-sided tape. We start by drawing the interactive patterns on the acrylic sheet (shown in Figure 12 a, b), following by automatically switch to our 5.5 W laser cutting head to cut the outlines (shown in Figure 12 b). We used four acrylic sheets in total, with first three sheets producing two lamp shades each, and the last acrylic sheet producing the lamp base which is composed of two semi-circle pieces, shown in Figure 12 e. The entire process is completed autonomously with involving minimal human intervention. After we finish the drawing and cutting tasks, the pieces are assembled by using liquid glue, and then we connect the traces to the Bare Conductive Touch Board by using silver epoxy. Figure 12 c shows the assembled look of the lamp when in its turned on state by touching the capacitive pattern that we drew. We also would like to note for the fumes generated by the laser cutting process, similar to many commercial desktop laser cutter/engraver [26], the laser diode we implement will only generate a small amount of fumes, but a vacuuming system is strongly recommended when operating the system with more powerful laser cutting heads.

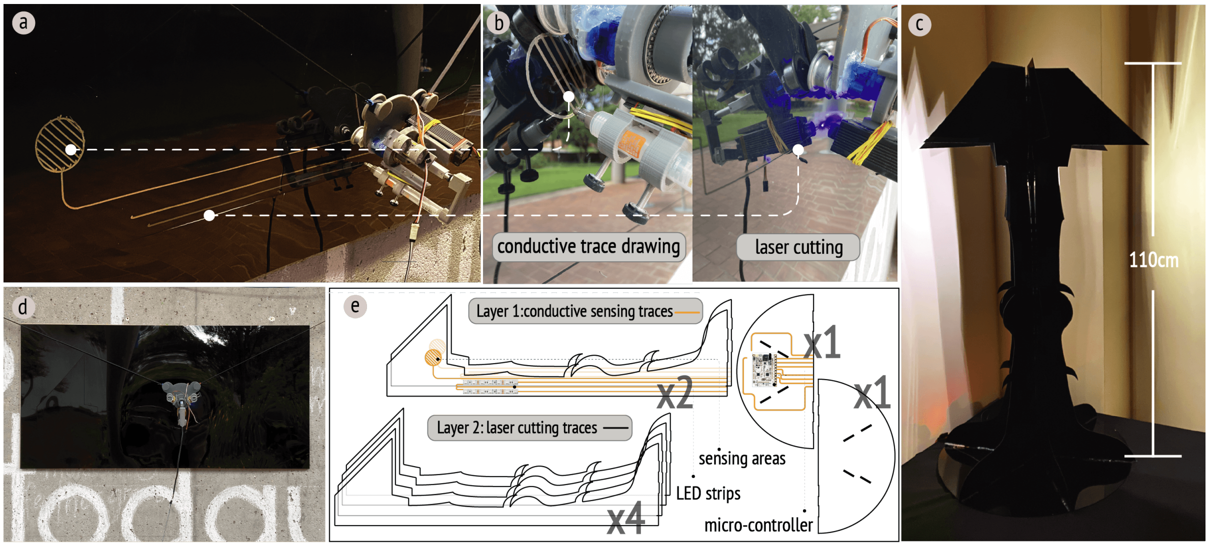

Fig. 12. 3D Interactive Lamp: (a) An overview when the system is drawing the circuits. (b) A zoom-in look of the drawing and laser cutting areas. (c) When the lamp is turned on via capacitive sensor. (d) The overview of the fabrication setup. (e) Detailed decomposition of the assembly.

10 DISCUSSION

We have demonstrated five application examples to highlight the key strength of using Duco system in making large-scale circuits. Here we discuss several other critical factors when operating the system, including the total fabrication time, the working area and the requirements for initial setup.

Net Fabrication Time. With conventional fabrication approaches, large-scale circuits would require significant human efforts. Manual calibrations, masking, and drawing must be carried out, which not only waste time but are also prone to errors. Similar to many digital fabrication techniques such as 3D printing, Duco frees users from laborious manual efforts by offloading the drawing process to autonomous robotic mechanisms. We believe the automation of the drawing process is a critical breakthrough, even though there might not be a significant reduction on net fabrication time. All of the application examples presented here adopted a recommended optimal drawing speed of 10.72 cm/s. At this speed, the interactive piano can take up to 3 hours (15 minutes for the non-conductive outline, 2 hour and 45 minutes for the conductive parts) to complete the drawing process while the coffee maker control takes 2 hours (1 hour and 10 minutes for the non-conductive outline, 50 minutes for the conductive parts), the FM energy harvester takes 50 minutes, 5.5 hours for the entire interactive lamp (25 minutes for drawing and 35 minutes for cutting of each lamp shade, 1 hour 10 minutes for the base), and 7.5 hours for the capacitive sensing wall (1.5 hour and 1 hour for the top and bottom conductive layer, 5 hours for the insulation layer). It is noteworthy that the curing process for the insulation layer takes a substantial length of time. This length of time is not only due to the 30 seconds curing time at each of the 120 overlapping circuit trace nodes, but also because we repeated this process three times to ensure the insulation layer's performance. Even though the drawing process does not require human intervention, further fabrication time reduction will be necessary for the system improvement. One direction for improvement would utilize more advanced path planning algorithms. The drawing time for the interactive piano application was shrunk from 6 hours (by using the path planning algorithm reported in *Polargraph* [41]) to 3 hours (by using our modified algorithm respectively). With this experimental confirmation, we believe there is still room on the software front to further cut down the fabrication time. Another direction for improvement could be increasing the moving speed of Duco. In this work, we are mainly adopting the optimal drawing speed for our application examples but, one can apply a higher speed for the fabrication which inevitably will sacrifice the drawing quality.

Working Surfaces & Areas. With our goal of augmenting vertical everyday surfaces, we realized that not all the vertical surfaces are completely flat. Practical surface extrusions such as hanging frames, LED decorations, or wall mounted lamps, can all block the drawing path for Duco. The current system setup does not support a camera to detect these existing objects or an advanced path planning algorithm to avoid these objects. Also, daily surfaces can easily have transition from one type to another (*e.g.,* from a wall to its connected window glass), so far Duco is not able to handle these surfaces transitions with a major vertical gap in between. Additionally, the current drawing area is slightly smaller than the anchors' setup area due to certain geometrically extreme locations (*e.g.,* the area above Duco's initial starting point and the areas close to the anchors/ weights). When we carry out drawing tasks, a 20-centimeter gap on the two sides, and the area above Duco's starting point are marked as non-optimal drawing areas which are also reflected in our interface. Our future efforts will focus on making advancements in Duco's hardware and software designs to work with a wider spectrum of real-life surfaces.

Initial Machine Setup. As previously introduced, the two anchors and their corresponding motors are required to be manually mounted on the top two corners of the drawing canvas. They are to be mounted horizontally and at the same height, with the distance between the two anchors needing to be measured. Through our working experience, this is by far a time consuming step which in general consumes 20-30 minutes. Additionally, this step prevents Duco from providing a completely autonomous fabrication experience. We propose in the future to utilize small robots to drive the anchors to the designated locations and apply a vacuuming system to fix the anchor.

11 LIMITATION & FUTURE WORK

Duco has shed light on an unusual but worthwhile problem - the fabrication of large and precise circuits on and around vertical surfaces while requiring minimal human intervention. However, while working with Duco, we also identified several limiting factors effecting the current setup which can be further improved to advance the performance of Duco.

Curing Time. With the ink selection discussed earlier, we chose a silver nanoparticle based conductive ink due to its advantages of ease of loading into a marker, high conductivity and high reliability. However, the required heat sintering post treatment process for this ink can be a cumbersome step. This step demands the users to use a heat gun to cure the circuits (*e.g.,* the piano application requires a sintering time of 30 minutes or more), which not only requires manual efforts from users, but also risks damaging the drawing substrates (*e.g.,* low melting point plastic substrates might not be applicable to our approach). In order to tackle this problem, we aim to either use our laser cutter to cure the ink, or by mounting a heater onto the platform to automatically heat-sinter the circuits, similar to how we cure the dielectric ink by mounting a UV LED on the platform.

Hardware Platform Limitation. The compact design of Duco enabled a robust and low-cost platform which can be easily deployed on various surfaces. However, during our working experiences with Duco, several hardware platform limitations were noticed. First of all, the ink refilling process sometimes causes issues. Since currently there is no automatic refilling mechanism for the paint markers, sometimes a machine pause is required in order to manually add more ink to the pen, which might cause discontinuity of the circuits or dis-location of the platform. These limitations suggest a ink refilling mechanism will be necessary for future system improvements. Secondly, we also observed that when approaching extreme locations on the drawing canvas, the entire platform tends to tilt to one side. During this platform tilting, the drawn line is still continuous and straight, but tends to tilt in accordance with the platform (*e.g.,* the very left drawing line presented in the Capacitive Sensing Wall application is tilted counter clock-wise).

Future Field Deployment. The current anchor-weight design enables Duco to move on vertical surfaces to automatically draw large-scale circuits, but can be challenging to enable circuit fabrication in certain hard-to-reach areas or areas that are not suitable/safe to stay for long time. Figure 13 b-c demonstrates potentials of Duco being used in these scenarios, for example, Duco can be mounted on the windows outside a tall building or on the sides of a bridge for more practical use (*e.g.,* harvesting energy, structural health monitor or mold/humidity detection). For doing so, we will explore a new and more compact anchor design shown in Figure 13 a, by replacing the timing belts with fishing line which can endure bigger tension, and adding a recoiling system with a tension enhancer that the system will not need to rely on the weights to tighten the belt anymore.

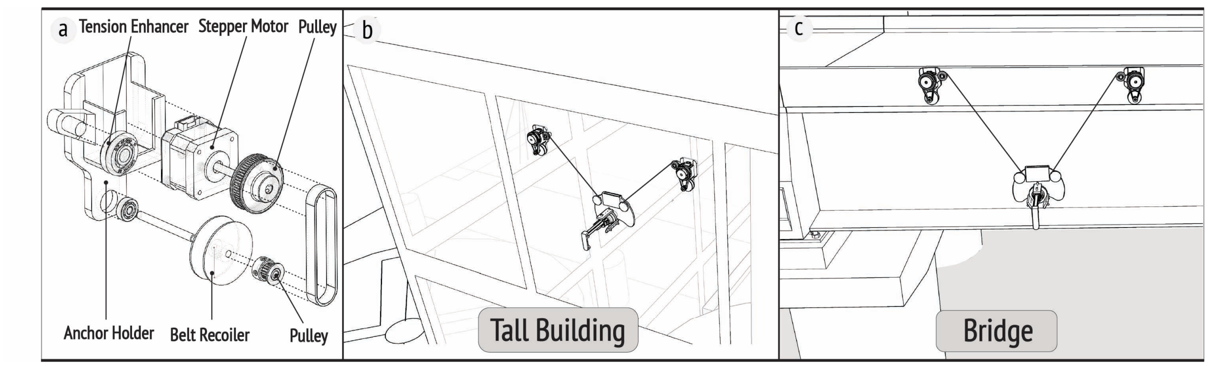

Fig. 13. Future field installments: (a) advanced design of the anchors. (b) Installment on the windows for tall buildings. (c) Installment on the side of bridges.

Exploratory Toolings. Current work has presented three types of tools, but the most promising advantage of Duco is how easy it is to equip different kinds of tools to serve different purposes. Similar to some existing tool changing platforms which support multiple functionalities within a single platform [55, 58], we have identified and tested three additional tools in Figure 14. First, a craft knife together with a swivel mechanism can be an alternative to the laser cutter head for cutting thin sheets to make large-scale interactive paper crafts, without creating any fumes. Also, a pneumatic dispenser will be a possible extension to automatically pick and place electronic components after the system finishes the circuitry drawing. Finally, inspired by *Jubilee* [55], we expect to use a USB microscope to examine the evenness and the continuity of the printed circuitry. We believe the microscope application will be particular useful when the system is drawing circuits around hard-to-reach heights or areas.

12 CONCLUSION

In this work, we presented Duco, a compact robotic drawing system for the digital fabrication of circuits in large-scale on vertical surfaces. Duco was developed to maintain a low-cost manner with an open-source mechanical design to enable users to make or potentially modify their own drawing robot. We showed promising test results to validate the performance of this drawing system and built a facilitated user interface. We also identified 3 domains that are greatly favored by utilizing large interactive areas or spaces: human-scale sensing, energy harvesting, large 3D interactive objects, and demonstrated five practical applications: interactive piano, interactive coffee maker controller, FM energy harvester, 3D interactive lamp and human-scale sensing wall. We believe this enabling technology will broaden the design spaces of printed circuits and fill the gap beyond the conventional

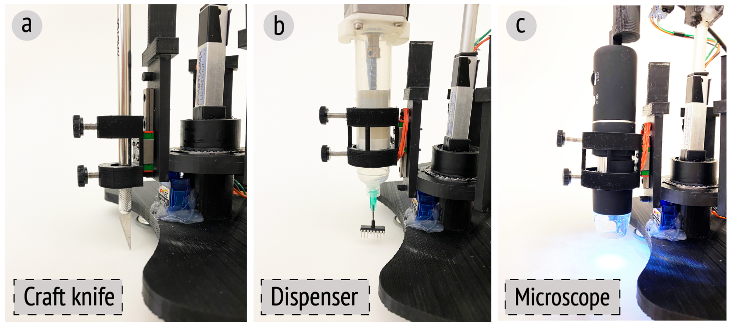

Fig. 14. Exploratory tools: (a) Craft knife. (b) Dispenser. (c) USB microscope.

printing tooling sizes. For future works, we would like to further enrich the functionalities of the system for a broader spectrum of applications in a collaboration with the maker community.

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