Evaluation of Body-Worn FPCBs with Bluetooth Low Energy, Capacitive Touch, and Resistive Flex Sensing

Martin Weigel
martin.weigel@honda-ri.de
Honda Research Institute Europe
Offenbach am Main, Germany

Oliver Schön
oliver.schoen@honda-ri.de
Honda Research Institute Europe
Offenbach am Main, Germany

Herbert Janssen
herbert.janssen@honda-ri.de
Honda Research Institute Europe
Offenbach am Main, Germany

ABSTRACT

Commercially available flexible printed circuit boards (FPCBs) have the potential to embed electronics, connectivity, and interactivity into the same surface. This makes them an ideal platform for untethered and interactive wearable devices. However, we lack an understanding how well FPCB-based antennas and sensors perform when worn directly on the body. This work contributes an understanding by studying body-worn FPCBs in three technical evaluations: First, we study the integration of Bluetooth Low Energy and compare the signal strength of our body-worn FPCB with a rigid BLE developer board. Second, we study the accuracy of capacitive touch sensing with two electrode sizes. Finally, we develop a resistive flex sensor based on commercially available FPCB materials and compare its accuracy with a state-of-the-art flex sensor. Taken together, our results demonstrate a high usability of FPCB-based wearable devices.

CCS CONCEPTS

• **Human-centered computing → Interaction devices**.

KEYWORDS

Wearables; flexible; wireless; touch input; flex sensing

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1 INTRODUCTION

Many input and output techniques for mobile interaction depend on close proximity to the human body. Various body parts can be used for touch input, motion tracking, or health monitoring. However, the complex shape of the human body creates a challenging foundation for body-worn devices [6]. Flexible printed circuit boards (FPCBs) provide commercially available means to create thin and flexible devices that can conform the shape of the body. HCI researchers can create such FPCBs in a purely digital design approach, without purchasing and maintaining manufacturing hardware. Prior research presented tools [3], robots [4], and wearable devices [7, 8, 11, 13, 15] demonstrating their potential.

In this work, we contribute three evaluations of body-worn FPCBs. First, we evaluate *Bluetooth Low Energy* to enable wireless data transmission. In a technical evaluation, we compare its signal strength on the body with an off-body rigid developer board. We show the signal strength is high enough to be used for HCI user studies to log sensor data or to control one or multiple devices from an external PC or mobile device. Second, we study the accuracy of *capacitive touch sensors* embedded into the body-worn FPCB and report the accuracy for two electrode sizes. Finally, we design a *resistive flex sensor* using off-the-shelf carbon-ink used by many PCB manufacturers. This digitally designed sensor can be completely manufactured by external FPCB companies. In a technical evaluation, we show the sensor is reliable and accurate enough for infrequent operations and applications that do not require precise angular measurements. Taken together, this demonstrates that FPCBs are a good platform for wearable devices, which allows for electronics, connectivity, and interactivity on the same surface.

2 FPCBS IN RELATED RESEARCH

FPCBs are an established technology [1] and part of many commercial wearable devices. In HCI research, they have been used to create a 3D-aware tape with proximity and IMU-based shape sensing [3]. SensorTape integrates multiple SMDs and can be cut to different shapes. Flexible printed circuits also have been used for self-actuating robots [4]. Their FPCBs support pneumatics and shape memory alloys for actuation, as well as, shape sensing using a chain of

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IMUs. MagTics [8] develops wearable magnetic actuators using FPCBs as flexible actuation coils. *Touch input* on on-body FPCBs has been used by [13, 15]. TouchRing proposes a finger-worn FPCB for capacitive touch sensing [13]. They created a ring device with 48 electrodes, but have not evaluated their FPCB prototype. Xu et al. [15] evaluate typing performance on two finger-worn FPCBs. They primarily evaluate their input technique. In contrast, this work evaluates the basic accuracy of the touch sensing itself. On-body *flex sensing* has been demonstrated in [7, 11]. O'Flynn et al. [7] developed a FPCB-based glove for arthritis rehabiliation. Their FPCB connects to a rigid PCB and their sensing relies on commercial flex sensors. ShArc [11] studies multi-bend and shape sensing using two capacitive-coupled FPCBs at a fixed distance. In contrast to these sensors, we contribute a resistive flex sensor that can be manufactured completely by FPCB manufacturers. They offer an easier read-out and are made out of a single piece of FPCB.

3 PROTOTYPE IMPLEMENTATION

In three prototypes, we embed electronics, connectivity, and interactivity into body-worn FPCBs.

Untethered Vibrotactile Bracelets

The first body-worn FPCB prototype is a vibrotactile bracelet, which can be used for motion guidance [10]. It gives directional haptic feedback and measures body movements using an IMU. This prototype highlights the integration of *electronics* and *connectivity.* One main advantage of FPCBs is their ability to integrate fine-pitch surface mounted devices (SMDs). In total, our FPCB design uses seven different SMD packages. All of them work robustly on our wearable device while sitting, standing, and walking.

The FPCB contains a microcontroller (nRF52832), which supports Bluetooth 5.2. We chose *Bluetooth Low Energy (BLE)* for communication with other devices due to its low power consumption. It is connected to a standard meander-line antenna from the EAGLE library (see Figure 1a). Our average communication rate is set to 20 Hz to balance the update speed with the energy consumption. The FPCB was manufactured [1] and assembled [2] by two companies. Both companies accepted EAGLE files. We hand-soldered the four ERMs and connected a Lithium-Polymer battery (3.7 V, 400 mA h) using the FPCB connector. Self-adhesive velcro band was added to the ends of the FPCB for attachment. An optional 3 mm craft foam was adhered under the bracelet for comfort. The complete device weights 14.79 g.

Capacitive Touch Sensors

Touch is one of the most important input methods in HCI. We use capacitive loading mode sensing (single capacitance) to measure touch contact on the wearable device since it is the simplest and most common type of capacitive sensing in HCI research [5]. The touch electrodes are designed as footprints on the FPCB and hence embedded inside the layers of the FPCB. The electrodes are made with copper and encapsulated by a layer of polyimide.

Resistive Flex Sensors

Another important input modality for wearable devices is flex sensing to measure body movements [9]. For example, sensors on the fingers could sense the triggering of a virtual gun in a game. The flex sensor is embedded into the FPCB and allows for simple resistive measurement. They can be designed with custom-shapes and completely manufactured by many FPCB manufacturers [3]. The embedded sensors support sensing flex in one or both directions.

A *one-directional* sensor contains one copper layer and one carbon layer. The copper layer contains multiple sequential, but disconnected, patches along the sensing direction (see Figure 3b). One solid carbon layer (Capton BH-06, solid content: 72.5–78.5%) connects the copper patches. When the sensor is bent, the carbon-particles are spread apart and the resistance of the sensor increases. The resistance change is measured using a voltage divider circuit. Bending in the opposite direction decreases the resistance slightly, but not enough for precise measurements.

While this is enough for the measurement of many body movements (e.g., elbow or finger movements), some applications require flex measurements in *both directions* (e.g., wrist movements). We built a prototype that supports this by stacking two flex-sensor layers, one facing in each direction. This allows precise measurement in one direction with one of the sensors and in the other direction with the other sensor. However, dual-side flex sensing increases the thickness of the sensor and makes the material stiffer compared to the one-directional flex sensor.

4 EVALUATIONS

Signal Strength of Body-Worn BLE

FPCBs have different properties than rigid PCBs and are slightly curved when worn on the body. We evaluated their signal strength to understand how BLE on body-worn FPCBs compares to a rigid off-body nRF52832 developer board. Both transmitted with a signal strength of 0 dBm (decibel-milliwatt). The measurements were taken with a smartphone (based on a Qualcomm Snapdragon 845 with Bluetooth 5) from 25 cm to 500 cm distance without obstacles in an office

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[1] Multi Circuit Boards Ltd. (www.multi-circuit-boards.eu)

[2] HUG Elektronik (www.hug-elektronik.de)

[3] In our case, LeitOn GmbH (www.leiton.de)

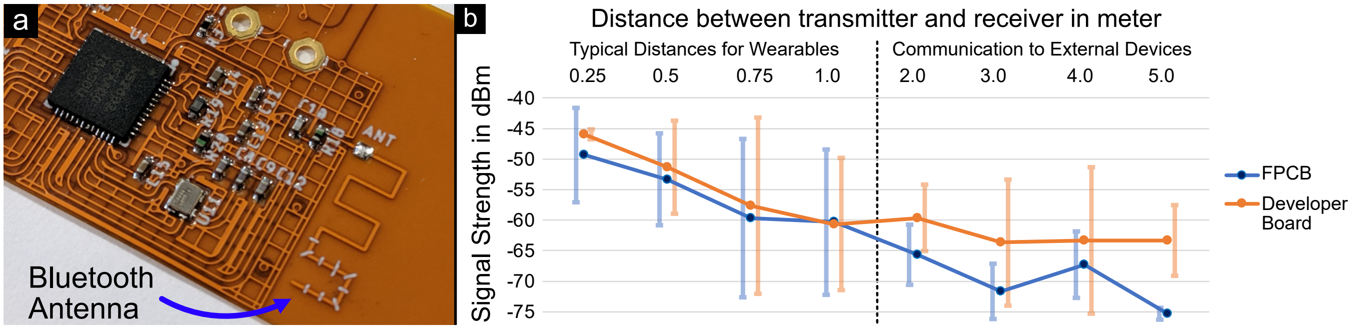

Figure 1: Bluetooth Low Energy evaluation: (a) FPCB antenna design; (b) Comparison of the average received signal strength (and standard deviations) from different distances for an FPCB and a development board.

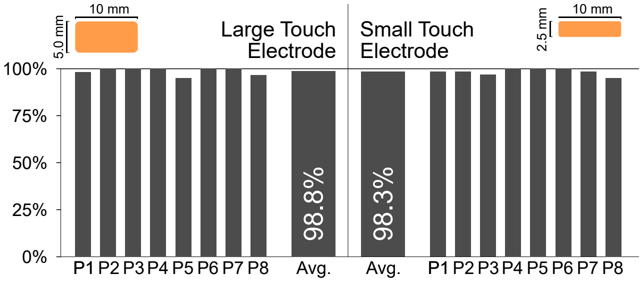

Figure 2: Accuracy with a large and a small touch sensor.

environment. The FPCB was worn as a bracelet around the wrist with the BLE antenna facing the receiver. The development kit was standing on the floor. The measurements were taken in three different rooms to avoid environmental bias.

The averaged received signal strength can be found in Figure 1b. For the FPCB device, the average measured signal strength was −62.8 dBm. Taking only typical distances between wearable devices into account (25 cm to 100 cm), the average signal strength increases to −55.7 dBm. In contrast to the development board, the FPCB performance is on average −4.6 dBm lower (−1.8 dBm for 25 cm to 100 cm). Noteworthy, the Bluetooth 5.0 specification [12] requires a minimum receiver sensitivity of −70 dBm to −82 dBm, which covers all of our measurements (max. −78 dBm) and is usually exceeded by current Bluetooth receivers.

Capacitive Touch Sensing

We evaluated the reliability of body-worn capacitive touch sensing. Eight voluntary participants (5m/3f) were recruited for the study. We tested a large (10 mm × 5 mm) and a small touch electrode (10 mm × 2.5 mm) with the shape of a rounded rectangle. The order of the sensors was counterbalanced. The sensor was attached to the participant's wrist with a strap of Velcro. Participants were seated and asked to keep their arm rested on a table to avoid fatigue effects influencing the results. Similar to [14], participants touched the sensor electrode repeatedly in 2.5 sec intervals. An auditory metronome was used to guide participants without requiring their visual attention. Each detected touch input created an additional auditory feedback in a different frequency. The study started after a short training phase that accustomed the participant with the task. The touch events were sensed with the capacitive sensing library of an Arduino Uno and a 1 MΩ resistor. On the microcontroller, we calculated a moving average low-pass filter and used a hysteresis. We prompted 120 touch inputs per participant (60 per sensor, 960 in total). The study took approximately 10 min per participant. After each trial, we asked participants to press the sensor for 1 sec and release it for the same time to calculate the signal-to-noise ratio.

The percentage of correctly recognized touch contacts (i.e., exactly one touch event per interval) is shown in Figure 2. The average accuracy was 98.5 % (SD=1.1 %). The large sensor had an accuracy of 98.8 % (SD=1.2 %) and the small one of 98.3 % (SD=1.1 %). These results show a high reliability and accuracy of body-worn FPCB-based touch sensors. This is supported by a high average signal-to-noise ratio of 166.0 (SD=100.5; min=60.0, max=367.6) for the large and 92.7 (SD=56.1; min=28.6, max=191.3) for the small sensor. The SNR was higher than the recommended minimum for capacitive sensing (≈15 [2]) for all participants.

Resistive Flex Sensing

We evaluated *repeated resistive flex sensing* using our unidirectional flex sensor. The flex sensors base was firmly held in place and the sensor was manually bent over a cylinder with the diameter of 4 cm. The sensor bent approximately around half of the cylinder (≈180 °). We measured the rest and bent state of the sensor with an Agilent U1241B in three sessions with 10 bends each (Figure 3a). We waited 15 s between each measurement and 2 min between each session. The sensor was bent 20 times before the evaluation started to avoid initial break-in effects.

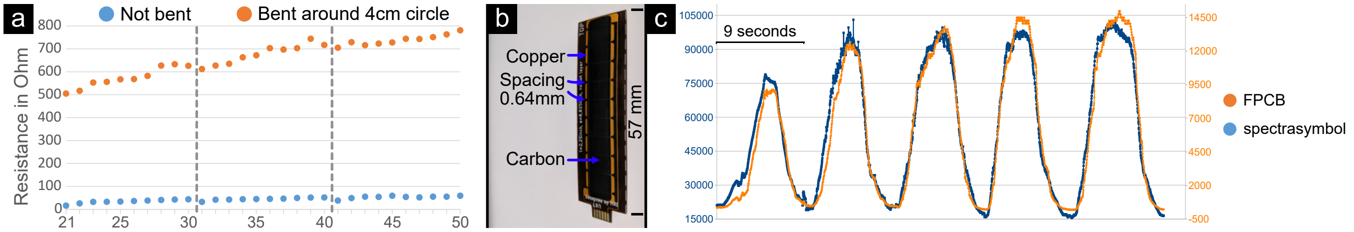

Figure 3: Resistive flex sensor: (a) Three sessions with 10 measurements each. (b) Flex sensor prototype. (c) Measured resistances of the FPCB-based sensor and a spectrasymbol sensor for five bend inputs. The y-axes were aligned for comparison.

The average resistance was 44.2 Ω (SD=10.0 Ω) in the resting state and 663.0 Ω (SD=77.1 Ω) in the bent state. The large difference between both states shows that they can be easily distinguished with a hysteresis. It is noticeable that the resistance of the bent state increases permanently over the 30 bends (from 505 Ω to 781 Ω). We believe the flex stress creates small cracks in the carbon layer, leading to this increase in resistance. In the resting state, the sensor did not revert to a completely flat position, but remained slightly curved. This explains the small increase in the resistance of the resting state (from 16.2 Ω to 59.2 Ω). Bending the sensor back to a flat position decreased the resistance to its initial value.

We compared the *accuracy of our flex sensor* to a state-of-the-art sensor from spectrasymbol [4] to understand its accuracy. Both sensors had the same length. They were attached together to allow sensing the same bent angle with both sensors. The carbon width of the FPCB sensor was twice the width of the commercial sensor. The same FPCB sensor from the previous experiment was used, which was bent over 100 times before the experiment. The resistances were measured through a voltage divider using an Arduino Uno. We chose an 1 kΩ resistor value for FPCB sensor and a 40 kΩ for spectrasymbol. Figure 3c shows the resistance values of both sensors during five manual bends. Both sensors show a smooth increase in resistance when the sensor is bent and a decrease in resistance when the sensor is flattened. The findings show that our self-designed flex sensors have a good repeatability and accuracy. However, their resistance during bending increases over multiple bends. Therefore, the same angle can lead to different resistances during operation. Different carbon concentrations or an additional polyimide stiffener might reduce this problem in the future.

5 CONCLUSION

This work evaluated body-worn FPCBs in three technical evaluations showing a high reliability of interactive, body-worn FPCBs. In the future, we plan to develop and investigate other body-worn FPCB form factors to demonstrate novel combinations of electronics, BLE, touch and flex sensing.

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