Finger-Augmented RFID System to Restore Peripheral Thermal Feeling

V. Di Cecco, S. Amendola, P.P. Valentini, and G. Marrocco

Abstract—Finger-Augmented Devices (FAD) identify a particular wearable technology suitable to turn the human fingers into enhanced sensing surfaces for advanced human-computer interfaces. The feasibility of a full on-body UHF RFID-based FAD is here investigated for the first time. The system is aimed at providing impaired people suffering from a lack of thermal feeling, due to pathological disorders, with a realtime feedback of the temperature sensed by the fingertips. The considered RFID-FAD comprises an epidermal tag suitable to conformal application over the fingertip and an interrogation wrist patch antenna. The electromagnetic challenge concerns the possibility to establish a robust RFID link when both the reader antenna and the passive fingertip tag are attached onto the lossy human skin. The occurring near-field interaction is modeled by a two-port system and experimentally tested by means of a 3D hand mockup made by additive manufacturing. Simulations and measurement permitted to derive the upper-bound performance and to estimate the required power budget. The idea is finally demonstrated with a proof of concept in a realistic application.

Index Terms—Radiofrequency Identification, FAD, Wearable sensors, wireless sensor, Epidermal Electronics, UHF antennas, additive manufacturing.

I. INTRODUCTION

Peripheral neuropathy [1] is a pathological condition caused by damages to the nerve pathways responsible for receiving, transmitting, or processing external stimuli. Diabetes, thyroid disorders, rheumatoid arthritis, alcoholism and vitamin B12 deficiency as well as medical treatments (HIV drugs, statins, radio and chemotherapy) are common causes of this transient or permanent disorder, which is usually accompanied by somatosensory impairments, including the loss of pain, touch and/or temperature sensation. Among these disease-related crippling symptoms, dealing with lack of the temperature feeling, especially concerning the heat sensation, seriously impacts on the execution of common tasks which require judging the temperature of everyday things like the dish or bath water. It can even result in severe burns occurring before the subjects’ awareness. While medical treatments (antidepressant and anti-seizure) are often merely a palliative, and in any case not tolerable over the long-term in the form of irreversible pathology, there exists a concrete social need to provide impaired people with comfortable technological recovering of their physical limitations, thus improving the quality of their daily life.

This paper investigates the possibility of wireless Finger-Augmented Devices (FAD) [2] based on the passive UHF Radiofrequency Identification and Sensing, denoted as RadioFingerTip, able to artificially restore the temperature feeling of the fingertips and to provide the wearer with a real-time feedback about the sensed temperature. The considered hand-free system comprises an epidermal-like battery-less tag properly shaped around the fingers with temperature sensing capability and a wristband interrogating antenna. The fingertip tag is illuminated by the reader antenna and, as soon as the user touches an object with its fingertip, the temperature value of the contacted surface is transmitted back to the reader where it becomes available for processing.

Figure 1. Concept of the RADIOFingerTip system for augmented touch comprising an epdermal UHF RFID sensor tag and a wrist interrogating device potentially integrable with a smartwatch.

Having in mind the RadioFingerTip system as target application, this paper investigates the wrist-to-finger communication occurring in the near field. The aim is to demonstrate whether it is possible to establish a reliable UHF RFID-sensing link through the hand and to quantify the power required to activate the sensor tag. Numerical analysis and then laboratory experimentations were performed in reference conditions by using a CAD model of a human hand that was manufactured by 3D printing. Prototypes of a folded wrist patch and of a conformal fingertip meandered-dipole were designed and fabricated for the tests. The communication performance are discussed by the two-port power gains which account for the near field interactions between the fingertip tag and the wrist antenna. Finally the resulting device was preliminary experimented by a volunteer in a realistic application.

A. Related Works

The idea of providing the hand with RFID capability has been already considered in recent years. The use of a glove or RFID bracelet readers, mostly working in the HF band, was
proposed to detect the tagged tools people interact with and, accordingly, to infer the performed activities [3], [4], [5]. In the latter case, the tags were placed over everyday objects. From another side, finger-worn antennas were presented for general purpose BAN applications in the UHF, ISM and UWB band [6], [7], [8], [9]. More recently, even fingernails have been considered as suitable surface where to place electronic components, including small displays and cameras [10], [11], touch-sensitive pads [12], radio-controlled LED and vibration motor [13], [14] and even HF RFID chips [15]. These FADs are aimed at turning the humans’ fingers into input enhanced surfaces for human–computer interaction [2]. However, to the best of authors’ knowledge, FADs are usually intended to be interrogated by wired, or even wireless, off-the body devices while the case of a whole on-the arm sensing RFID system, interacting with the high electromagnetic loss of the body, has not yet been considered so far.

II. THE REFERENCE HAND

The feasibility and the design of the components of the RadioFingertip system are hereafter referred to a realistic representation of the hand suitable to both numerical modeling and rapid prototyping by 3D additive manufacturing. The hand phantom (Fig. 2) consists of a 3D hollow structure made of a polymer shell filled by a liquid simulating the electromagnetic parameters of human tissues.

The hand mockup was fabricated by the Zortrax M200 printer using ABS filler with a density of 1.06 kg/dm³. The equivalent permittivity of the plastic shell (a weighted average of ABS and air) was measured by a ring-resonator set-up [16] and resulted equal to \( \varepsilon_{ABS} = 1.8, \sigma_{ABS} = 0.001 \) S/m. The palm and fingers were separately printed and then united by silicone glue. The mockup was filled by a liquid \( \varepsilon_{\text{phantom}} = 41.2, \sigma_{\text{phantom}} = 0.95 \) S/m) [17], simulating the electromagnetic properties of the human body in the UHF-RFID band, and then sealed through a cover at the wrist level. In overall, the hand model is oversized and the filling liquid is a bit lossier than the averaged hand tissues so that the presented analysis will provide conservative results.

III. THE RADIOFINGERIP SYSTEM: ELECTROMAGNETIC LINK AND UPPER-BOUND PERFORMANCE

The RadioFingertip system includes an interrogation antenna placed onto the wrist and connected to a reader unit and a conformal tag having temperature sensing capability to be applied over the fingertip. The electromagnetic challenge of this wearable architecture, wherein both antennas are placed at direct touch with the lossy human body, is to establish a robust RFID communication link so that the power the wrist antenna delivers to the microchip of the finger-tag is sufficient to turn-on the tag and send back the collected physical information. Moreover, as the on-body electromagnetic channel between the wrist and fingertip antennas takes place in the radiative near field, wherein the human body produces a strong interactions with the radiators (scattering and huge power absorption), the usual Friis equation can not be used to quantify the communication performance and a more accurate model has to be established.

A. Modeling strategy

The RFID link is here properly modeled by means of a lossy two-ports network that is characterized through its impedance or scattering matrix. Port 1 and port 2 corresponds to the reader’s antenna and to the tag terminals, respectively. For a viable application of the reader module over the wrist, the minimum reader’s power required to activate the finger sensor has to be compliant with the power output of small-size battery-driven readers. This performance parameter depends on the specific layout of the two antennas, their impedance matching to the respective load, their position over the hand and the physical parameters of the arm itself.

In the first step, we are interested in estimating the optimal achievable performance, i.e. the upper bound in the maximum
Figure 4. a) Layout of the wrist-worn folded patch antenna with a tunable short circuit. Sizes (in \text{[mm]}): a=50, b=5, c=37, d=56, e=3, f=20. b) Map of the near electric field radiated by the wrist patch sourced by 1W power in the surrounding of the hand.

power delivered to the microchip under perfect matching conditions of both the wrist and the finger antennas, which is evaluated in terms of the \textit{System Power Gain} [18] of the two-port network defined as:

\[
g = \frac{P_{\text{out.avg}}}{P_{\text{in}}} = \frac{|S_{21}|^2}{(1 - |S_{11}|^2)(1 - |S_{22}|^2)} \tag{1}
\]

where \(P_{\text{in}}\) is the net power entering the wrist antenna and \(P_{\text{out.avg}}\) the maximum available power that can be delivered to the fingertip antenna’s load (in case of a perfect impedance matching). This metric can be obtained from a numerical simulation of the reference hand equipped with the wrist and the finger antennas aimed at evaluating the scattering matrix of the corresponding two-ports network. All the numerical data hereafter presented were obtained by using the transient Finite-Difference Time-Domain solver of the CST- Microwave Studio 2016 suite which permits to import the above CAD model of the hand.

\textbf{B. Wrist Antenna}

The considered wrist antenna (Fig.4a) was derived from [19]. The layout consists of a shorted patch provided with a miniaturization slot and a variable short-circuit edge to easily adjust the resonance frequency when the antenna is placed onto the hand mockup. The presence of a ground plane enables a partial electromagnetic decoupling from the arm. The dielectric substrate is a low-permittivity foam (Forex, \(\varepsilon_F = 1.55, \sigma_F = 6 \cdot 10^{-4} S/m\)) capable of moderate bending around the wrist.

Fig.4b shows a snapshot of the electric field radiated by the wrist antenna in the surrounding of the hand model. The guiding effect of the hand is clearly visible as well as the high field values in correspondence of the palm producing a huge power loss within the palm muscle tissues. Finally, remarkable hot spots appear close to the fingertips where the sensor should be placed.

\textbf{C. Fingertip Antenna}

In principle, several options for the layout and the position of the finger antenna are possible. A preliminary numerical analysis considered three configurations involving two dipoles and a loop having a same size (L=1.5 cm) and placed at 1.5 mm distance from the tip of the index finger (Fig.5). For each finger-wrist configuration the corresponding system gain was numerically evaluated as in (1). Fig. 5 shows that the vertical dipole (case a) provides the highest gain and it is hence the most appropriate choice for the RadioFingertip system involving a wearable patch placed as in Fig.4. In this configuration, by assuming the wrist antenna sourced by input power \(P_{\text{in}}=\{0.5W, 1W\}\) - representing the case of battery-driven reader modules and of a fixed reader, respectively- the corresponding maximum deliverable power (at 900 MHz) to the tag’s electronics would be -8 dBmW and -5 dBmW. These values are compatible with the currently available families of microchip for combined identification and sensing purposes.

Figure 5. Preliminary trade-off, through system power gain, among three possible layouts for the fingertip’s antenna (vertical dipole, horizontal dipole and loop, L=1.5 cm) placed at a separation distance \(d=1.5\) mm from the fingertip.
Starting from the previous results, the vertical dipole was refined to be comfortably wrapped around the finger and matched to the IC impedance. The resulting geometry is a U-shaped meandered line with the sensitive part, i.e. the microchip, just aligned at the tip of the finger (Fig. 6a). The considered microchip was the NXP G2IL ($Z_{\text{chip}} = 25 + j237 \Omega$, $P_{\text{chip}} = -18 \text{ dBmW}$). It worth specifying that this chip does not provide temperature sensing but its good power sensitivity allowed a useful flexibility during the preliminary experimentation of the RFID link. A more realistic configuration with a true sensor-oriented IC will be described in the last Section. Finally, the edge of the MLA is provided with tuning pinnacles for post-fabrication impedance adjustment with a rather linear rate of 5 MHz/pinnacle (Fig. 6).

Copper-made prototypes of the antennas were fabricated by two-axis digital plotter. The epidermal tag (Fig. 7a) was soldered to the IC terminals and then stuck over the U-shaped bio-silicone substrate ($\varepsilon_r = 2.2$, $\sigma = 5 \cdot 10^{-3} \text{s/m}$).

Finally, the patch antenna (Fig. 7b) was soldered to a L-SMA connector and then integrated within a sport wristband for better wearability.

The two antennas were separately characterized over the mockup in terms of realized gain (fingertip tag) and of reflection coefficient (reader antenna). Measurements results shown in Fig.8 are in good agreement with the corresponding simulations despite some differences in the wrapping modality of the finger tag.

V. EXPERIMENTAL CHARACTERIZATION OF THE RADIOFINGER TIP LINK

The wrist-mounted patch antenna and the fingertip sensor-tag were finally characterized as a whole system accounting for all the physical parameters. The real communication performance was quantified in terms of the Transduction Power Gain ($G_T$), i.e. the ratio of the power $P_{R\rightarrow T}$ really delivered by the reader to the chip to the power available from the reader generator $P_{av,R}$ [20]:

$$G_T = \frac{P_{R\rightarrow T}}{P_{av,R}} = \frac{4R_{\text{chip}}R_G|Z_{21}|^2}{|(Z_{22} + Z_{\text{chip}})(Z_{11} + Z_G) - Z_{12}Z_{21}|^2}$$

(2)

where $Z_G$ is the internal impedance of the reader (hereafter assumed as 50 ohm). Unlike the system gain in (1), $G_T$ accounts for the possible impedance mismatch at the reader-antenna port as well as at the RFID tag-microchip interconnection caused by the disturbing effects of the human body. The transducer gain coincides with the system gain only in case of perfect impedance matching of both the tag and the patch. Therefore, it is generally expected to be lower.

The transducer power gain can be experimentally derived from the measurement of the turn-on power $P_{to}$ of the tag, e.g. by increasing the reader’s power until the chip activates. At the turn-on the transducer power gain is accordingly determined as:

$$G_T = \frac{P_{\text{chip}}}{P_{to}}$$

(3)

Three measurements were repeated by removing and repositioning the tag on the same finger. A few dispersion is observed among the three sets (Fig.9b) due to the un-perfect reproduction of the same conformation of the tag over the hand. In
overall, results and simulations are in reasonable agreement within the band of the wrist antenna. In the most favorable conditions, the maximum transduction gain was $G_T = -40$ dB and, accordingly, the maximum power delivered to the chip would be $P_{R-T} = [-13 \text{ dBmW}, -10 \text{ dBmW}]$ in case of available power from the reader module $P_{\text{in}} = [0.5 \text{W}, 1.0 \text{W}]$, respectively. The achieved power values are smaller than the upper bounds numerically predicted above, meaning that there is still room for improvement by working on the antenna design.

VI. APPLICATION TO THE SENSING OF OBJECTS’ TEMPERATURE

The proposed system was finally experimented for the sensing of the temperature of touched objects. At this purpose the fingertip tag was connected to the EM4325 microchip ($Z_{\text{chip}} = 23.4 - 145j \Omega$, $p_C = -4dBmW$) having the native capability of temperature sensing in the range $-40^\circ C < T < +65^\circ C$ with a resolution and accuracy of 0.25°C [21].

The fingertip and the wrist antennas were worn by a volunteer with smaller hands in comparison with the mockup (palm-to-index finger distance 160 mm). During the experiment the finger firstly touched a desk whose surface was at the environmental-temperature and then a plastic object previously heated up by means of a hair dryer. The acquisition software returned in real time the backscattered power and the instantaneous temperature. The various steps of the experiment are summarized in Fig. 10 by means of some snapshots, while a full live demo is available online\(^2\). The turn-on power required to read the temperature was comprised between $-25 dBmW \leq P_{to} \leq -23 dBmW$ during all the performed hand gestures. These values look compatible with extremely low-power keyfob-like readers suitable to be easily embedded into a battery-driven module onboard the wrist patch.

As visible in Fig. 10, the hand motion produced some changes of the backscattered field by the fingertip antenna

\(^2\)https://youtu.be/DBGUKYqmt-5Q

Figure 8. Measured and simulated realized gain and reflection coefficient of a) the fingertip antenna and b) the wrist antenna.

Figure 9. a) Full-system measurement set-up. b) Simulated and measured operating power gain in three measurement sets (M1... M3).

Figure 10. Example of real-time temperature and RSSI measurement by the RADIOFingerTip. The sensor cyclically touches the desk surface kept at environment temperature and a hot plastic object.

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toward the reader due to variable relative positions and shadowing between the two antennas. In particular, sharp power discontinuities occur when the finger touches the object due to the substantial change of the boundary conditions seen by the antenna. Such a power signature can be exploited to detect and recognize particular hand gestures, and in particular to discriminate the touch gesture itself, by adopting classification algorithms as in [22]. Even tough the variation of the temperature is clearly correlated to the touching of the hot and cold objects, the temperature values measured by the fingertip sensor is different from the real temperature of the object because of the thermal inertia of the microchip. Nevertheless, the combined processing of both temperature and backscattered power signals permits to retrieve the real temperature of the object avoiding an overlapped touching. Indeed, denoting with \( \Delta t \) the time interval wherein the sensor contacts the target objects - which can be derived from the backscattered power variations with respect to a rest condition (see the discontinuities in Fig.10) - with \( T_0 \) and with \( T(\Delta t) \) the temperature returned by sensor respectively before and after touching the object, the true temperature of the object \( T_\infty \) can be estimated through the step response of an equivalent RC circuit accounting for the thermal balance among two contacting bodies as:

\[
T_\infty = \frac{T(\Delta t) - e^{-\frac{\Delta t}{\tau}} T_0}{1 - e^{-\frac{\Delta t}{\tau}}}
\]  

where \( \tau \) is the time constant of the RFID sensor \( (\tau = 6.5 \text{ s from [21]}) \).

As a proof of concept, Fig.11 shows an example of the temperature measured by sensor when contacting the surface of a glass filled with hot water (58°C) for different interval time reducing from 5 sec down to 0.1 sec.

As expected, the longer the touching, the closer the measured temperature to that of the touched object, while short contacts returned lower temperature values. By applying eq. (4), \( T_\infty \) is correctly estimated for all the considered durations of the gesture (Table I), apart from the case \( \Delta t = 2s \) which can be considered as an outlier. It is worth noticing that the real temperature of the glass is retrieved even for very short (half a second) contact, thus significantly reducing the risk of burns when the user interacts with everyday hot things (electric iron, boiling water). A video demonstrating the real-time temperature estimation is available online\(^3\).

VII. CONCLUSIONS

We have introduced and demonstrated the proof-of-concept of an RFID-based Finger Augmented Device suitable to expand the sensorial capability of the finger, with possible application to the aid of impaired people lacking thermal sensitivity. The reported numerical analysis and laboratory experimentation with a 3D printed mockup and a real hand proved that a robust link between an interrogating wearable antenna and a battery-less epidermal tag can be established

\(^3\)https://youtu.be/6quuuEiNEBs

\[\text{Figure 11. Example of estimated real temperature } T_\infty \text{ of a hot glass starting from Temperature recorded by the fingertip sensors when contacting the target objects for different time intervals.}\]

<table>
<thead>
<tr>
<th>( \Delta t [\text{s}] )</th>
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<th>( T_\infty ) [°C]</th>
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<tr>
<td>5</td>
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<td>0.5</td>
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in spite of the strong power loss induced by the human body. The power required to activate state-of-the-art microchips with sensing capability revealed compatible with battery-driven readers so that a real integration of all the required electronics within a standalone wristband device looks feasible.

The next step of the research will address the retrieval of the meaningful temperature in more realistic conditions, e.g. when the users repeatedly and quickly touches hot/cold/warm surfaces or when the temperature of the object is time-variant. Moreover it is of interest to assess the configuration of all the five fingertips equipped with sensors as well as to analyze the communication link during the execution of common hand gestures. The multi-finger system is particularly attractive for a multi-parametric sensing, for example to quantify the touch pressure (medical diagnostic, robotic sensor), to restore the haptic perception and even measure some not tactile-sensitive parameters of the touched object like the PH. The arising electromagnetic shadowing and coupling among several fingertip antennas deserves a dedicated investigation. Some preliminary results will be shown at the conference.
Finally, the design and manufacturing of fingertip tags need to be improved to account for the deformation of the tag during the hand movements such to realize deformation-tolerant sensors with maximum comfort and minimal obstacle for the users. Appealing solutions may be borrowed from the technological process of bio-integrated epidermal electronics [23].

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