Paper Modular Robot: Circuit, Sensation Feedback, and 3D Geometry

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ABSTRACT

Modular robots have proven valuable for STEM education. However, modular robot kits are often expensive, which makes them limited in accessibility. My research focuses on using paper and approachable techniques to create modular robots. The kit's design encompasses three core technologies: paper circuits, sensation feedback mechanisms, and 3D geometry. I have developed proof-of-concept demonstrations of technologies for each aspect. I will integrate these technologies to design and build a paper modular robot kit. This kit includes various types of modules for input, output, and other functions. My dissertation will discuss the development of these technologies and how they are integrated. This research will address the considerations and techniques for paper as an interactive material, providing a guideline for future research and development of paper-based interaction.

CCS CONCEPTS

• **Human-centered computing** → **Interaction design process and methods**.

KEYWORDS

Paper-based Interaction; Modular Robot; Paper Circuit; Paper Folding; Sensation Feedback; Tangible Interaction

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1 INTRODUCTION

Robot building is a common activity in STEM education. Among them, modular robotics kits are widely recognized for their educational advantages. Such building kits have been proven to be valuable in developing children's creativity and understanding of engineering and design principles [14]. While they offer hands-on learning experiences and interactive model-building opportunities, these kits can often be expensive. This results in these modular robot kits not being accessible to all.

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To address this challenge, my work has focused on developing modular robot kits using paper and other simple technologies. I chose paper as a material to improve the approachability and sustainability of modular robotics kits. The focus of my research is on how to build interaction with paper. Traditional fabrication techniques and interaction designs based on plastic or other rigid interfaces are not necessarily suitable for paper. Therefore, I need to explore technologies specifically for paper-based interactions, thus ensuring that paper modular robots maintain comparable functionality to existing modular robots. At the same time, these technologies should be approachable to maximize the benefits of using paper as the material. My goal is to make it easier for a wider audience to participate and enjoy making robots.

2 RELATED WORK

The study of paper modular robots is based on prior research on paper-based interactions and modular robots.

The unique advantages of paper make it an attractive medium for interaction. Many researchers have investigated paper circuits. Coelho pioneered embedding conductive materials in paper for electronic components [6]. Others used circuit stickers [7] and inkjet printing [9, 11] for paper circuits. The Electronic Popables project combined books with electronics [12], and Sensing Kirigami explored paper's sensing capabilities [23]. Meanwhile, research in movable paper crafts merges handcraft and technology, creating computationally enhanced crafts. Researchers like Zhu and Qi explore shape memory alloys (SMAs) to transform paper structures [13, 24]. Yasu suggests using microwave ovens to reshape paper postcards at home [19]. Combining paper with plastic, Wang uses 3D printing with polypropylene oxide (PLA) to create paper actuators with reversible deformations [18]. Oh's motor-based cardboard system has diverse applications [10]. These studies emphasize cost-effectiveness, creativity, and customization in this field.

Modular robots are vital in STEM education, hands-on building, and entertainment. They consist of interchangeable modules for sensing, logic, and actuation, enhancing reliability and cost-effectiveness [21]. Early designs like Programmable Brick and Topobo encouraged younger users to program robots [14, 15]. Popular kits like Lego Mindstorm and VEX Robotics followed [2, 3]. Some employ centralized computing, while others, like ActiveCube and Cubelets, use distributed systems for versatile interfaces and programming [1, 8, 17]. Kinematics robot kit adds structural modules to make building more flexible [4]. Meanwhile, the M-block project proposes a physical rotating cube model that allows their modules to move and rotate autonomously [16].

3 RESEARCH QUESTIONS AND OBJECTIVES

The success of paper modular robots depends on three distinct technologies: complex paper circuits, sensation feedback on paper interface, and 3D geometry of paper folding. Within this context, I aim to answer the following research questions:

RQ 1: How to make complex paper circuits in a more approachable way?

RQ 2: How to create sensation feedback on paper interfaces?

RQ 3: What are the considerations in designing the 3D geometry of paper modules?

RQ 4: How do these three technologies integrate together?

I have developed proof-of-concept demonstrations of each of these technologies. My dissertation work will focus on the practical use of these technologies and the integration of them. My overall research objectives are:

1. Circuits: Propose approachable ways of making complex paper circuits.

2. Sensation Feedback: Propose ways of creating sensation feedback on paper interfaces.

3. Geometry: Propose design considerations for the 3D geometry of paper modules.

4. Integration of Technologies: Demonstrate how these three technologies can be integrated through practical examples. That is, to design and fabricate a paper modular robot kit.

4 PRELIMINARY RESEARCH

4.1 Approachable fabrication of complex paper circuits

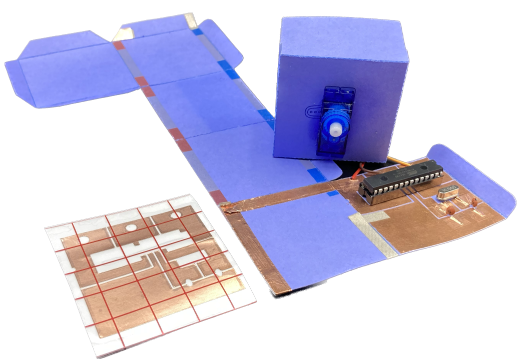

Figure 1: Zone-Based Circuit Stickers: create complex paper circuits with pre-cut copper tape stickers

Modular robots usually contain controllers in every module. This implies that we need to fabricate paper circuits that are compatible with multi-pin chips in order to develop paper modular robots. Handmade paper circuits often employ copper tape for simple designs, but they struggle with complex components due to manual limitations. Complex paper circuits require conductive ink printing, which demands specific paper, materials, and printers. This complexity can be daunting for non-technical users, limiting the approachability of complex paper circuit fabrication.

In my prior work on Zone-Based Circuit Stickers, I introduced a technique for creating complex paper circuits using copper tape. This involved redesigning the circuit layout to optimize conductive zones and producing circuit stickers through copper tape subtractive processing. Using these stickers simplifies complex paper circuit fabrication, making paper circuits accessible to users with no prior experience. Additionally, I used these circuit stickers to create Paper Box Robots, a collection of paper robots, each featuring a complex paper circuit. These circuits include 28-pin microchips like ATMEGA329P. Figure 1 shows the servo motor unit and the circuit sticker used in it. I also organized a workshop where participants built two of these robots using the circuit stickers, with all attendees successfully completing their constructions.

As part of future work, I plan to develop PaperCAD (Paper Circuit Art Design), a software tool for converting trace-based circuits into area-based circuits. This tool will aid users in circuit design and customizing circuit stickers.

4.2 Sensation feedback on paper interfaces

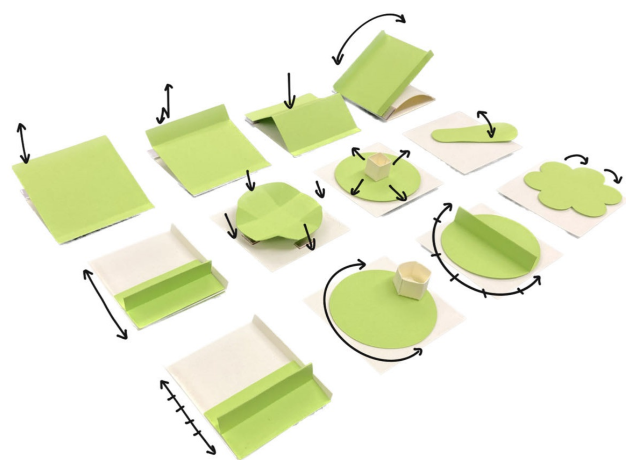

Figure 2: Paper Fidget: create sensation feedback on paper interfaces by attaching neodymium magnets to papers

Sensation feedback is critical for input interfaces, it confirms user actions and enhances engagement, providing an immersive experience. While some studies, like Chang's work on haptic feedback using kirigami and origami techniques, exist [5], these technologies often require prior experience and fine motor skills. There's a need for simpler force simulation technology for paper interfaces.

In the Paper Fidget project, I attached neodymium magnets into paper structures, enabling a variety of haptic feedback scenarios without complex electronics or programming. This approach overcomes the limitations of dynamic and responsive sensation feedback on paper interfaces. I developed three magnet-driven sensation feedback mechanisms, targeting inputs made by pressing, rotating, and linear movements. Figure 2 shows the 12 different units of Paper Fidget. Previous research has explored the use of magnets in tangible interfaces. Yasu's work focuses on arranging permanent magnets to create a sense of bumps [20]. Zheng's research discusses embedding magnets in 3D printed parts for quick fabrication of haptic and functional inputs [22]. These studies provide valuable insights for the development of the Paper Fidget.

Figure 3: Paper Polyhedron: create paper modules with different polyhedrons

The future development of Paper Fidget includes designing software to assist users in creating various sensation feedback for paper interfaces.

4.3 3D geometry of paper modules

Most modular robots today rely on cube-shaped modules for plastic products, which streamline manufacturing and transportation due to efficient molding and close packing. However, the cube design limits playability by allowing assembly only from three directions.

I advocate for paper as a versatile material that allows for a wider variety of shapes in modular robots. Figure 3 shows paper modules with various 3D geometries that I created in the Paper Polyhedron project. Along the process, I identified two aspects to consider when designing 3D shapes for paper modules. The first is the geometric characteristics of these shapes. I have found that there is more flexibility in assembling paper modules when using regular polyhedrons that can tile 3D space. Each face of these polyhedrons can be used to make connections, and users can assemble these modules in different arrangements by shifting and rotating them. I am currently working on the Paper Polyhedron, and plan to explore more 3D shapes for the paper modules. Through the practical making of these 3D shapes, I aim to discuss the challenges encountered in the design and fabrication.

5 PROPOSED RESEARCH

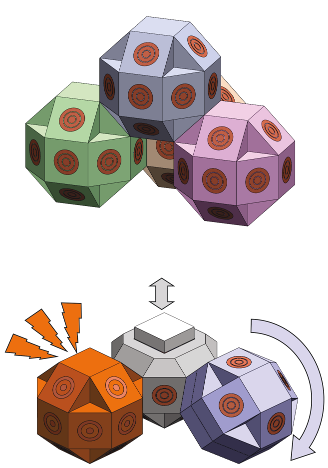

Figure 4: Paper Module Robot: paper-based interactive robot modules (conceptual illustration)

I propose to create a paper modular robot kit to explore the practical applications and integration of three core technologies. This kit will feature three module types: inputs, outputs, and functions, with particular inspiration drawn from Cubelets [1]. My tentative design is to use a rhombicuboctahedron with 30mm edges as a shell for the paper modular robot. It can be folded from a single sheet of paper and is designed to be able to open on two end faces. Figure 4 shows the design of the paper modular robots, including different ways of assembling them and different module functions.

The modules transmit signals and power to each other through the ring connectors that have three ports, each module has connectors on all square faces, except for the two that can be opened. The triangular faces without ports are concave inward. Each module contains a microchip and electronic components. The circuit will be made on a regular octagonal piece of paper, which will be placed inside the rhombicuboctahedron and connected to the connectors by copper tape.

My goal is to propose approachable ways of making paper-module robots that allow people without a technical background to participate in making and designing.

6 CONTRIBUTIONS

My work presents a contribution at the intersection of education, human-computer interaction, and robotics. The development of paper modular robots will address the limited accessibility of current modular robot kits. Meanwhile, this research explores the three technologies of paper circuits, sensation feedback mechanisms, and 3D geometry. It not only promotes wider participation in hands-on learning and STEM disciplines, but also advances the field of paper-based interaction.

7 TIMELINE

I have completed initial exploration and proof-of-concept demonstrations of three technologies at this point. I will continue to iterate on these technologies over the next two months. By March 2024, I will explore how to integrate these three technologies by prototyping interactive paper modules. Then, I will work on designing and building a full set of paper modular robots, followed by testing and design iterations. Finally, I will organize these efforts and complete my dissertation over six months.

November-December 2023: Iteration of the three core technologies

January-March 2024: Explore how to integrate these three technologies together

April-August 2024: Design and fabrication of a paper modular robot kit

September-December 2024: Test and design iterations of the paper modular robot kit

January - May 2025: Writing of dissertation

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