A Novel Chipless RFID-Based Stretchable and Wearable Hand Gesture Sensor

Taoran Le, Ryan A. Bahr, Manos M. Tentzeris
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, U.S.A.
Taoran.le@ece.gatech.edu

Bo Song, Ching-ping Wong
School of Material Science Engineering
Georgia Institute of Technology
Atlanta, U.S.A.

***Abstract*— The continuous monitoring of hand gestures is a very challenging application due to the demanding requirements for robustness, accuracy, efficiency and cost effectiveness. Although several vision-based gesture sensors have made good progress in human action recognition, the human hand is a smaller object with more dexterity and is more easily affected by segmentation errors. In this paper, we present a novel chipless RFID-based hand gesture sensor utilizing stretchable silicone-based electrically conductive adhesives (silo-ECAs) which effectively create a "smart-skin". The hand sensor uses wearable multi-resonator spectral signatures to encode data and to provide a unique ID for every hand gesture.**

Keywords*— Chipless RFID, stretchable, wearable, electrically conductive adhesive, wireless, hand gesture sensor.

I. Introduction

There is a pressing demand for more accurate techniques to wirelessly detect hand gestures in a robust manner, especially in low - or no - visibility scenarios and in harsh environments such as underwater applications and smoke filled rooms. The currently available wireless depth sensors such as those found in the Microsoft Kinect platform [1] are expensive and inapplicable for use under extreme conditions.

For these applications, a novel approach is desirable - we present here such a method. Instead of utilizing wireless technologies to transmit digitized data captured by conventional sensors, the basic sensing mechanism here relies upon the strain-dependent behavior of electromagnetic waves in resonance/scattering based systems. The movement of the various joints in the hand produces differences in electromagnetic signature for various hand gestures. By continuously monitoring the electromagnetic signature of the gestures using a strain sensor at each hand joint, we can uniquely code and characterize various hand gestures across a range of movements using a short-range reader (50cm interrogation distance).

In our preliminary proof-of-concept prototype, 14 strain sensors were placed on the 14 joints of the hand as presented as all the colored dots in Fig.1 (a). The sensors are made from cascaded spiral resonators, with each resonator having a slightly different resonant frequency. All the strain sensors are then coupled with a microstrip transmission line that is terminated on both ends with receiving and transmitting antennas. A reader sends out a multi-frequency interrogation signal and the multi-resonators of the hand gesture sensor tag create a unique spectral signature which characterizes every individual hand gesture. The transmission and receive signals are cross-polarized in order to achieve isolation between them.

The chipless hand gesture sensor encodes the data regarding gesture characteristic in the frequency spectrum itself. The varying geometry produced in a given gesture causes the resonators to resonate at particular frequencies and to create narrow, high Q factor stopbands. The hand gesture sensor retransmits the received interrogation signal and the resulting backscatter radiation contains the useful information characterizing the gesture encoded in both magnitude and phase. In this paper a four joint hand gesture sensor, as shown as the red dots in the Fig.1. (a), is presented to prove the concepts discussed.

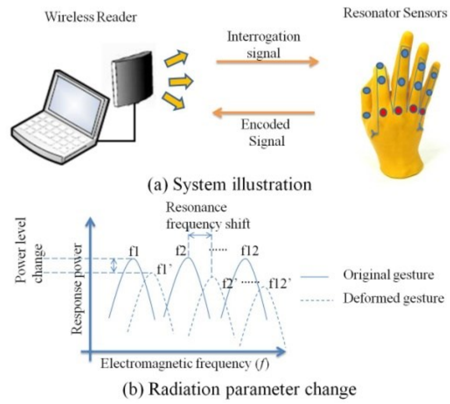


Fig.1. The proposed RFID based hand gesture sensor system.

To create resonators which vary their electrical properties (resonant frequency, etc) as a function of the strain induced, we incorporated stretchable / flowable conductive materials into the design. Common materials for stretchable electronics include conductive polymers [2] conductive polymer composites [3], and liquid metal alloys [4] as stretchable conductive lines. In this experiment we chose to use stretchable silo-ECAs as the stretchable conductive material and pure silicone elastomers as the dielectric substrate to fabricate the stretchable hand sensor tag for several key reasons. The silo-ECAs feature a higher conductivity

(1.51×10^6 Sm^{-1}) than most previously reported stretchable conductors [2, 3]. More importantly, the conductivity of silo-ECA is as high as 1.11×10^5 Sm^{-1} at a strain of 240% and remains almost invariant over 500 cycles of stretching at 100% applied strain [5]. These silo-ECAs are highly suitable for building stretchable RF devices.

In the following section, we will introduce the design of the chipless RFID based wireless hand gesture sensor, which is comprised of two ultra wide band (UWB) antennas and a four-resonator circuit. For the reader, a broadband log periodic dipole array (LPDA) and a dual-band, circularly polarized antenna are proposed. Section III will present the measurement results of the hand sensor system. Finally, section IV discusses the preliminary conclusion of the experiment.

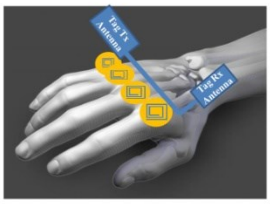
II. RFID Based Hand Sensor prototype

Chipless RFID technology provides a potentially promising solution to lowering the total RFID system cost [6]. Preradovic et al. demonstrated a chipless RFID system with a multi-frequency signal to detect the variation in the magnitude and phase of the received interrogation signal and to decode the binary information stored within through the structure of the tag [7]. This research group successfully designed a 35-bit chipless tag operating in the UWB frequency band.

A. The Chipless RFID Tag Design on "Smart Skin"

As a first step in developing a hand gesture sensor to cover all possible gestures, we began with an initial goal of obtaining the ability to encode the various positions of the four fingers as presented in Fig. 2. (a). The layout for the hand gesture sensor is presented in Fig.2. (b) – here the Tag Rx/Tx antennas are located on the backside of the hand. The four resonators are placed on the largest joint of each finger, also known as the metacarpophalangeal (MCP) joint. Each resonator will be placed on a 5mm×5mm area to accurately represent the available space above each MCP joint. Due to the required narrow cavity resonant bandwidth and the size limitation constraints, the compact rectangular spiral resonator was chosen here [8].

(a) The coding of each hand gesture for 4-resonator circuit



(b) Layout of 4 resonators with Tag Tx/Rx antennas

Fig. 2. RFID hand-gesture sensor tag

The proposed hand gesture sensor is built on a silicone rubber. Silicone rubber features a unique combination of features such as biocompatibility, patternable fabrication methods, high elasticity, and a low dielectric constant, making it an excellent candidate for stretchable electronics substrates. The selected Elastosil M 4642 has a low dielectric constant and dissipation factor and an elongation at break of 787% [5]. A ground plane of ECA is located beneath the silicone which isolates the hand gesture sensor from the human body.

The largest challenge for stretchable electronics, especially RF devices, is that the conductivity has a significant drop under a certain mechanical strain. In order to minimize the conductivity change under strain, a 80 wt% silver filled ECA was produced in house. The shape and morphology of the silver fillers are carefully engineered to achieve an initial conductivity value of 1.51×10^6 Sm^{-1}. After embedding ECA onto the silicone substrate, the conductivity reduces to 5.03×10^5 Sm^{-1}.

The in-house silo-ECA is capable of high-definition stencil-printing as well as soft lithography to fabricate the hand sensor RFID tag. Fig. 3 presents the stencil printing process to fabricate the RFID tag using a facile two step process. First, a silicone pre-polymer is poured onto the convex pattern and is cured to form an elastic mold with patterned cavity. After peeling off from the convex pattern, another silicone based ECA is stencil printed into the cavity of the mold to form the elastic and conductive pattern. In the soft-lithography process, a master mold by patterning a silicon wafer is treated with 1H,1H,2H,2H-perfluorododecyltrichlorosilane to make it hydrophobic and to facilitate the peeling of the silicone substrate from the silicon wafer. The rest process is similar to the stencil printing process. Due to the cost effect, we decided to use the stencil printing process for this paper.

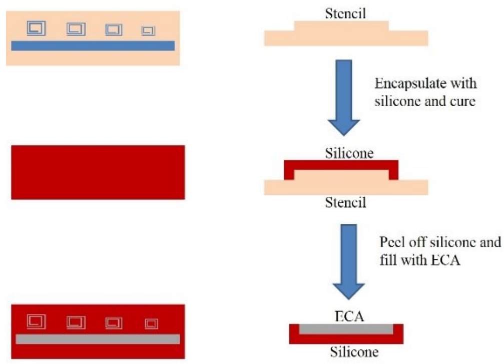


Fig.3. Stencil printing fabrication process of a stretchable RFID tag

Due to the hand joint's size limitation, a 4-bit chipless RFID based hand gesture sensor was designed in the frequency range of 2-3GHz for proof-of-concept. The 4 resonators introduce a gesture-specific variable attenuation and phase ripple to the transmitted interrogation signal at the designed resonant frequency, which can be detected at the reader side. Based on the resonators of silo-ECA under 50% strain and a total bending of 90°, the simulation results of each gesture using the Computer Simulation Technology (CST) STUDIO SUITE® 2014 are shown in Table I, which presents the attenuation and phase ripple. The Q factor values of the 4 resonators fabricated with silo-ECA are in the range of 30-40.

Table I. Simulated Insertion Loss and Phase for Each gesture

Gesture		Insertion Loss	Phase
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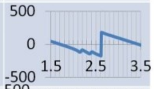
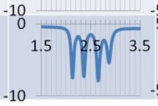
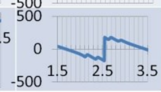
	0001		
	0011		
	0111		
	1111		

B. *Cross-polarized RFID Antenna*

The operating frequency bandwidth of the RFID tag antenna determines the number of bits that can be used or encoded into the tag. The wireless hand-gesture RFID-based sensing tag requires preferably an omni-directional or wide-beamwidth wideband antenna. The chosen microstrip-fed trapezoidal antenna has a simple structure and a large bandwidth. The microstrip line is designed around a 50 ohm impedance at 2.3 Ghz. The trapezoidal antenna is matched to the microstrip line, which then transfers the power through the multi-resonator system. As the RFID antennas will be located on the back side of the hand, there is little need for the flexibility of these antennas compared to the resonators at the joints. A benchmarking RFID antenna was printed on photo paper ($\mathcal{E}_r$ =3.1, $tan\delta$ =0.05) using silver nano-particles with inkjet printing technology [9]. The preliminary tag antenna prototype that can be easily integrated in a wearable glove or uniform and can be coupled inductively with the resonators is presented in Fig.4.

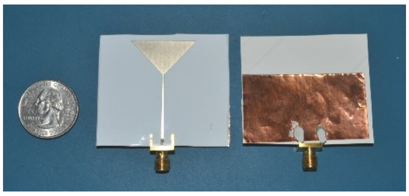


Fig.4. Inkjet printed RFID antenna top side and bottom side

The hand sensor tag includes two UWB antennas: one is for receiving the interrogation signal, the other is for transmitting the signal passing through the resonant structures back to the reader antenna. In order to minimize the cross-coupling of these two antennas, the reader and tag antennas are cross-polarized, which introduces further restrictions on the sensor tag's positioning and orientation.

C. *Reader Tx/Rx Antenna Design*

The reading range highly depends on the radiation pattern and on the gain of the interrogating reader antenna. The LPDA is one of the preferred candidates for the reader antenna interrogating the hand gesture sensor due to its inherent good isolation between two cross-polarized antennas, which are 90 degrees to each other, directive radiation pattern, and very high bandwidth. A custom designed LPDA reader antenna on RT/duroid 5880 ($\mathcal{E}_r$ =2.2, $tan\delta$ =0.0009) is proposed for this hand gesture sensor system, due to the requirement of high gain and reliability, shown in Fig.5.

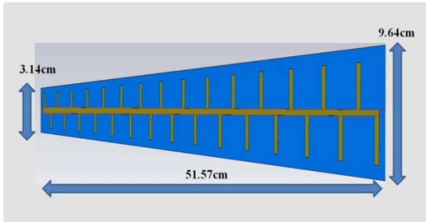


Fig.5.The top view of the proposed LPDA reader antenna

III. Hand-Gesture Sensor Prototytping

A. *The Chipless RFID Tag*

A benchmarking proof-of-concept 4-resonator circuit was fabricated by stencil printing silo-ECA on silicone, as shown in Fig.6. A copper sheet at the bottom of the silicone acts as the ground plane, which we will replace with ECA in the future. The ECA conductivity remains almost invariant under a 50% strain. Nevertheless, the current ECA in the proposed stencil printing method can not guarantee the ECA uniformity, due to the resonators' 100 um thickness and the 200 um gap between the transmission line and the resonators. We need to change ECA's viscosity to improve the uniformity of the silo-ECA to fit for the circuit design without impairing the mechanical and electrical properties of the composite. To tune the ECA's viscosity, a shorter chain of poly-dimethylsiloxane precursors with lower molecular weight and degree of functional groups has been applied. The decreased crosslink density will allow for an easier flow of the elastic resin to fully fill the patterned cavity and to enhance the printing uniformity on the substrate as well.

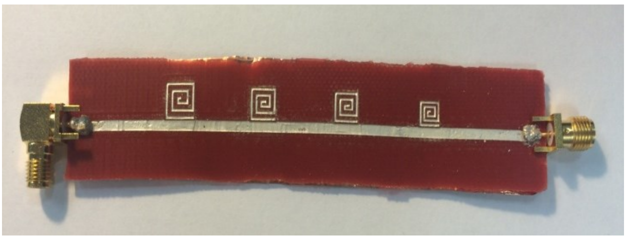


Fig.6. Stencil printed silo-ECA resonators

B. The RFID Tag Measurement

Test results for two specific gestures are presented in Fig. 7 below. The first gesture has all 4 fingers out, whereas the second gesture has the pinky at 90 degrees. The resonant frequency for the resonator on the pinky finger was shifted by 136 MHz in response to the bending action. However, other frequencies were also shifted by up to 70 MHz. It is believed that the copper sheet at the bottom of the silicone substrate negatively affected the isolation of each figure's action. We plan to use ECA instead of a copper sheet to make the tag more flexible in the next prototype to prevent this issue. We have recorded the gesture signatures into our data bank for later machine learning exercises.

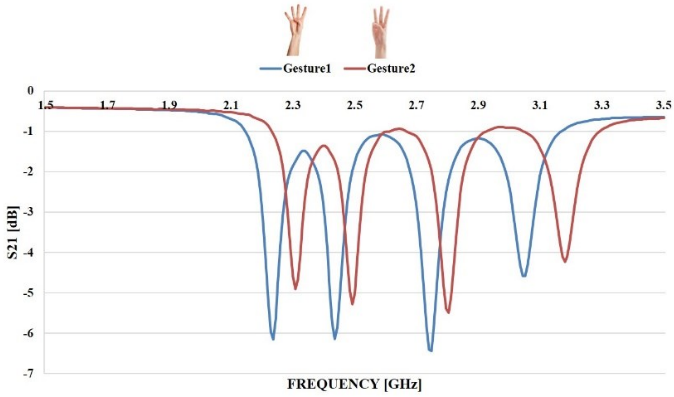


Fig.7. Two gestures insertion loss measurement results

C. The Cross-polarized RFID Antenna Measurement

The measured vs simulated return loss of the inkjet printed trapezoidal antenna is presented in Fig.8 below. This antenna can cover the 2-3 GHz band for the 4 resonators of the hand sensor. The realized gain is 2.52 dBi.

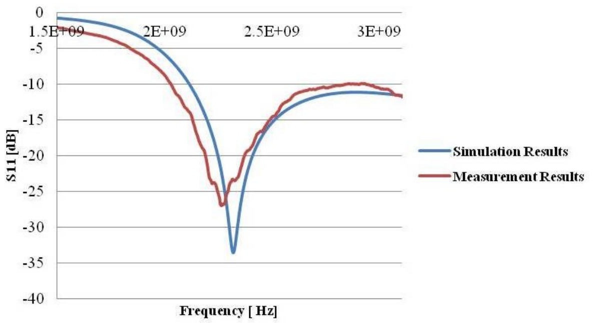


Fig.8. Simulated and measured return loss of tag antenna

IV. Conclusion

We have presented the concept of a novel chipless RFID-based stretchable hand-gesture sensor system, which can be realized using silo-ECAs. Various reader antennas including a dual-band circularly-polarized antenna topology will be evaluated in terms of interrogation range and system-level results will be presented at the conference.

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