Clothing-Integrated Passive RFID Strain Sensor Platform for Body Movement-Based Controlling

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***Abstract*— This paper introduces the fabrication and wireless performance evaluation of a passive ultra-high frequency (UHF) radiofrequency identification (RFID)-based strain sensor platform, which is designed for body movement-based human-technology interaction. The used RFID platform is fabricated from electro-textile materials and can thus be seamlessly integrated into clothing. A two-part antenna structure is utilized in this work to avoid the reliability challenges caused by mechanical stresses that clothing-integrated electronics need to endure. The fabricated sensor has an initial peak read range of 5 meters, which is an excellent result for on-body performance. Further, the platform is functional throughout the global UHF RFID frequency band. During elongation, the peak read range of the sensor has a significant decrease, but it is still readable from distances of 2.5 meters. Thus, this sensor can be read wirelessly from a convenient distance, when considering its practical use in body movement-based controlling of digital devices. The wireless performance of the sensor platform has a significant change caused by arm elongation, which based on our initial results can be clearly read from the changed backscattered signal. Thus, based on these preliminary results, our sensor platform shows potential as a passive clothing-integrated controller, which can turn simple gestures into inputs for digital devices.**

Keywords—Electro-textiles; human-technology interaction; passive UHF RFID technology; strain sensor; clothing-integrated electronics

I. INTRODUCTION

Due to the requirement of simple, cost-effective, and maintenance-free solution, the use of passive RFID (radio frequency identification) –tags, especially in the UHF (ultra-high frequency) range, has been suggested for body movement monitoring. Such monitoring would allow us to use simple gestures as inputs in human-technology interaction. Passive RFID uses battery-free, remotely addressable electronic tags, composed only of an antenna and a small IC (integrated circuit) component, having a unique ID.

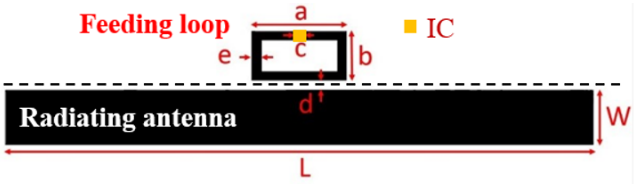
Variations of backscattered signal strengths and phases from on-body passive RFID tags have been shown to provide information about body positions and movements [1]-[6]. It has also been shown, that when a user actually touches an RFID tag with finger, it manifests as a change in phase of the tag's backscattered signal [7][8]. Further, adding sensing capabilities to passive RFID tags has been widely studied and by tracking changes in the tags' backscattered signals, passive UHF RFID tags have been used for sensing without external sensors, especially as strain [9]-[12] and moisture [13]-[15] sensors.

In this article, we establish the first prototype of our clothing-integrated passive UHF RFID-based strain sensor platform, which can turn simple gestures into inputs for digital devices. As the antenna materials are electro-textiles, our platform can be seamlessly integrated into clothing. We optimize a two-part antenna structure in order to solve the common reliability challenges of clothing-integrated electronics, caused by mechanical stresses. The separate antenna structure contains a radiating antenna and a feeding loop with the IC. These two parts of the antenna are connected by inductive coupling and thus the IC part can be placed at a small distance from the radiating antenna. In case of a wearable sensor, the antenna-electronics interconnections are usually under strong stress, which may cause electrical and mechanical reliability challenges for the interconnections [16]. Furthermore, since the antenna's structure changes when stretched, it may cause the antenna-IC matching to change [16]-[18]. Thus, in this work, due to the separate antenna design, the small feeding loop part of the antenna, including the antenna-IC interconnection, can be protected from mechanical stresses during elongation of the radiating antenna, which can significantly improve the reliability of the RFID sensor platform.

II. MANUFACTURING

The structure and dimensions of the two-part antennas are shown in Fig. 1. This antenna has been initially presented in [19], where it was evaluated for reliability during harsh stretching. The antenna design has two separate parts, the feeding loop and the radiating antenna, with a 2.5 mm gap between them. Thus, it is possible to attach the IC to a non-stretchable substrate, while the radiating antenna can be fully stretchable.

We fabricated the radiating antenna using Less EMF stretch conductive fabric, which is a commercial stretchable silver textile material, fabricated by plain knitting [20]. The feeding loop was cut from nickel plated Less EMF Shieldit Super Fabric (Cat. #A1220) [21]. Both of these electro-textile antennas were cut using a laser cutter (Epilog Fusion Laser Model 13000). After antenna fabrication, in order to establish the actual sensor structure, NXP UCODE G2iL series RFID ICs, provided by the manufacturer in a strap with copper pads, were attached to the feeding loop with conductive silver epoxy (Circuit Works CW2400). As shown in Fig. 2, the fabricated sensor platform is then attached on a normal cotton-based shirt using textile glue (Prym Textil+ Adhesive).



a	b	c	d	e	W	L
21.6 mm	11.3 mm	2 mm	2.5 mm	1.9 mm	12.6 mm	135 mm

Fig. 1. The design and dimensions of the two-part antenna.

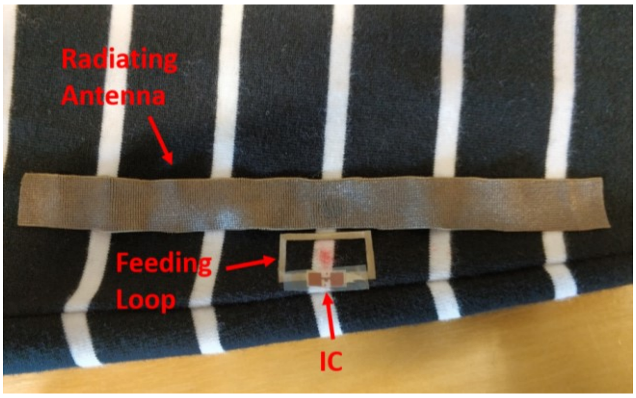


Fig. 2. The fabricated sensor platform on a normal cotton-based shirt.

III. MEASUREMENTS AND RESULTS

The strain sensor was measured in an anechoic room, using a measurement system containing an RFID reader unit with a capability to a power-frequency sweeps. All the measurements were conducted on the human body from a distance of 1meter. The sensors were measured initially and when they were elongated. The measurement setup is shown in Fig. 3.

The theoretical read range describes the maximal distance between the tag and reader antenna in free space, i.e., in an environment without any reflections or external disturbances. The measurement equipment calculates the theoretical read range of the tag using its measured threshold power and the measured forward losses, which are first calculated using a reference tag that has known properties. Thus, it's called theoretical read range, which can then be calculated assuming that the read range was limited by the maximum allowed transmitted power levels. The theoretical read range is calculated using Equation 1:

$$d_{Tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{P_{TS}L_{fwd}}} \qquad (1)$$

where λ is the wavelength transmitted from the reader antenna, EIRP is the maximum equivalent isotropically radiated power allowed by local regulations, P_{TS} and L_{fwd} are the measured threshold power and forward losses, respectively. Our results are corresponding to maximum EIRP = 3.28 W, which is the emission limit in European countries.

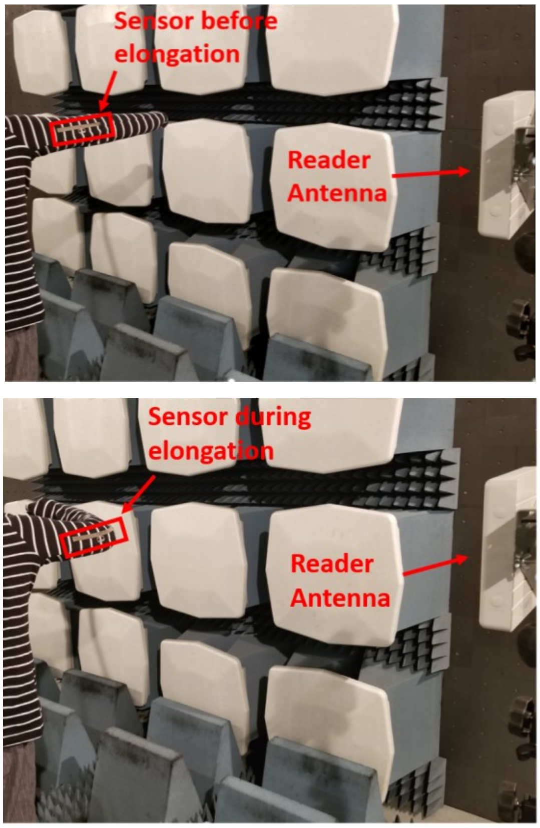


Fig. 3. The measurement setup of on-body measuremnts in anechoic room: before elongation (top) and during elongation (bottom).

In this study, the backscattered signal power is utilized to monitor the wireless performance of the sensor. In an anechoic space, the backscattered power at the reader antenna at distance d from the tags is given by Equation 2:

$$P_{rx} = P_{tx}{G_{tag}}^2{G_{reader}}^2\left(\frac{\lambda}{4\pi d}\right)^4 \alpha|\rho_1 - \rho_1|^2 \qquad (2)$$

where P_{tx} is the transmitted power from the reader, G_{tag} is the gain of the tag antenna, G_{reader} is the gain of the reader (transmit/receive) antenna, λ is wavelength, d is distance from the tag, ρ_1 and ρ_2 are the power wave reflection coefficients of the tag in two different chip impedance states (used for modulating the backscattered signal) and α is a coefficient that depends on the specific modulation details.

The wireless performance of the sensor platform was evaluated when attached on the shirt and worn on a male test subject, as presented in Fig 3. The read range results of the platform, before and during elongation, are shown in Fig. 4. The original length of the radiating antenna is 135 mm, when it is attached on the straight arm. After that, the radiating antenna is elongated to 160 mm, when the elbow is bent to 90 degrees. Based on the results, the initial peak read range of the tag is around 5 meters. When the sensor is elongated, the read range decreases to 2.5 meters. Both of these read ranges are definitely suitable for many practical strain sensor applications, when we are considering the use in human-technology interaction. Further, the platform stays functional in both arm positions, from a distance of at least 1 meter, throughout the global UHF RFID frequency band.

Fig. 5 shows the change of the backscattered power of the sensor tag (at 915 MHz) before elongation, during elongation, and when back to the initial stage again. The sensor is in unloaded condition initially, when the arm is held straight.

Then it is elongated gradually by the arm and then it returns back to the original status, as presented in Fig 3. The backscattered power of the sensor in original status and elongation status has a significant difference, which is more than 10 dB. Thus, the strain sensor has a great sensitivity on the human body to detect the movement of the arm. Although we are now initially only evaluating this kind of on/off type controlling, our plan is to study the possibility of more accurate controlling.

Our next plan is, that the changing length of the clothing-integrated radiating antenna, caused by specific body movements, could be detected from the changed backscattered signal strengths. These changes will then be used as wireless inputs for connected devices. As each sensor platform has its unique ID, several sensor platforms can be used on different parts of the body. Thus, the next steps are to test these platforms on different parts of the body and integrate a reference tag into the platform, in order to avoid the effects of reflections or external disturbances on the sensor performance. Then, the goal is to use these sensor platforms to control for example smart home applications.

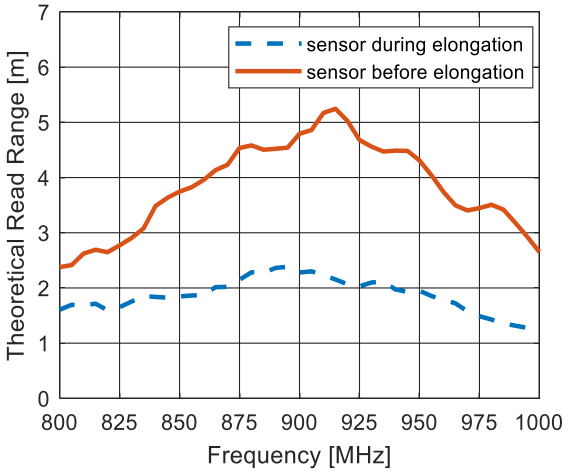


Fig. 4. The read range of the strain sensor platform before and during elongation.

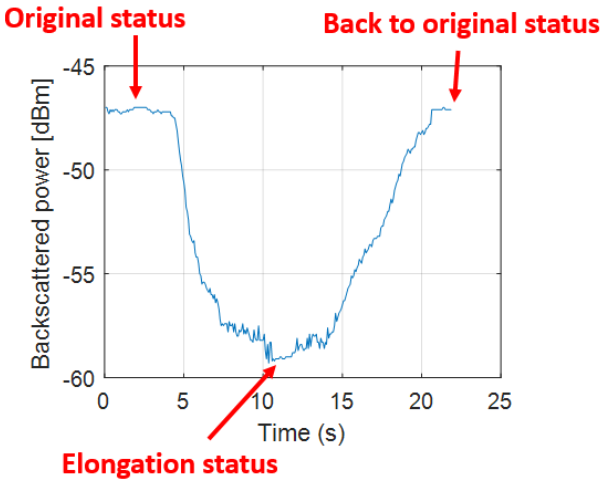


Fig. 5. The backscattered power of the strain sensor platform before and during elongation.

IV. CONCLUSION

The goal of this study was to develop a clothing-integrated passive and wireless strain sensor platform, based on the behavior of a strain-sensitive passive UHF RFID tag antenna. A two-part antenna structure was utilized in this work to avoid the reliability challenges caused by mechanical stresses that clothing-integrated electronics need to endure during normal use. Performance of this shirt-integrated sensor platform was examined on-body by backscattered signal power measurements under strain and in unloaded conditions. As a result, 20 percent elongation leads to 10 dB difference in the backscattered power, which means that this sensor can achieve great strain sensitivity. The sensor offers future potential for many human-technology applications, including smart home applications, rehabilitation and exercise monitoring, virtual reality, and gaming. For example, the sensor could be used for counting the movements of elbow, knee, and chest in exercise monitoring or it could be utilized as a controller in an embodied game.

Our future work is to design a strain sensitive antenna structure with a linear response and increased sensitivity in order to achieve more accurate controlling. This sensor platform will also include a reference tag and it will be tested on different parts of the body. The results of this paper will be utilized in the design process. Future work will also include the first practical applications.

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