PaBo Bot: Paper Box Robots for Everyone

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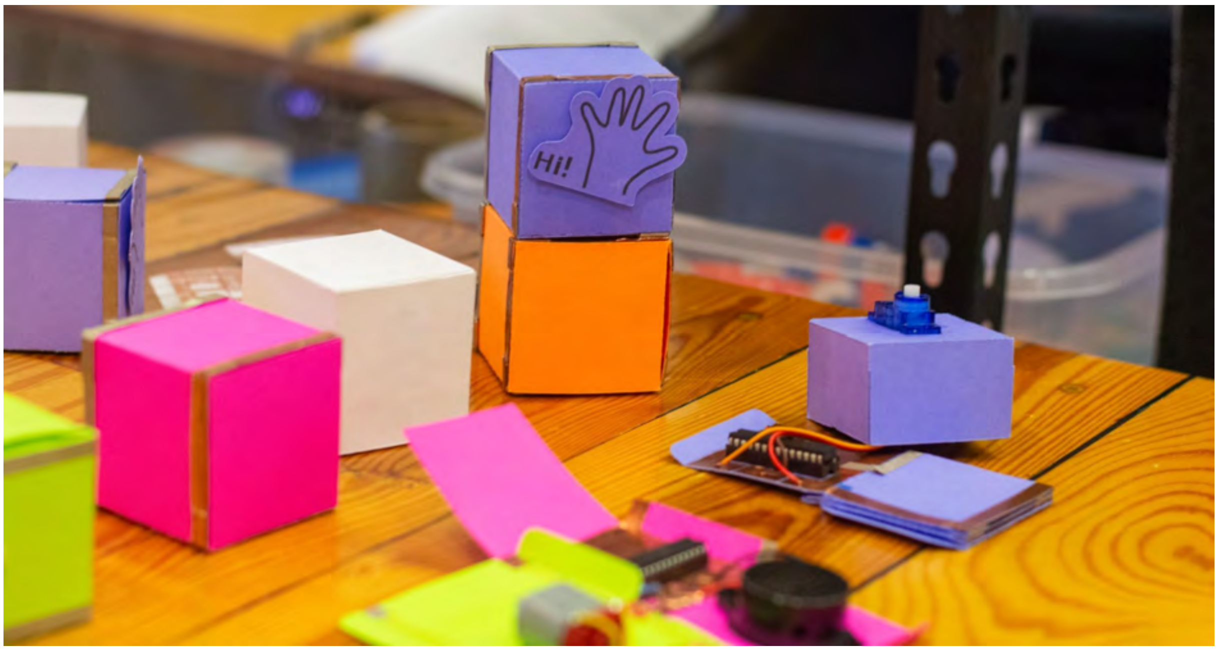

Figure 1: PaBo Bot is a set of modular robots made of colored cardstock paper.

ABSTRACT

Robot building is a fascinating hands-on learning activity, and we want to make it available to more people. Over the past year, we've been experimenting with making robot building more approachable. We presented the design and making of paper box robots PaBo Bot, a set of modular robots made with paper and everyday tools. To enable non-technical users to engage in robot building, we developed (1) a conductive sticker to support the rapid creation of controller circuits, and (2) a way to solder components using a toaster oven. We shared PaBo Bot methods and techniques by organizing hands-on workshops with novice robot builders. All participants successfully built the PaBo Bot. The results show that using our proposed techniques, people without technical backgrounds are able to participate and enjoy robot building.

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CCS CONCEPTS

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

KEYWORDS

Paper robot; modular robot; paper circuit; hands-on making

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1 INTRODUCTION

Robot building is an entertaining hands-on activity. Starting with LEGO MINDSTORMS [2], many children have been introduced to STEM concepts through robot building. Such building activities play an important role in fostering children's creativity [5]. However, the production of those plastic modular robots involves a specific and costly molding process, which makes robot building not accessible to everyone. Meanwhile, this also poses a challenge for end-user customization, robot builders could find it difficult to personalize the robots as they wish.

Building modular robots out of paper offers a unique solution to this issue. Paper is an everyday material that is ubiquitous, easy to fabricate, and recyclable. Robot builders can use scissors to cut paper, without relying on special tools or skills. Even if a mistake is made during handling, replacing the paper is easy without worrying about the material cost. Using paper also enables people to choose their favorite colors or paint directly on it. To enrich the functionality of paper robots, we designed the paper box robot PaBo Bot (Figure 1). The modular design of PaBo Bot makes it easier to make and maintain. This design also enables PaBo Bot to accomplish different interactions through various combinations, increasing its playability. With our proposed fabrication techniques, people would be able to make PaBo Bot at home using everyday tools and off-the-shelf materials. In this way we hope to make robot building accessible to more people of diverse backgrounds, thus promoting more involvement in the field of robotics. We organized workshops to investigate the usability of PaBo Bot methods and techniques, and the results indicated that users with no prior experience can enjoy building such robots.

2 RELATED WORK

Modular robots typically consist of multiple independent modules, each performing a specific function or task. These modules can be easily assembled and interchanged, offering significant advantages in reliability, functionality, and cost [7]. Programmable Brick embeds programmable modules into LEGO blocks, enabling students to create robots with complex behaviors [6]. Topobo offers users the ability to program their own robots by twisting and turning the modules [5]. Cubelets use a distributed system, encouraging users to program by connecting modules [1]. The use of distributed systems enhances the blocks to work together and optimize their behavior. The design of PaBo Bot was inspired by these efforts. We used a distributed system and added microchips inside the modules to control different functions.

The microchip of PaBo Bot is connected to other electronic components inside the box through paper circuits. Researchers have proposed different methods for making paper circuits, such as the use of copper tape and printed circuit stickers [3]. However, these circuit stickers only support specific simple components, such as LED lights. They are not yet able to support the creation of complex circuits, such as controller circuits. Fabricating paper circuits with inkjet printers has also been discussed [4]. While these conductive ink-based circuits are capable of supporting microchips, there is a long wait for the curing process during fabrication. Building on these works, we made circuit stickers by cutting copper tape. Such stickers go beyond the limitations of copper tape circuits in terms of complexity, while supporting rapid fabrication without having to wait for the curing process.

3 PABO BOT UNITS

The PaBo Bot includes five modules, the red speaker box, the orange power box, the blue waving box, the green spinning box, and the white light box (Figure 2). These units consist of common electronic components that allow PaBo Bot to have sound, motion, and visual interaction.

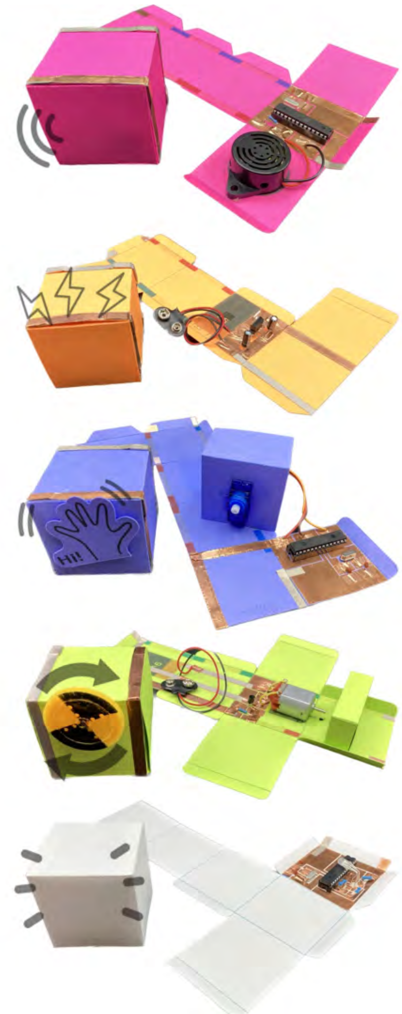

Figure 2: PaBo Bot units: the red speaker unit, the orange power unit, the blue waving unit, the green spinning unit, and the white light unit.

The speaker box (red) includes the controller circuit with a resistor and a buzzer. The buzzer produces a beep when connected to the power box. We made a set of different speaker boxes that emit frequencies between C4-C5, so we can "play music" with them.

The power box (orange) contains a simple circuit with two capacitors and a voltage regulator. This circuit converts the 9v power supply to a 5v output for the other boxes. By connecting and disconnecting the power box, we are able to control the acting and pause of other boxes.

The waving box (blue) includes the controller circuit and a servo motor held in the middle. The motor connects to the piece of paper on the outside of the box by magnets. Such magnetic coupling enables the robot to obtain more mechanical motion while being easy to assemble. When connected to the power box, the servo motor rotates from side to side to "wave".

The spinning box (green) uses a DC motor. As it requires more power to operate, we added an extra battery, a diode, and a transistor to the circuit. The motor shaft goes through the box from a small opening and is attached to a plastic disk. This disk can also be replaced with other components, such as a fan. When connected to the power box, the motor will drive the disk and start spinning.

The light box (white) includes the controller circuit, three resistors, and an RGB LED. This box also comes with an outer shell, the inside of which can be printed or painted with different patterns, and the patterns become visible when the shell is set on the lighted box. Once connected to the power box, the RGB LEDs will begin to fade. We made two different shells for Halloween and Christmas.

Except for the power and spinning boxes, the other three boxes have independent controller circuits. These controllers offer the capability of being reprogrammed by end-users, and the use of IC sockets makes it easier for users to replace these microchips. While keeping the overall structure simple, by matching different modules, users could build robots with different functions.

We created the conductive stickers (Figure 3) to make the building of these controller circuits easier. These stickers are cut from 2-inch wide copper tape. We redesigned the circuits to maximize the conductive areas, which reduces the amount of material that needs to be removed. We made these stickers by using a household vinyl cutter.

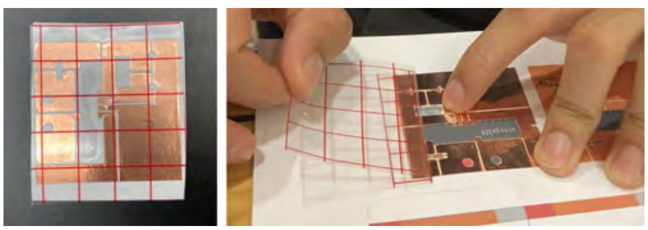

Figure 3: The conductive stickers (left) include a layer of transfer tape. The transfer tape helps the builder apply the conductive sticker to the paper more easily (right).

After applying the stickers, the user then places the components on the paper circuit, adds solder paste to the matching areas, and places the whole circuit in the toaster oven (Figure 4). We used a 650w Elite Gourmet toaster oven and Sn42/Bi58 solder paste with a melting point of 138°C. We set it at 450 F for two minutes. After the heating, we waited 30 seconds to ensure that the solder paste cooled and firmed up, and then we removed the soldered circuits from the oven.

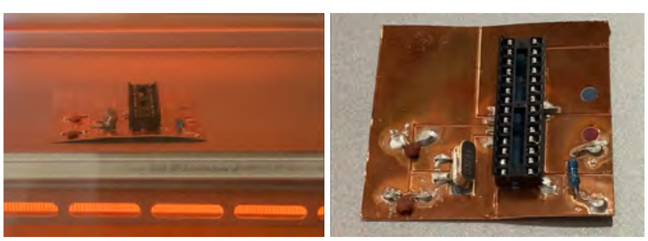

Figure 4: Using a toast oven to heat the circuit card as a whole (left), and the solder paste will melt and firmly solder the components to the paper circuit (right).

The circuits inside the PaBo Bot are connected to the outside through conductive tape, so the boxes could transmit power to each other. We also added magnets and nickel pieces underneath the conductive tape. This is to ensure that the boxes can be firmly connected to each other, while still being able to be quickly assembled and separated. The poles of the magnets also help users to connect in the correct orientation. In case of wrong orientation, the magnets will repel each other thus ensuring that the circuit will not be connected and shorted.

4 USER STUDY

We investigated the design and fabrication process of the PaBo Bot through a workshop. Eight participants from our local institution attended the workshop, three of whom had some experience with robotics and the others had no prior experience. The workshop lasted one hour, including an introduction and two rounds of guided tasks with feedback.

Participants were provided with two building kits, one for the power box and one for the speaker box. These kits included pre-cut cardstock paper, conductive stickers, electronic components, and copper tape (Figure 5). Step-by-step instructions for building are also included in the materials kit. In particular, each kit includes two circuit cards for the builder's reference of component placements (Figure 6). Participants were instructed to first complete the circuits on a piece of cardstock card, and then assemble the boxes. After both rounds of building, participants connected the two boxes together for testing (Figure 7). Participants then took a short survey to share their experiences of building the PaBo Bot.

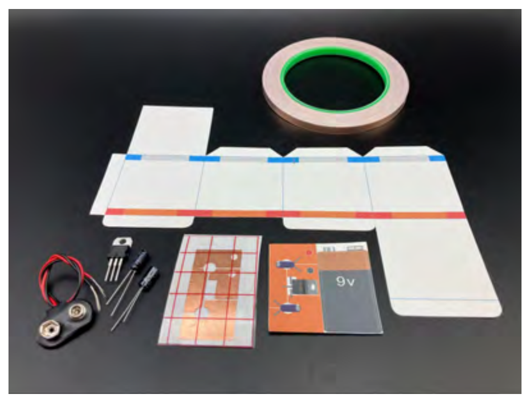

Figure 5: Materials included in the building kit: pre-cut cardstock paper, electronic components, conductive stickers, and copper tape.

Most of the participants did not experience any significant difficulty while building. One participant misplaced the copper tape during the process, but they quickly realized the issue and fixed it. All participants indicated that they could easily understand the task they were engaged in. Participants with no circuit design experience stated that the stickers made robot building easy and "fun".

We also demonstrated the PaBo Bot at public events at our university, including the ATLAS Institute Research Open House. Participants at these events were local residents from a variety of backgrounds, most of whom were students from nearby high schools and their parents. Participants actively interacted with the

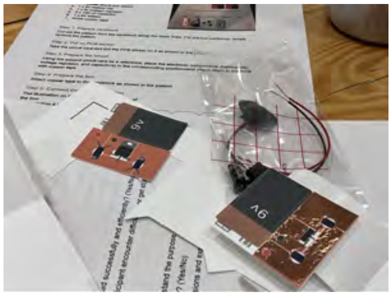

Figure 6: The building kit includes step-by-step building instructions and an extra circuit card for reference.

Figure 7: The participants connected the power box that they built to the speaker box for testing

PaBo Bot and experienced their features by connecting different boxes together. In particular, many participants waved back to the waving box and took videos of them waving at each other.

5 DISCUSSION

The results of the workshop were positive, with all participants successfully building the PaBo Bot and providing valuable feedback. The hands-on activity was widely regarded as engaging and enjoyable, with participants expressing that using stickers and a toaster oven made the process "less intimidating than initially imagined." As the workshop concluded, every participant expressed a strong desire to engage in more robot building activities. In particular, one of the participants with prior experience desired to design their own PaBo Bot units.

While this workshop provided valuable insights and feedback, it is essential to recognize its limitations. The small sample size and the specific context of the workshop might limit the generalizability of the results. Future workshops with a more diverse group of participants and real-world design scenarios could yield further valuable perspectives.

6 LIMITATION AND FUTURE WORK

PaBo Bot facilitates the easy construction of paper robots without creating accessibility challenges for users. Despite the successes achieved so far, there are still significant opportunities in the design. Some participants commented that it was difficult for them to troubleshoot the robot when it was not working. Some issues could be easily identified, such as incorrect positive and negative connections. However, when multiple components are involved, such as the speaker box, it is difficult to debug without using tools, such as the multimeter. Through discussions with participants, we concluded that providing clearer instructions could help address this issue. By describing common issues with troubleshooting steps, it would help users understand how the PaBo Bot works and identify potential problems. At the same time, designing additional diagnostic tools, such as a test box, would be helpful as well.

While the current user study provides initial validation of the usability of the PaBo Bot, there are some limitations that need to be addressed. We hope to discuss the applicability of the PaBo Bot design to a wider audience through a more comprehensive user study. As part of our future work, we will organize workshops for children to explore the potential of using the PaBo robot for educational purposes.

Another potential direction for future work would be to create more shapes for the PaBo Bot. The current modules are based on cubes, a relatively simple structure with intuitive connections between modules. However, participants suggested that using some other shapes might make robot building more interesting. We experimented with some other polyhedron such as the rhombicuboctahedron (Figure 8). This shape provided greater flexibility of movement and better structural strength. One participant described this new shape as "more organic and made it feel like a more friendly robot to me".

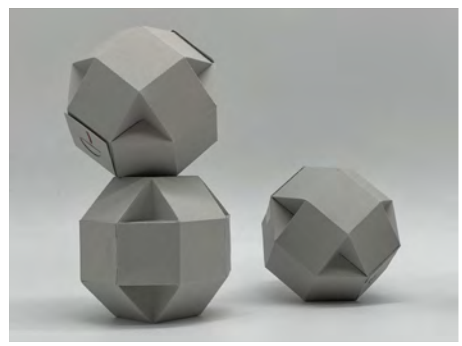

Figure 8: The rhombicuboctahedron is a potential shape for future PaBo Bot.

7 CONCLUSION

In this work, we presented the design and fabrication of PaBo Bot, a set of modular robots crafted from paper, using conductive stickers and toaster oven soldering techniques. We aimed to empower non-technical users to engage in hands-on robot building experiences, fostering creativity and learning. Through workshops and public demonstrations, we evaluated the usability of our proposed design and fabrication methods. Those techniques simplified the building process, made robot building more approachable and enjoyable for people with different backgrounds. In conclusion, our work demonstrates the potential of paper-based modular robots as a means to democratize robot building, making it accessible to a broader audience.

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