An Accessible Way to Rapidly Build Foldable Device Prototypes from Automatic Electromechanical Design

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***Abstract*— This work presents an integrated design-to-fabrication method for foldable electromechanical devices that rethinks the merging of mechanical and electrical designs. The mechanical substrate of this device can carry electrical functionality; the electrical circuits are parts of the device body. We developed a pipeline to implement electrical circuits on arbitrary geometric outlines, and created an abstraction for the electrical specifications to be described by simple tables. By utilizing an automatic routing tool and a modular system developed to transfer the electrical design to mechanical drawings, an electromechanical design can be created for rapid fabrication. The integrated fabrication process uses a single inexpensive desktop paper/vinyl cutter to create a foldable device with embedded circuitry in a timeframe of minutes. Non-experts can use this system to easily complete a foldable design having mechanical and electrical components, such as an origami-inspired printable robot. The software developed in this work is posted at https://git.uclalemur.com/roco_elec/roco_electrical.git**

I. INTRODUCTION

Printable or foldable robots are becoming a feasible approach for the goal of building robots rapidly with lower cost [1]. While the threshold of the requirement of knowledge for the design and fabricate foldable robots is a barrier to enable the public to create personalized robots, a system doing electrical and mechanical design from a limited amount of user effort is required. In order to be beneficial to the general public, a long-term goal is to develop a compiler that allows people to create a robot with the desired functions. [2].

Electromechanical design is a feasible way of solving designs that contain both electrical and mechanical designs [3], [4]. It handles the design while considering mechanism, functionality, and manufacturing process [4]. This paper makes a step towards the long-term goal with a system that merges mechanical and electrical design consistently. It allows non-experts to design and fabricate foldable electromechanical devices that can be used as foldable robot bodies.

The presented system is designed to generate fabrication files and provide a fabrication method. It simplifies the fabrication and assembly process of building foldable robot bodies. By utilizing automatic routing techniques, the electrical circuit can be parsed to a mechanical design automatically. One design file contains all information for fabrication that can be created in a short time with limited effort. The fabrication involves an inexpensive desktop paper/vinyl cutter and cleanup tools. The presented approach also allows low-cost material to be in use. The system results in a quick and accessible way to build foldable electromechanical devices without extra wiring and assembly effort.

The contributions presented in this paper include:

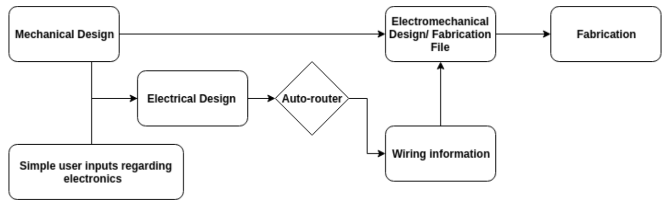


Fig. 1. The pipeline takes a mechanical design and simple electrical components inputs as system inputs. Both inputs are used for software to do electrical design. This design is merged with a processed mechanical design to output one single electromechanical design for fabrication

- A fabrication process to create a foldable device surface with functional electrical components.
- DFM (design for manufacturing) software package for the fabrication process we developed.
- PCB software package generates electrical routing from board outlines converted from an arbitrary mechanical design.

The presented system can help users to complete the electromechanical design and fabricate a device through the pipeline shown in Figure 1.

II. RELATED WORK

A. Foldable Structure

There have been many approaches to build foldable 2-D structures. The technology has been applied to robotics design [2], [5]–[9] and daily uses [10]. The works in [5]–[7] focus primarily on mechanical designs without electronics. [2] presents a work that enables non-experts to design foldable robots, however an included wiring guide is required to build electrical circuits. The author's future objective is to bring a tighter connection between mechanical and electrical designs. This paper develops that work to allow non-experts to create a foldable structure by providing an approach to do electromechanical design.

B. Electromechanical Designs

Electromechanical design handles both electrical and mechanical designs simultaneously [3], [4]. The work in [8] presents a way to fabricate circuit boards onto a foldable robot by etching on copper-polyimide. The electromechanical design was shown in some layers of this foldable robot to fit its functionality. The works presented in [11], [12] develop electromechanical designs that allow mechanical structures to adapt placement and needs of wiring spaces of electrical components. This paper develops the electromechanical design applied in foldable devices while considering not only fully merging electrical and mechanical designs but also the integrated fabrication process.

C. Flexible PCB

There have been attempts to have foldable or flexible circuits [13]–[17]. The fabrication process in [13] brings an approach to use specific tools and techniques to build a reliable foldable PCB on paper. Printable electronics have been developed in [14] using a pen filling with conductive ink to draw patterns on a paper. Such technology brings a low-cost method to build electronics on paper rapidly, but the fabrication process does not apply for electrical or mechanical designs. The work in [17] presents an approach to print electrodes by copper nanoparticle ink on a flexible glass epoxy. The output can provide good quality in terms of conduction. This paper develops the work of foldable PCBs to allow mechanical structures to be involved in the design phase and requires less equipment and tools.

D. Automatic PCB Design

For traditional PCB designs in [18], users need to put effort into learning software and electrical design principles. Works in automatic routing techniques such as [19]–[21] allow non-experts to do the routing process with less effort. This paper utilizes an auto-router [22] and takes advantage of foldable structures' properties to present a method to finish the PCB design with limited user inputs.

E. Rapid Fabrication

There are many rapid fabrication technologies used in the robotics field [12], [23]–[28]. Technology using a plate and reinforced flexure (PARF) [13] and Fused deposition modeling (FDM) [23] are mainly focused on mechanical structures. The electrical design is minimally involved in such a fabrication process. There is work developed in the rapid fabrication field for electronics through inkjet [26], laser [27], or 3D print [28]. 3D printing is another common way of rapid fabrication. The work in [29] can provide a reliable 3D printed electromechanical device in a matter of hours. Besides the extended timeframe, the current technology in 3D printing may be restricted to mechanical degrees of freedom as well [5]. This paper combines electromechanical design and rapid fabrication technology to rethink prototyping of foldable devices that can be used as robot bodies.

III. Fabrication

A traditional robot and PCB used in a device requires a greater timeframe of fabrication than a foldable robot [8]. A significant amount of technical experience [5] and equipment is usually required in the process of prototyping as well. To achieve the long-term goal that enables the general public to personalize robots, a fabrication process for foldable robots that uses less time, learning effort, technical experience, required tools, and material is necessary.

We developed a fabrication process that creates a foldable device that has surfaces with electrical components. The approach allows users to make a device body and an electrical circuit simultaneously through a single sheet of low-cost material. Additionally, the fabrication process uses only an inexpensive desktop paper/vinyl cutter and a small piece of foam for cleanup. The simple fabrication scheme and small amount of material and tools used in this approach result in a capability of enabling users to build a foldable device in a matter of minutes.

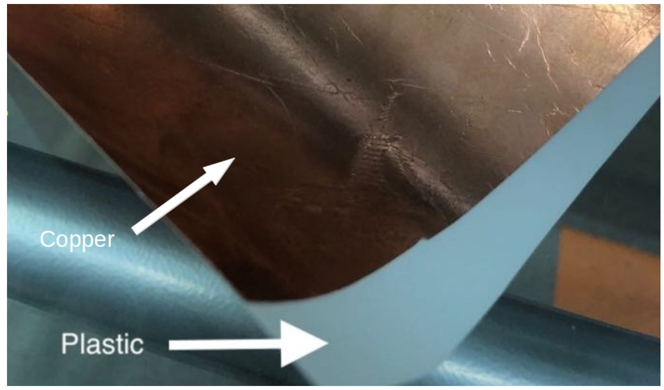


Fig. 2. The material is composed of a copper layer and a plastic layer. The copper layer provides conductivity for circuit. Plastic layer is used to support electronics and provides isolation.

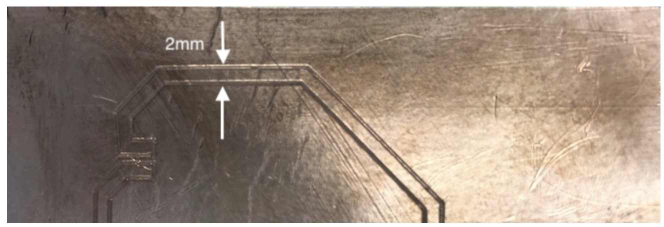


Fig. 3. Conductive traces allow pins to be electrically connected to each other.

A. Material

A copper sheet and a plastic sheet are the material that comprise the composed layers. A copper layer is applied on a plastic layer flatly, as shown in Figure 2. The copper sheet and plastic sheet are both generally available to the public at low cost. This composed material allows the copper layer to provide satisfactory conductivity, while the plastic sheet serves as an isolation material and can offer higher durability than typical paper.

B. Conductivity and Circuit Pattern

This fabrication approach allows the device to have conduction between electrical components by isolating a conductive area from the rest of the material. Such an area is covered by the copper layer that connects pins of electrical components to the edge of it. The area becomes a path-like trace to ensure sufficient conductivity. The isolation is ensured by peeling off the copper layer around the conductive trace. Since the surface of a device body embeds the circuit, it can perform conduction well even if the surface is folded or bent. A conductive trace with 2mm of width was used in the experiment as shown in Figure 3

TABLE I
FABRICATION CUT CATEGORIES

Category	Intensity	Functionality	Order
Circuit Cut	Shallow Cut	Circuit Isolation	1
Circuit Etching	Deep Etching	Circuit isolation	2
Robot Cut	Deep Cut	Mechanism	3
Fold Line	Shallow Etching	Folding Guide	4

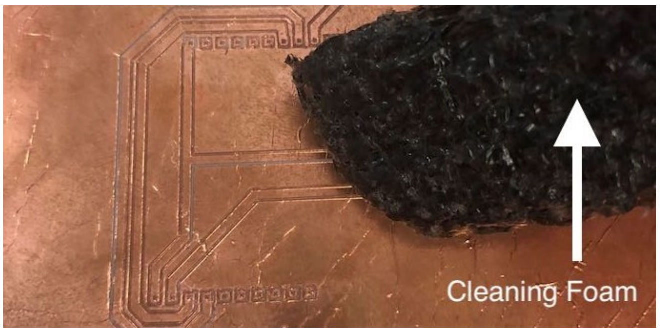


Fig. 4. Foam is used to remove residual copper shavings during the fabrication to ensure isolation.

C. Fabrication Schemes

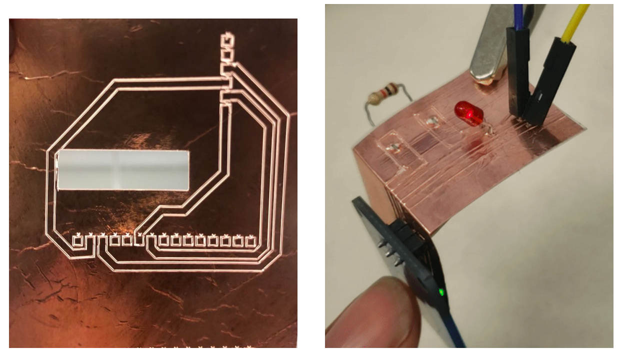
A desktop paper/vinyl cutter, Silhouette Cameo, is used in this fabrication approach to cut the circuit pattern on top of a device body. The cutter provides adjustable pressure for deep or shallow cuts, and different blades for cut or etching. An ordered sequence of cut was created to help users to ensure a successful fabrication process. The fabrication approach divides cut into four categories, as shown in Table I.

1. A two-layer shallow Circuit Cut leaves the plastic layer but cut through the copper layer. This ensures no electrical shorts. 2. The etching pen of the cutter handles Circuit Etching as all circuits become closed shapes after the delivery of the Circuit Cut. Applying Circuit Etching reduces the effort of removing material by hand. The combination of Circuit Cut and Circuit Etching ensures isolation between electrical connections. 3. Robot Cut is applied to cut through the material to generate cut-and-fold origami-inspired 3D structures. 4. Fold Line is a mark that provides a guide to fold the device. Since Robot Cut is likely to include holes or special shapes depending on the mechanical design of the device, the process order ensures that extraneous material removed by Robot Cut does not impede the fabrication process.

Foam was used to clean residual material between two layers of Circuit Cut upon completion of the fabrication cut process, as shown in Figure 4. This ensures no short circuit in the foldable surface.

D. Assembly

In order to enable the surface of a device to hold electrical components in position and provide good conductivity, a cross-cut insertion pattern and isolation boundaries are applied at pin positions. This pattern takes advantage of the elasticity of the plastic layer to make sure the copper layer is connected to the pin from four directions. Electrical components are inserted into the cut to finish electrical assembly. Additionally, the size of this insertion cut can be varied to provide a secure fastening depending on the size of the pins of electrical components.



(a) (b)

Fig. 5. Figure 5(a) shows the circuit trace that routed around an actual mechanical obstacle (rectangular hole). Figure 5(b) shows a circuit that includes a LED, a resistor and a touch sensor. The electronics can work properly on the folded surface

E. Validation

The electrical circuit relies on the mechanical structure by producing conductive traces around the hole in Figure 5(a). An electrical circuit can perform a connection properly on a folded surface in Figure 5(b). The fabricate time the sample in Figure 5(a) is 2 minutes and 3 minutes for Figure 5(b). Additionally, the cost of an 11.8inch by 8.9inch copper and plastic sheet used in the experiment is 1.7 and 1 US dollar respectively.

IV. ELECTROMECHANICAL DESIGN

The mechanical design of a foldable device is generally determined by the desired dimensions and mechanism requirements. Electrical design is usually separate process determined by its functionality during the design phase. The mismatch between the designs may fail in building prototypes [4]. In order to simplify the design phase and lower the risk of mismatch, a method to complete electromechanical design that merges electrical and mechanical design is required.

A DFM software package that generates an electromechanical design as a fabrication file was developed to guarantee the product created from the fabrication process can perform adequately. The package ensures the accuracy of the design by creating electrical and mechanical designs simultaneously. The approach allows users to draw arbitrary circuits directly on the mechanical drawing of a device. Additionally, any circuit design can be turned into circuit patterns. These circuit patterns are tunable via the package easily. For a single device, a fabrication file containing electrical and mechanical designs is generated within seconds.

(a) Connection from one pin to another. (b) Two wires connect at the same pin (c) A branch having one end connected to a pin (d) Pin with no connection, one connection, and two connections

Fig. 6. The circuit pattern design accounts for many different cases of pin locations by drawing the appropriate paths. The path patterns (pink and black) connect with insertion patterns (blue) to form a conductive area between pins.

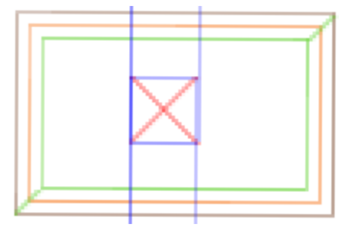


Fig. 7. A circuit pattern with three layers. The inner layer (green) and the outer layer (brown) form a closed area for isolation. The middle layer (red) and a diagonal cut (green) at the corner are designed to help remove material during the fabrication process. The cross-cut (red) in the center is an insertion pattern for placement and conduction of electronics. The blue lines are for drawing guides only.

A. Wiring Analysis

The package parses the wiring information stored in the text file. A pre-processor analyzes this information to allow a reduced run time and eliminate the risk of mismatch between mechanical and electrical designs.

During the wiring analysis, paths sharing the same endpoints are merged to remove redundant data carried in the original wiring information resulting in a faster process. In order to ensure there is no mismatch between electrical and mechanical designs, positions of pins of electronic components are sent to the drawing program to generate insertion patterns and ensure electrical and mechanical designs are consistent.

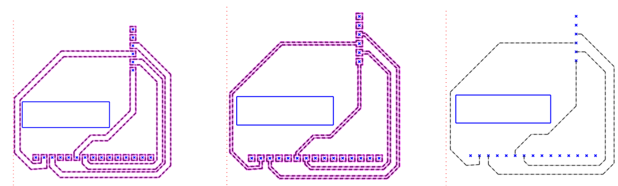
B. Circuit Pattern Design

Circuit patterns allow users to map wiring information onto mechanical drawings to generate an electromechanical design. Such patterns describe the circuit and provide conductivity and isolation on mechanical bodies. The patterns consist of path patterns and insertion patterns. These patterns can be changed individually by tuning parameters in the design process.

1) Path Pattern: The path pattern is designed to translate wiring paths into conductive traces that incorporate into mechanical drawings. Each path is turned into two parallel traces from a single-line path such that the region between the parallel traces becomes conductive, and traces isolate the conductive region from the rest of the device body. This package matches paths to pins for insertion pattern design or to a specific part of a path that a branch path is merging at for complex circuits.

2) Insertion Pattern: The insertion pattern is a design for fastening electrical components on the device and isolating each pin connection. It applies a cross-cut design at each pin position for the assembly process. It can provide full isolation or conduction to another pin depending on the connected path pattern. The insertion pattern is modified based on the direction of the connected path pattern. Figure 6 shows various circuit patterns around pin positions.

3) Pattern Modification: Users can easily change circuit patterns by tuning the size of the path pattern and the insertion pattern according to their fabrication process and materials. The widths of both patterns are allowed to be zero when using a conductive pen or conductive thread.



(a) (b) (c)

Fig. 8. Different patterns can be designed onto a mechanical drawing. Lines in pink and black are the circuit patterns. Blue lines and dashed lines are parts of the mechanical drawing. Figure 8(a) is the general pattern used for our copper-plastic material. Figure 8(b) has a narrow pattern that can be used for similar material with higher conductivity. Figure 8(c) has insert patterns and single-line path patterns. The design can be used for conductive ink or thread.

The pattern typically has three incrementally sized layers, as shown in the closure drawing in Figure 7. The inner and outer layers isolate the conductive area from the rest of the body, and the middle layer denotes the extra conductive material to be removed.

4) Complex Circuit: The complex circuit pattern enables more functionality and capability for complex electrical designs. The pattern allows multiple wiring paths to connect at the same pin, as in Figure 6(b) and Figure 6(d), or merge on another path as a branch. This approach, therefore, reduces the complexity of the user inputted netlist during electrical design.

C. Validation

Figure 8 shows the design with various sizes of the circuit pattern. Figure 8(a) and Figure 8(b) can be used for metal sheet material as described in the fabrication section. A material or fabrication that takes single-line conductive traces such as conductive ink or thread may use the design in Figure 8(c).

V. PCB Design

For any device that contains electrical components, a well-designed circuit is necessary to ensure its functionality. Engineers mainly use PCBs instead of external wires for building robots [29]. A typical PCB developed by an electrical engineer can benefit mechanical engineers, robotics engineers, or other design engineers. PCB technology makes building robots straightforward and accessible [29], [30].

However, for non-experts with less experience in circuit design, may require extra time and effort to learn PCB design tools.

We developed a novel Python-based PCB package for non-experts. This package includes a Template and a Design package. This approach allows non-experts to use simple inputs to design electrical routing for foldable devices. This software outputs geometrically correct PCBs when inputted with mechanical drawing including non-rectilinear shapes.

A. Design Package

The Design package is a flexible, programmable PCB design package. This package can be used as standalone replacement for professional design tools for experts or with our design Template package for non-experts. Since it is Python-based, this module can be integrated with other Python compatible design tools. This package outputs PCB design data in a single structured-text file. The package also allows users to import mechanical drawings as the PCB outlines or keep-outs. User supplied electrical specification and optional mechanical designs are inputted and processed by this package to output a valid wiring path.

1) Wiring with Mechanical Design: To make this package enable to combine mechanical and electrical design, it parses mechanical drawings to text data and defines a board boundary with keep-outs. Keep-outs define regions for the placement of mechanical components or space. A boundary is added to flexible PCB designs when there are cuts in the sheet for folding.

2) Electrical Modules: In order to read electrical component data directly from names inputted from a user, this package loads a library storing footprints of electrical components automatically. Experts can add an electrical component to the library by drawing customized footprint, while non-experts can find standard components in the library or import components from third-party sources.

B. Template Package

Though experts can create PCB designs programmatically with detailed electrical parameters, non-experts may possess the prior knowledge to use this method. The Template package abstracts away the detailed electrical parameters and enable an non-expert to enter high-level design specifications into a configuration file. This package calls the Design package and utilizes default parameters based on foldable structures' properties to simplify user inputs.

1) Electrical Design Parameters: The default parameter settings are based on the fact that a 2D foldable pattern has one layer. Experts can change those settings in the scripts based on the complexity of their project. The package defaults to blank square board boundary based on the size and position of electrical components when there is no mechanical design.

2) Implementation for electromechanical designs: The Design package takes user input, including electrical components, connections, and mechanical drawings. By using automatic routing techniques, wiring information is created automatically. Such information can be sent to the DFM package to apply circuit patterns for electromechanical design.

netList

Connection name	Pins	Netclass
3v3	U1-16;J1-1;T1-2	default
GND	U1-24;J1-2;T1-3;L1-2	default
NET1	T1-1;R1-1	default
NET2	R1-2;L1-1	default
SCL	J1-3;U1-22	default
SDA	J1-4;U1-23	default

moduleList

Module name	Reference	XCoord	YCoord	Flip	Orientation
mpu-9250.kicad_mod	J1	103000	88000		270
ESP12F-Devkit-V3.kicad_mod	U1	103000	48000		90

netclass

Netclass	Via name	Width	Clearance
default		1000	200

Fig. 9. Electrical components inputs are composed of two tables; electrical component list (upper right) and net connections (left), and one optional table representing width of wire and routing clearance (bottom right).

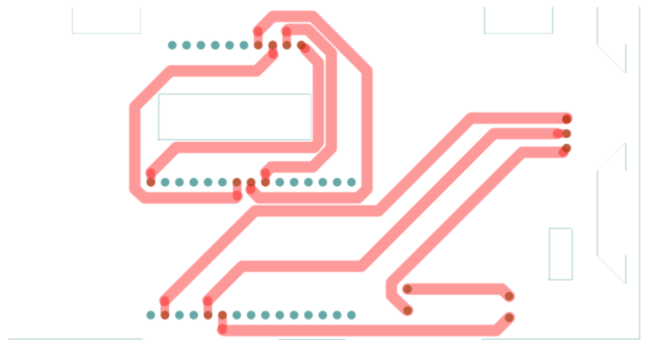


Fig. 10. A completed routing is generated automatically in the auto-router interface

3) Mechanical Drawing: In order to finish an electrical design on the mechanical drawing, automatic routing techniques were used in the system. There are specifications for drawings that must be followed in the automatic routing tool we used [22]. Additional software developed takes arbitrary 2D-mechanical designs to meet such specifications. Since some intricate mechanical drawings may not have clear outlines, the module turns all entities in the mechanical drawing into a closed polyline path. Those polylines are treated as keep-outs while routing. An artificial boundary that encompasses all entities was added to the mechanical design that serves as a board outline during PCB design.

C. Validation

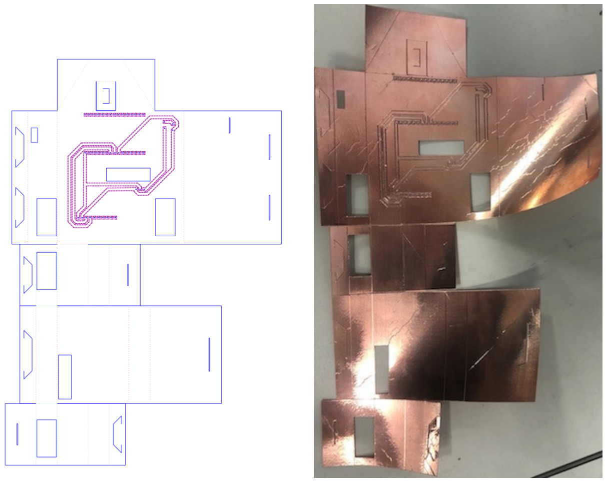
Figure 9 is an example of user inputs. It contains module list, net connections, and net-class definitions (optional).

The auto-router software can view the output of the PCB package and proceed to auto-route based on user input of net connections in Figure 10.

VI. Results

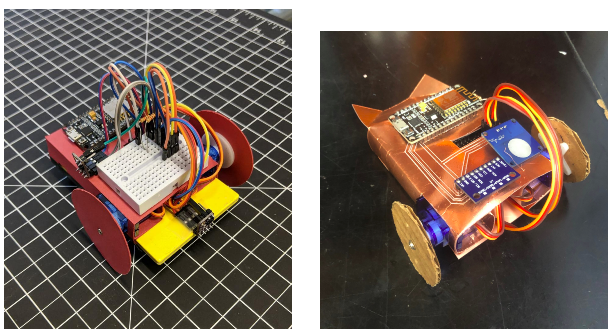
The system that combines the software and the fabrication process described generates a fully functional foldable device that can be used as a robot body. This section shows a design-to-fabrication process to create a foldable vehicle robot body. The mechanical design of this robot is a result of [2].

By using the PCB software package, the system can produce the electrical design file by joining user electrical components inputs and the mechanical design. This process stores the wiring information in a text file. Then, an



(a) (b)

Fig. 11. Figure 11(a) : The output from software. The electromechanical drawing/ fabrication file was generated after applying circuit patterns (pink line for shallow cut, black line for etching) onto the mechanical drawing (blue line for outlines, dash lines for folding guide). Figure 11(b) : After feeding the material into a paper cutter and uploading the design file, the foldable robot body is ready to be manufactured.



(a) (b)

Fig. 12. Figure 12(a): The paper robot from work in [2] contains a micro-controller two range sensors and one IMU. Figure 12(b): The robot body from the presented system contains a micro-controller, one IMU, a touch sensor, an LED, and a Resistor. The model generated from the presented system requires much less external wires than that directly from the mechanical design, which indicates that there are less effort and risk of human error during the assembly process in the presented system

electromechanical/ fabrication drawing is generated by using the DFM software package, as shown in Figure 11(a). This drawing is the last file generated by the system, and users are ready to manufacture the device with our fabrication process.

Following the fabrication cut order introduced in the fabrication process can avoid malfunction during the fabrication section. Figure 11(b) shows the 2-D shape of the foldable robot. A comparison between the old paper robot from [2] and a model generated by the presented system is in Figure 12. The only external wires in the new model come with the servo motor, which does not use pins. The process, therefore, shows it requires less effort during the assembly process.

In the experiment, to fabricate this foldable device in Figure 12(b), the time used from user input to fabrication drawing is around 3 minutes. The fabrication process, including cutting, cleanup, and assembly, takes around 30 minutes. Additionally, the material used in this prototype is around 2 US dollars.

VII. Conclusion

The presented system contains a script-based design toolset and a fabrication method aimed at enabling the public to create foldable electromechanical devices, including custom robot prototypes. Non-experts with limited technical experience can complete a design having mechanical and electrical components in a matter of minutes. Our fabrication method uses an inexpensive desktop paper/vinyl cutter to create these integrated devices in a single step process. Our presented work can extend the tools of [2], [5] to get closer to an end-to-end foldable robot compiler.

The work presented here primarily focused on the manufacturing process and associated DFM regarding the creation of foldable device prototypes. The pin insertion pattern was not optimized for iterated component reuse on the copper-plastic material, and so follow-on projects may consider enhancing device stability for production design through the use of additional materials or optimized electromechanical design. The circuit designs generated herein are limited to single-layer planar topologies; however, our fabrication process can easily achieve multi-layer routing through the stacking of substrate layers. New design algorithms can take advantage of this fact to expand the electrical capabilities of this process. In additional, higher level graphical user interfaces for design input and feedback could enhance accessibility.

Ultimately, this system paves the way towards making personalized electromechanical devices/robots more accessible to the public by lowering the barriers of technical experience and infrastructure requirements.

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