Low-Cost Wearable Human-Computer Interface with Conductive Fabric for STEAM Education

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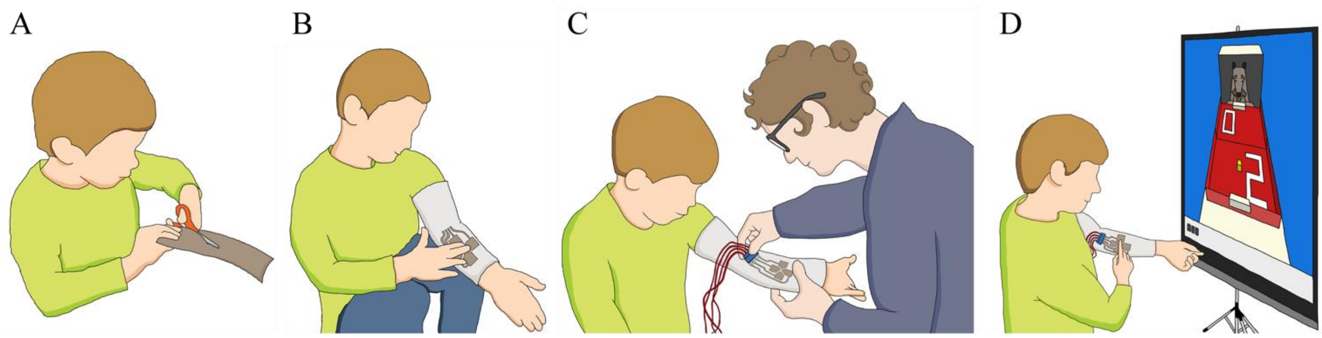

FIGURE I

ILLUSTRATION OF PRIMARY SEGMENTS OF THE STEAM WORKSHOP ON WEARABLE TECHNOLOGIES. A) STUDENTS FABRICATE A WEARABLE HUMAN-INTERFACE DEVICE OUT OF CONDUCTIVE FABRIC TAPE. B) THE CONDUCTIVE TAPE TOUCH SENSORS ARE ADHESIVELY BONDED TO AN ARM SLEEVE. C) THE WEARABLE DEVICE EMULATES A USB KEYBOARD AND IS INTERFACED TO A COMPUTER USING OPEN-SOURCE HARDWARE. D) THE DEVICE CAN BE USED TO CONTROL A COMPUTER PROGRAM OR GAME.

***Abstract* – There has been growing popularity in do-it-yourself (DIY) electronics for wearable computing and human-machine interaction. This has introduced exciting opportunities to promote science, technology, engineering, art, and mathematics (STEAM) education that highlights the intersection of electronics, materials, and artistic expression. Here, we present a systematic guide to a low-cost (<$10 per student) outreach workshop on wearable electronics for middle school students (and potentially high school students with minor modifications) that is complementary to existing STEM outreach programs. In this workshop, students use basic craft skills to fabricate a wearable human-computer interface out of commercially available materials. The device is interfaced with a computer via open-source hardware and software, using the universal serial bus (USB) human interface device (HID) protocol. The workshop exposes students to wearable technologies, a rapidly growing and exciting sub-domain of the electronics industry, and provides a fun and engaging hands-on activity that draws connections between fashion, technology, and personal electronics.**

Index Terms – wearable electronics, flexible electronics, outreach, human-computer interaction

INTRODUCTION

I. Background

Between 2009 and 2015, jobs in science, technology, engineering and mathematics (STEM) grew by 10.5%, more than twice the growth rate of other occupations. Training in these fields gives students access to a wide variety of stable careers, with an average salary almost twice the national average [1]. Early education plays a critical role in inspiring the next generation of innovators, educators, researchers, and leaders, and is important in preparing them for higher education. However, access to high quality STEM education can depend on geographic location, race/ethnicity, and socioeconomic status [2]. While many policy initiatives strive to address these problems, community outreach that focuses on educating K-12 students is a key mechanism to accelerate this process. Middle school is an especially critical tipping point where students decide to pursue the necessary progression of courses in science and mathematics to be prepared for a career in the STEM fields [3]. Many workshops and teaching tools effectively address these issues through open-source technologies [4,5], including educational thrusts in wearable computing [6] and soft robotics [7,8]. Using cheap and easily accessible materials can make these programs more feasible for communities that lack funding and resources.

Such initiatives build upon previous efforts to incorporate art into STEM education (STEAM), encourage creative thinking, and empower students with useful tools for innovation. By integrating these disciplines into a cohesive project, students learn to simultaneously call upon technical skills, analytical reasoning, and creativity in order to solve real-world problems [8]. A wide variety of programs have sought to merge these disciplines, including the Robofest RoboArts competition [9], University of Nebraska's WearTec curriculum [6], and STEM to STEAM at the Rhode Island School of Design [10].

Some work has focused on engaging students' creativity by introducing them to e-textiles and wearable interfaces. Due to the ubiquity and accessibility of clothing materials, projects involving wearable technology can be relevant to students of all ages regardless of their social and economic backgrounds. Such activities are especially effective in increasing participation and leadership in STEAM activities, particularly among females [11,12].

Here, we present an outreach program that integrates engineering and the arts to create a wearable human-computer interface device. In this workshop, students learn the scientific principles underlying this type of technology, and apply them to design and build a device that is both functional and aesthetic. Our design leverages inexpensive, commercially available materials, basic craft skills, and open-source hardware and software to emulate a USB keyboard that students can use to control a computer program or game. Illustrations of primary segments of the STEAM outreach workshop is shown in Figure I. In this paper, we provide the essential resources to enable educators, parents, hobbyists, and other researchers to develop new outreach efforts based around wearable technologies. In particular, we use open-source hardware and software that can be easily modified to complement or enhance existing educational programs and curricula. This is the third consecutive year that these materials have been incorporated into an outreach program being taught as part of the Gelfand Saturday Outreach Series at Carnegie Mellon University for middle school students (grades 7-9) [15].

II. Wearable Electronics

Wearable electronics and computing is a new, rapidly growing field that combines principles of sensing and wireless communication to transform how people sense and interact with the world around them. Although there are thousands of wearable devices on the market today, most are constructed using traditionally rigid components. Replacing stiff materials with those that are intrinsically soft and flexible allows these technologies to be integrated onto either textiles or the human skin directly, introducing a new and exciting paradigm for students exploring the field of electronics. Not only are such materials familiar and relatable, but they can be utilized in a broad range of applications of interest to students including gaming, human-computer interaction, interactive fashion, and athletic biomonitoring.

We have previously developed methods for creating a wearable keypad for data entry [16], sensorized skin for gesture recognition [17], and skin-worn sensors for touch input [18], using only highly flexible and stretchable materials. These devices are not only functional but can be customized for visual aesthetics [18]. Although these wearable sensors can function effectively as a human-computer interface, they currently require expensive or hard-to-find materials and equipment. Here, we adapt these methods to produce a rapid fabrication process for customizable wearable computer input devices that is accessible to students in middle school and above, and can be constructed using only craft scissors.

III. Learning Outcomes

The objective of this multidisciplinary program is to use the expressive nature of materials, electronics, and prototyping as a means to promote participation in science and engineering. The workshop builds upon the curricula from the NSF-sponsored Nebraska WearTec project (UNL; Lead PI: Brad Barker) [6]. Within this workshop, students can learn about the state-of-the-art in wearable electronics, basics of resistive and capacitive touch sensing, and current challenges in the field. They are also introduced to some of the basic functions of the open-source electronics prototyping platform (Arduino) that is used. While this workshop is currently an independent event, future work will include efforts to integrate this program with existing 7-9th grade curricula.

FABRICATION OF WEARABLE DEVICE

The wearable human-computer interface is composed of four conductive fabric touch sensors that are adhesively secured on a compressive arm sleeve (Figure I). The touch sensors are first individually cut from a sheet of conductive fabric tape, and attached to an iron-on fabric adhesive, preserving a robust connection between the sleeve and the electrodes even under dramatic strain (Figure IA, IB). The device is interfaced to a computer using open-source hardware to map the touch sensors to the arrow keys on a keyboard (Figure IC, ID).

I. Overview and Materials

The STEM workshop on wearable technologies is affordable ($7 per student) and requires a minimal baseline investment in materials and supplies ($27.75). The manufacturer and current prices of the required materials are listed in Table I. Additional details and product links are provided in Appendix A- Materials. The microcontroller and capacitive touch sensor are considered initial investments and are reusable between workshops.

TABLE I
MATERIALS AND PRICES PER STUDENT

Item	Manufacturer	Price
Microcontroller	Arduino Leonardo	$19.80
Capacitive touch sensor	CAP1188, 1602 Adafruit	$7.95
Arm sleeve	CompressionZ	$5.63 PER DEVICE
Fabric adhesive	3914 Bemis	DONATED
Conductive fabric tape	CSTK-040 MEC	$0.38 PER DEVICE
FFC connector	65801-006LF Amphenol FCI	$0.98 PER DEVICE
Transparency film	TF-LP TruOffice	$0.01 PER DEVICE
INITIAL INVESTMENT:		**$27.75**
PRICE PER STUDENT:		**$7.00**

II. Step-by-Step Fabrication Process

A step-by-step guide to the process of fabricating the human-computer interface is illustrated in Figure II. Steps 1-4 are intended to be prepared by supervisors prior to the workshop, but can be performed by students depending on their ages and the duration of the workshop. Source files for the conductive fabric adapter and example electrode pattern are provided in Appendix B- Source Files.

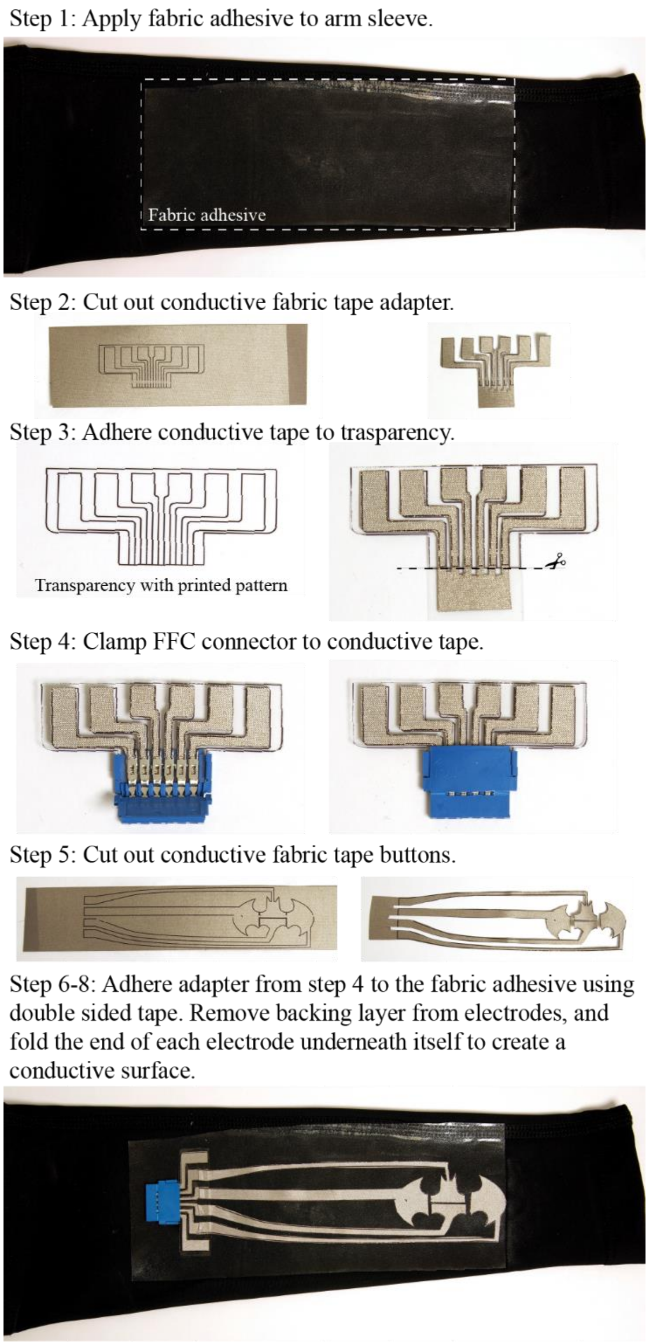

FIGURE II
STEP-BY-STEP HUMAN-COMPUTER INTERFACE DEVICE FABRICATION GUIDE.

1. Apply the iron-on fabric adhesive (Bemis, 3914) to the arm sleeves (Arm Sleeve, CompressionZ).
2. Cut the conductive fabric tape (MEC, CSTK-040) into the adapter pattern. The desired pattern can either be printed onto the fabric with a standard office printer (ColorQube 8580, Xerox) to allow students to cut out the adhesive tape by hand, or can be pre-cut with a laser cutter (Universal Laser System VLS 3.50). For pattern printing, first print the pattern on standard printer paper to provide a reference. Then place the conductive fabric tape over the pattern on the printer paper and use cellophane tape to adhere the top edge of the conductive tape to the printer paper. Finally, print the pattern on the conductive tape.
3. Remove the backing layer and adhere the conductive tape electrode connections to a flexible transparency, cut to the appropriate size. The pattern can be printed onto the transparency to help with alignment.
4. Insert the electrode connections into the flat flexible connector (FFC) clip (65801-006LF, Amphenol FCI) and crimp wire terminals to the conductive tape electrodes, ensuring that none of the terminals are touching. This part will henceforth be referred to as "the adapter".
5. Sketch the desired button pattern on the conductive fabric tape, and cut it into the desired shape.
6. Attach the adapter from Step 4 to the iron-on fabric adhesive from step 1 using double-sided tape.
7. Remove the backing layer from the electrodes, and fold the end of each electrode (0.5 cm) underneath itself to create a conductive surface on both sides of the tape.
8. Adhere the electrodes to the iron-on fabric adhesive, ensuring that none of the traces are crossing or touching. Cellophane tape can be used to secure the ends of the electrodes to the adapter from Step 4.

COMPUTER INTERFACE HARDWARE

I. Electronics

An ATmega32u4 microcontroller (Arduino Leonardo) with built-in universal serial bus (USB) communication is used to interface the wearable touch sensor with a computer. The microcontroller is programmed to emulate a USB human interface device (HID), similar to a USB keyboard or mouse. Each of the touch sensors on the wearable device is directly wired to channels 1-4 on the capacitive touch sensor breakout board (1602, Adafruit Industries) using jumper wires – see Figure III for wiring schematic. The capacitive touch sensor is interfaced with the microcontroller using I^2C and is used to detect touch inputs. The reset pin is wired to pin 10 of the microcontroller to ensure stable operation of the sensor.

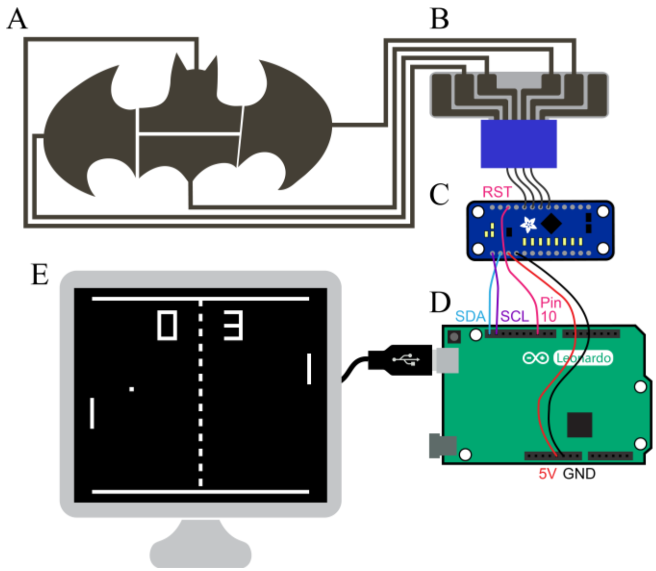

FIGURE III

WIRING SCHEMATIC OF THE HUMAN-COMPUTER INTERFACE DEVICE. THE USER TOUCHES AN ELECTRODE ON THE DEVICE (A), WHICH IS CONNECTED TO THE FFC CONNECTOR (B). THE FFC CONNECTOR INTERFACES THE CONDUCTIVE FABRIC TAPE TO THE CAPACITIVE TOUCH SENSOR BREAKOUT BOARD (C). THE SENSOR IS WIRED TO THE MICROPROCESSOR (D), WHICH MAPS THE TOUCH EVENTS TO KEYSTROKES. THE HUMAN COMPUTER-INTERFACE DEVICE IS USED TO CONTROL A COMPUTER PROGRAM OR GAME (E).

Unlike resistive touch sensors, capacitive touch sensors do not depend on the applied pressure to create a change in the flow of electricity. Capacitive touch sensing works by applying an alternating current (AC) to induce charge flow. When a finger comes within close proximity or touches one of the electrodes, a virtual capacitor is formed, changing the flow of AC current (Figure IV). This change in AC current is measured by the capacitive touch sensor breakout board, and converted to keystrokes using the microcontroller. Capacitive touch sensing is a highly versatile and efficient way to sense touch and is ubiquitous in human-interface devices.

II. Open-Source Software

We have provided the basic example software used to map channels 1-4 on the capacitive touch sensor to the keyboard arrow keys up, left, down, and right, respectively. A link to the example code is provided within Appendix B- Source Files. To upload the code to a microcontroller, follow the provided detailed instructions.

The code currently allows multi-touch sensing and scans the sensor every 0.05 seconds to check for new touch events. This code provides a starting point for other STEM outreach coordinators who are seeking to create new outreach programs or to complement existing programs. The code can be easily modified to add additional touch sensors, map sensors to different keyboard keys or key combinations, or create a new type of touch interface (e.g. slider).

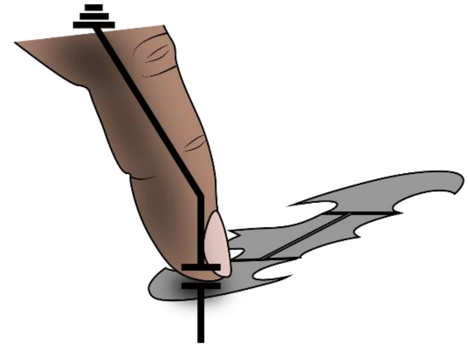

FIGURE IV

ILLUSTRATION OF CAPACITIVE CONTACT FORMED BETWEEN HUMAN FINGER AND CAPACITIVE TOUCH SENSOR ELECTRODE.

1. Navigate to the Arduino web editor and follow the instructions to install the Arduino Plugin (https://create.arduino.cc/editor).
2. Connect the Arduino Leonardo microcontroller board, capacitive touch sensor, and wearable human-computer interface device as illustrated in Figure III. Only 32u4 and SAMD micro based boards (Leonardo, Esplora, Zero, Due, and MKR Family) can be used to send keystrokes to an attached computer.
3. Connect the Arduino Leonardo to the computer using a micro-USB cable. Select Arduino Leonardo at COM* from the dropdown menu at the top of the page. The COM port number will be specific to your computer.
4. Select the new sketch button and copy and paste the software that has been provided in Appendix B- Source Files in the new *.ino file. Select the upload button to load the code onto the Arduino Leonardo.
5. When connecting a new wearable human-computer interface device to the capacitive touch sensor, press the reset button on the Arduino Leonardo to recalibrate the capacitive touch sensor.

OUTREACH PROGRAM

Through the Gelfand Center for Service Learning and Outreach at CMU, we hosted a workshop on wearable computers (Figure V). Approximately 20 middle school students (grades 7-9) participated in the workshop. We began the workshop by presenting background (approximately 45 minutes) on wearable technology, electronics, and the theory of operation of the capacitive touch sensing device. Students then applied their new knowledge to construct the personal, wearable human-computer interface described above, which they used to play the arcade video game Pong.

The current workshop did not include any formal assessments of student experience or device performance. We plan to include such assessments as part of future workshops. Qualitatively, the students enjoyed the hands-on activity and every student was able to produce a working human-computer interface device. Some of the student-made devices did not initially work, and a brief list of common problems and solutions is provided in Appendix C-Troubleshooting. In particular, delamination of the conductive paper can occur under extreme stretch when wearing the device. Double-sided tape (4905, 3M) can be used to improve bonding and prevent delamination.

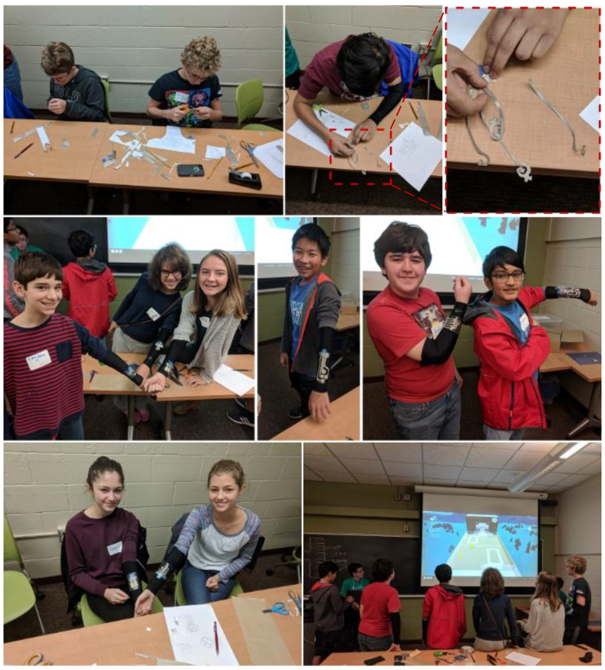

FIGURE V
PHOTOGRAPHS FROM THE WORKSHOP ON WEARABLE ELECTRONICS.

CONCLUSION

We have presented ideas and resources to enable STEAM educators, parents, hobbyists, and other researchers to develop new and affordable outreach programs on wearable electronics and human-computer interaction. The program is one way to introduce middle school students to the rapidly growing fields of smart fabrics and wearable technology, while offering them the opportunity to use their artistic creativity within a technical context. We believe that touch-sensitive wearable electronics represent an outreach topic to which teens and pre-teens can easily relate. This workshop could be extended towards high school students by including curriculum on programming, thus enabling each student to modify the example code and create a personalized human computer-interface. Future programs may also include a larger emphasis on design, fashion, and the potential role of aesthetics in wearable computing.

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APPENDIX A- MATERIALS

Web links to materials used within the STEM workshop are presented below.

- **Microcontroller:** https://store.arduino.cc/usa/arduino-leonardo-with-headers
- **Capacitive touch sensor:** https://www.adafruit.com/product/1602
- **Arm sleeve:** https://goo.gl/ugPQ8H
- **Fabric adhesive (donated by Can-Do National Tape):** www.can-dotape.com
- **Conductive fabric tape:** https://goo.gl/thP5za
- **FFC connector:** https://goo.gl/iL9Te2
- **Transparency film:** https://goo.gl/KZnJGB

APPENDIX B- SOURCE FILES

Patterns for the conductive fabric connector, transparency film, and example electrode pattern, in addition to the example code, can be found on the Outreach page of the Integrated Soft Materials Laboratory website: sml.me.cmu.edu/?page_id=49.

APPENDIX C- TROUBLESHOOTING

If your human-computer interface device is not working, refer to the guide below.

- *All of the touch sensors are on or not working.* Typically, this is due to improper calibration of the capacitive touch sensor. Press the reset button on the microcontroller to recalibrate the sensor.
- *One of the capacitive touch sensors is not working.*
  - Check to ensure the button electrode is a single continuous piece of conductive paper. If the electrode was patched together, fold the last 0.5 cm of the top piece of conductive paper on itself and secure with cellophane tape.
  - Check to ensure the conductive electrode is not torn.
  - Check the terminals in the FFC connector to ensure they are connected to the conductive paper.
- *When touching a single touch sensor, more than one touch event is triggered (i.e. multiple LEDs are illuminated on the capacitive touch sensor board).* Check to ensure the conductive electrode touch sensors and terminals in the FFC connector are not overlapping or touching.