SwitchBack: An On-Body RF-based Gesture Input Device

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ABSTRACT

We present SwitchBack, a novel e-textile input device that can register multiple forms of input (tapping and bi-directional swiping) with minimal calibration. The technique is based on measuring the input impedance of a 7 cm microstrip short-circuit stub consisting of a strip of conductive fabric separated from a conductive fabric ground plane (also made of conductive fabric) by a layer of denim. The input impedance is calculated by measuring the stub's reflection coefficient using a simple RF reflectometer circuit, operating at 900MHz. The input impedance of the stub is affected by the dielectric properties of the surrounding material, and changes in a predictable manner when touched. We present the theoretical formulation, device and circuit design, and experimental results. Future work is also discussed.

Author Keywords

Electronic textiles; wearable sensors; RF.

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation: User Interfaces

INTRODUCTION

On-body forms of technology continue to grow in both commercial and research sectors. As these devices become more prolific, they can benefit from novel interfaces that can more robustly support existing and new interaction techniques. E-textiles and non-traditional forms of conductive materials, such as inks and tape, lend new opportunities for flexible and textile-based on-body input devices. The physical downsizing of hardware has allowed previously unrealized on-body form factors. The proliferation of wireless and cell phone devices has resulted in cheap, robust and readily available surface mount components for RF circuits. We can create novel sensing devices using RF circuits which integrate easily in existing e-textiles [9, 2] and extend to a number of different on-body and mobile applications. We present an RF-based sensing device that can detect two-way swiping and tapping with minimal calibration, which we call SwitchBack

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Figure 1. Clockwise starting from upper left: SwitchBack; on backpack strap; on tie; weatherproofed on sleeve; underneath pant leg.

(See Figure 1). We explore embedding and weatherproofing techniques to demonstrate how SwitchBack is not only resilient to the elements but functional in a number of different scenarios and contexts-offering flexibility for interface design. The system is lightweight and can be coupled directly with the detection circuit, or decoupled using a coaxial cable, permitting for placement on numerous on-body locations. We see such an interface as being used on t-shirt sleeves, the side of ones trousers, backpack straps, or extending more ubiquitously into ones environment through placement on dog leashes or embedded in chair arms. SwitchBack is eyes-free, unobtrusive, and supports multiple forms of input and one-handed access.

RELATED WORK

Post and Orth explored e-textile interfaces by embroidering conductive thread into clothing [10]. A number of e-textile interfaces have since been devised that use capacitive [7], resistive, circuit completion [8] or hybrid resistive-capacitive [15, 5] sensing methods for implementation. These interfaces permit for touch input, and are conducive for wearable forms of technology as they can be directly sewn into garments. Each method offers particular advantages (resistive yields direct touching, capacitive enables hovering activation, and the hybrid approach addresses issues with resistive or capacitive sensing alone). However, they also face a number of limitations. In the case of the hybrid sensing method, often elaborate interfaces need to be constructed to avoid shorting and involuntary activation. Capacitive sensing is often non-discriminatory with respect to the conducting agent, lending to false triggering. Resistive surfaces offer closed-circuit solutions ideal for discrete touch, but localizing triggers usually require the integration of numerous leads. This applies to all of the sensing methods mentioned, as these interfaces fall short in their ability to arbitrarily assess multipoint touch or continuous input without extensive lead construction–a huge fabrication challenge. These interfaces are also susceptible to malfunctioning if exposed to the elements.

Wimmer and Baudish have recently introduced a family of single and two wire sensors capable of measuring the position of a touch using time domain reflectometry (TDR) [14], a measurement technique where an electrical pulse is injected into a transmission line, and partial reflections (echos) of the pulse indicate the position at discontinuities in the line. While TDR was first developed to detect flaws in transmission lines, the approach can be used to detect and localize changes in the environment surrounding the line. For example, Sun et al. designed a coaxial cable to be embedded in concrete structures to determine position and size of cracks [12].

With SwitchBack, we present an eyes-free, one-handed interface capable of discrete and multi-directional continuous on-body input. The methods reviewed above [15, 5, 8, 7] rely on discrete sensors, requiring an increased number of measurements and computational cost for similar resolution. SwitchBack is both fabrication-simplistic and competent when either conspicuously or inconspicuously embedded in clothing. Using RF also allows SwitchBack to be weatherproofed (limiting susceptibility to the elements), provides for multiple input methods, and is more robust to accidental triggering. The design of wearable antennas for airwave, mobile telephone and Wifi network communications in [4, 16] have shown the feasibility of using textiles for body-worn antennas, and demonstrate that many fabrics are low-loss and robust to moisture and washing. Like the TDR approach in [14], our approach relies on changes to transmission line properties. However, our measurements are performed in the frequency domain, whereas TDR measurements are performed in the time domain. We measure a complex (magnitude and phase) reflection coefficient at the input of the transmission line using a continuous, single frequency RF signal. There are several tradeoffs between the TDR approach and ours. TDR measurements suffer from multiple echos, which may cause erroneous measurements. In the frequency domain, each multiple reflection simply contributes to the measured steady-state reflected signal [11]. Determining the position of a touch using TDR involves peak detection, which involves calculating zero-crossing points of the derivative of the measurement. Using our approach, touch position has a near linear relationship with the phase of reflection coefficient, making detecting and locating a touch much simpler. Unlike our approach, TDR is designed for use with very long transmission lines. In our approach, the length of transmission line is limited by the frequency of transmitted wave, in order to ensure a unique measurement for any touch location. Despite this limitation, the frequency range of our circuit components (100MHz - 2.7GHz) allows for textile interfaces up to 75cm in length, suitable for most wearable sensors.

SWITCHBACK PROTOTYPE

The fabric portion of the interface was designed using a layering construction of conductive and non-conductive fabric. The base layer is a 3.8cm by 12.7cm Rip-Stop Conductive Metallized Nylon fabric, which serves as the ground plane for a microstrip line. A 2mm layer of iron-on adhesive denim constitutes the middle layer and was ironed directly to the conductive base. The top layer consists of a 10cm by 0.635cm strip of Rip-Stop conductive fabric that is centered and adhered to the denim layer using fabric glue. On one end of the interface, the top strip and base were connected using 117/17 2-ply conductive thread, forming a short-circuit. On the opposite end of the interface, the base and the conductive top strip were attached to the measurement port and ground plane of the RF circuit using copper tape. This interface was designed to attach to a number of on-body clothing articles or other textile-based items. The length of the interface and frequency of operation can be adjusted so that the interface is the ideal length of 1/4 of the wavelength of the RF signal. The thickness of the dielectric layer, and width and thickness of the microstrip line are independent of frequency.

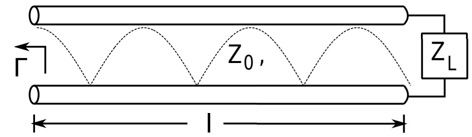

Figure 2. Standing wave on a loaded transmission line.

THEORETICAL FORMULATION

RF signals are alternating current signals with frequencies in the range of several hundred kHz to several hundred GHz. In this range, the wavelength of the signal is small enough that the phase of a signal varies significantly over the area of a circuit. This section describes transmission line theory and calculation of parameters relevant to this investigation. A more complete description of the topic is available in [11].

Reflection Coefficient

In an RF circuit, a transmission line is schematically represented as a two-wire line, and can be electrically described with a complex propagation constant, $\gamma = \alpha + j\beta$, and characteristic impedance, Z_0, for lines with negligible loss [11], as shown in Figure 2. This line is terminated at location $z = l$ with an arbitrary load Z_L. An incident RF signal is injected at $z = 0$ propagates down the line, and may be partially or fully reflected at $z = l$, due to the mismatch of line and load impedances. The incident and reflected waves form a standing wave, as shown in Figure 2. The standing wave represents the voltage on the line as a function of position. The maximum, minimum and phase of the standing wave vary as a function of the characteristic impedance of the line and load impedance. The input impedance of the line and reflection coefficient, measured at the input of the line, vary based on the value of the standing wave at that point. The reflection coefficient, Γ, is a complex value representing the ratio of the incident and reflected wave. The standing wave, reflection coefficient and input impedance all change with variations in length, characteristic impedance, or load impedance.

Microstrip Parameters

A microstrip consists of a conducting strip separated from a ground plane using a dielectric substrate, as shown in Figure

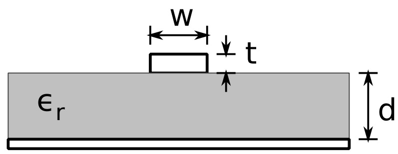

Figure 3. Cross-section of a microstrip transmission line.

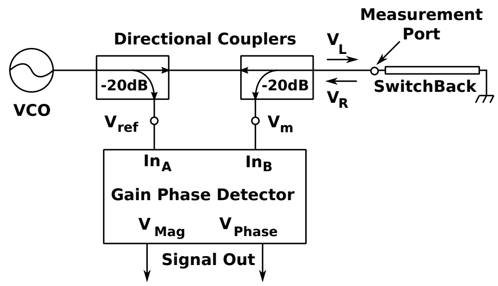

Figure 4. Schematic of reflectometer circuit connected to SwitchBack.

3. The characteristic impedance of the microstrip line with line width w, thickness t, dielectric height d and relative (to free space) dielectric constant ϵ_r can be calculated [11, 13]. A derivation of these equations is beyond the scope of this paper. Touching the microstrip is equivalent to covering the strip with a layer of generally lossy dielectric. Because human skin has a very high permittivity (relative to free space) [6], and the average thickness of an adult fingertip is much thicker than the layer of denim [3], analysis can be simplified by treating the layer of human skin as an infinite dielectric layer. The characteristic impedance of a microstrip covered by an infinite dielectric layer is given in [1].

Reflectometer Circuit

The reflectometer circuit used to measure the input impedance of SwicthBack is shown in Figure 4. This circuit consists of a Maxim MAX2623 Voltage Controlled Oscillator (VCO)[1], two Skyworks DC09-73 20dB directional couplers[2], and an Analog Devices AD8302 gain phase detector[3]. Circuit transmission lines have a characteristic impedance of 50Ω, to match the impedance of the components. The gain phase detector is the most expensive component, but may be replaced with any component or circuit capable of measuring the phase difference between two signals, such as a mixer.

The VCO generates a 900MHz signal at -3dBm (500μW). The first directional coupler is used to maintain a -23dBm reference signal, V_{ref}. The remaining signal power is passed through the second directional coupler and provides an input signal at the measurement port, V_L. The reflected signal, V_R, is then transmitted to the second directional coupler, which provides a measurement signal V_m. The reference and measurement signals, V_r and V_m are used as inputs to the gain phase detector. This component generates two DC voltages, V_{Mag} and V_{Phase}. V_{Mag} is based on the gain of the measured signal to the reference signal ($|V_m|/|V_r|$) and V_{Phase} is based on the phase difference between the two signals ($\angle V_m - \angle V_r$). This provides a measurement of the coherent reflection coefficient measured at the input of the detector. This reflection coefficient consists of the superposition of the static reflection coefficient internal to the circuit, and a dynamic reflection coefficient due to interaction with SwitchBack.

[1]http://datasheets.maximintegrated.com/en/ds/MAX2622-MAX2624.pdf
[2]http://www.skyworksinc.com/uploads/documents/200228B.pdf
[3]http://www.analog.com/static/imported-files/data_sheets/AD8302.pdf

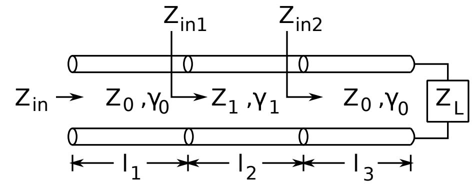

Figure 5. Input impedance of a microstrip transmission line touched at an arbitrary position.

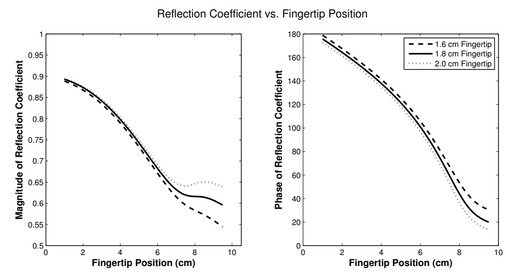

Figure 6. Calculated magnitude and phase of reflection coefficient of SwitchBack touched at various positions.

RESULTS

Calculated Results

The magnitudes and phases of reflection coefficients were calculated for fingertips of different widths (1.6 cm, 1.8 cm, and 2.0 cm) located at different positions along SwitchBack, as shown in Figure 6. The magnitude and phase of the line when untouched vary greatly from the values calculated when touched, and the calculated phases are unique for the given line properties. From phase measurements alone, it is possible to determine the position of the fingertip uniquely. Tapping (sudden jump in phase), upward swipe (increase in phase) and downward swipe (decrease in phase) can be recognized by continuous monitoring of these values.

Experimental Results

Experiments were performed by measuring the voltage output of the magnitude of reflection coefficient while performing three different gestures (downswipe, upswipe and tap) on the SwitchBack prototype. Three sets of experiments were performed on SwitchBack–uncovered, covered by a layer of cotton/polyester canvas, and when weatherproofed using EcoFlex silicone rubber, reflecting the scenarios in Figure 1.

Figure 7 shows the results of these three measurements. Downswipe gestures are represented by a jump in voltage when the finger touches the measurement port end of SwitchBack, which declines as the finger slides down. Upswipes are mirrored–a steady increase in voltage followed by a sharp return to baseline as the finger is released. Finally, taps result in a simple spike as the finger touches and releases the interface.

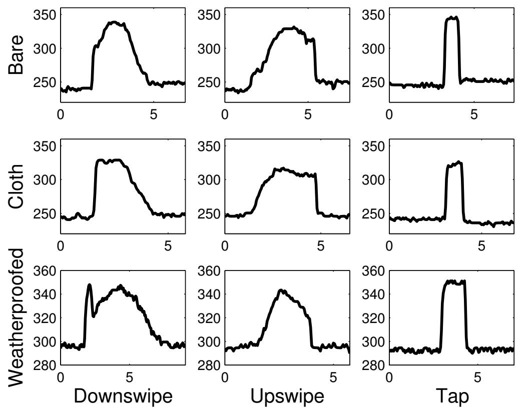

Figure 7. Characteristic gesture signals for downswiping, upswiping and tapping, for three configurations of SwitchBack. Horizontal axes are time (in seconds). Vertical axes are measured voltage (in millivolts).

The characteristic signals vary little between the three swatch configurations. When embedded in EcoFlex, however, the dynamic range of the signal is reduced some, though not enough to affect detection. This is likely due to EcoFlex soaking into the denim, resulting in a change in the permittivity of the dielectric layer and increase in the static reflection of the line at the port of the reflectometer circuit.

DISCUSSION AND FUTURE WORK

The use of RF lends to an eyes-free, one-handed interface capable of multiple types of input. Because the RF signal is only sensitive to dielectric and geometric properties, textile substitutions can be made without altering the circuitry or the sensing mechanism. The data from our experimental findings demonstrate a handful of possible usage scenarios for SwitchBack. The weatherproofed system tackles the issue of susceptibility to the elements. The ability to use the interface in a covered, uncovered, or weatherproofed state lends to the optional conspicuity of the device and permits for flexibility in usage scenarios. Currently, our system can support three types of input. However, by modifying the interface with an additional conductive layer or elastic conductive fabric we can build in additional functionality, including pressure detection, multi-touch, and twist recognition. Designing the interface as a coaxial line can make it less sensitive to indirect touching and more robust to accidental triggering.

CONCLUSION

SwitchBack explores the use of RF and non-traditional conductive materials to create on-body interfaces capable of multiple forms of eyes-free, one-handed input. We have also shown the manufacturing simplicity of Switchback, as well as its ability to perform reliably in exposed, embedded, and weatherproofed scenarios. SwitchBack is just one possible example of novel interfaces which could be designed by combining decades of RF research with wearable technology.

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