SECOND SKIN Project: BioIntegrated Wireless Sensors for the Epidermal Monitoring and Restoring of Sensorial Injuries

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***Abstract*—SECOND SKIN was a two-year project addressing bio-integrated wireless-sensing epidermal membranes. Being flexible and elastic, they are suitable to be placed in direct contact with the human skin. As the Radio Frequency Identification (RFID) technology is exploited for data acquisition and communication, they are able to work without a battery and can be interrogated remotely through fixed and/or wearable readers. The innovations of the project spanned from the definition of designing methodologies and manufacturing techniques for prototyping, up to real-world experimental evaluations to assess usability, durability and insensitivity to body variability. The project findings have now led to the consolidation of the RFID technology potentialities with respect to the monitoring of the human body's biophysical data.**

***Keywords*—epidermal antenna, RFID, healthcare internet of things (H-IoT), 5G, temperature, pH**

I. Introduction

SECOND SKIN was a two-year project funded by *Regione Lazio* (Lazio Innova "Gruppi di Ricerca", Ref. 85-2017-14774) and carried out by the *Pervasive Electromagnetics Lab* at the Tor Vergata University of Rome (Italy). The project started in July 2018 and ended in August 2020.

The project addressed bio-integrated wireless-sensing epidermal membranes that can act as a *second skin* over the body (Fig. 1), involving the Radio Frequency Identification (RFID) technology for data acquisition and communication. Inspiring previous researches had already shown that RFID technology, widely used in goods logistics, can be also exploited to power electronic devices applied on the skin and to read biophysical data up to a distance of about $0.5 \div 1.5\,m$ [1]. The SECOND SKIN project fostered the realization of devices so that they will be truly applicable in the real world in terms of materials, reproducibility of the data collected, immunity to human body variability, ergonomics and methods of use. In particular, the project aimed to develop: *(i)* different kind of epidermal antennas, that are robust with respect to individual variability; *(ii)* eco-friendly and low-cost designing and manufacturing techniques; *(iii)* algorithms for real-time conditioning and processing of the collected biometric data; *(iv)* protocols for the experimental characterization of epidermal sensors.

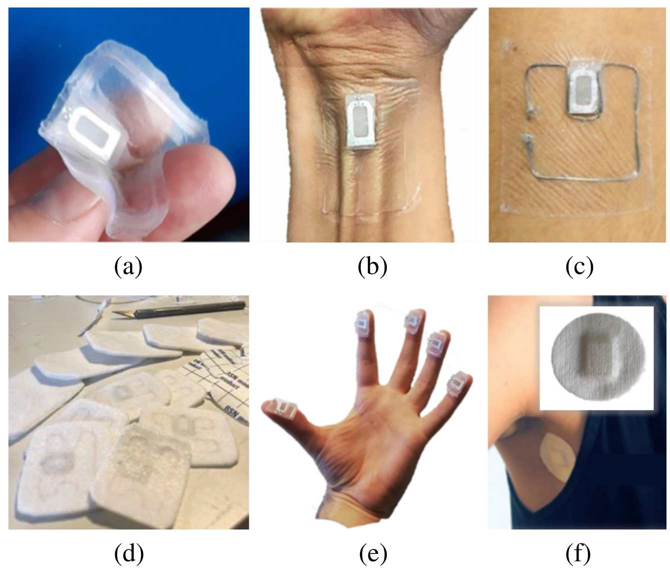
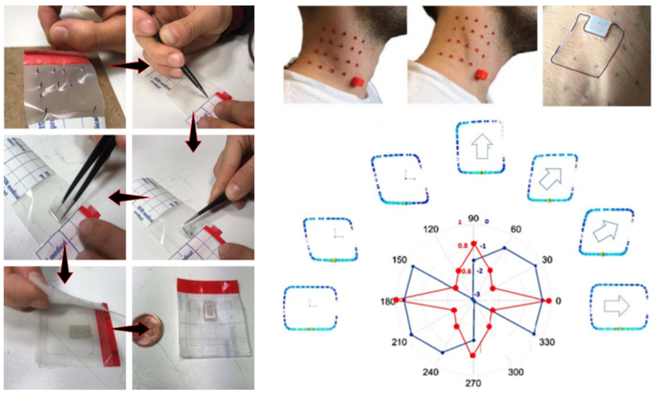


Fig. 1. Examples of epidermal battery-less RFID transponders UHF bands. (a,b,c) Stretchable epidermal tags for temperature measurement [2], [3]. (d,f) Plaster-like epidermal thermometers [4]. (e) Fingertip antennas for sensory ultrability [5].

This paper reviews the main technological innovations and research outcomes brought by the research activities of the SECOND SKIN project, which have now led to the consolidation of the RFID technology potentialities with respect to the monitoring of the human body. Hence, an overview of the new research directions undertaken in the last months following the project findings is also given at the end of the paper.

II. Before SECOND SKIN

At the time of writing the project proposal, the proposing group already had a strong background on the RFID technologies and applications in the conventional fields of Industry 4.0 and Logistics. Furthermore, in those recent years, new research topics involving RFID with the human body were beginning to unfold, giving rise to innovative RFID application fields, such as Smart Spaces and Epidermal Electromagnetics.



(a) (b)

Fig. 2. (a) Manufacturing steps for prototyping the epidermal tags [3]. (b) Database of the deformations of the surface of the human body [14].

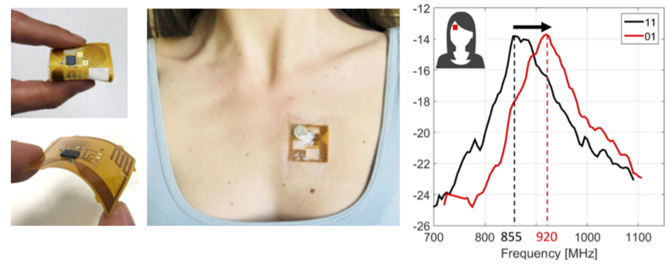


Fig. 3. BAP epidermal RFID tag with practical (measurement) example of on-skin retuning [15].

The feasibility of establishing an RF communication channel on-the-body [6], [1] and through-the-body [7] to collect health-relevant biophysical parameters were already partly assessed. In particular, through-the-body communication was mainly referred to applications of passive UHF tags implanted into human limbs to allow sensing and tracking [7], [8]. Alongside, on-the-body (i.e. *on-the-skin*) wireless communication was envisaged to enable three main applications: *(i)* skin temperature measurements [9], *(ii)* breath monitoring [10], and *(iii)* regeneration of impaired sensory functionalities at the hand level [11].

Many challenges were still open. Despite some initial clues about the manufacturing techniques and materials for the prototyping of epidermal tags [12], [13], many other methods and substrates could still be considered. Moreover, when designing epidermal tags, the human body variability could affect the performance and hence the reading distance of the devices [6]. Thus, ways to keep stable the tag response needed to be implemented. Finally, efforts to expand the pool of physiological parameters to be monitored with the UHF RFID technology were expected.

III. Research Outcomes

In this section, the most relevant scientific results obtained during the SECOND SKIN research project are briefly summarized.

A. Epidermal Sensors: Manufacturing, Materials, Durability and Usability

Innovative epidermal sensors are required to be lightweight, breathable, flexible and conformable to the human body discontinuities. An effective manufacturing technique (Fig. 2.a) has been outlined to prototype the devices [3]. It consists of the deposition of a metallic or textile wire over a thin ($22\,\mu m$) biocompatible auto-adhesive medical plaster membrane [2]. This adheres to the skin like a tattoo as it is elastic and transparent. Moreover, being breathable, it makes the epidermal device insensitive to sweat. The overall footprint of the final devices is comparable to the size of a medical plaster or patch.

A study of usability and durability of the epidermal sensors was carried out by varying the type of materials and the position on the body [3]. The use of conductive textile wires allows the tag to withstand prolonged use for over a month. The obtainable reading distances are at least $70\,cm$ in most of the cases, up to $2\,m$ in the most lucky configurations.

Moreover, to evaluate the performance of epidermal antennas in real conditions, a quantitative database of the deformations of the surface of the human body produced during natural gestures and movements was obtained with a 3D optical scanner [14] (Fig. 2.b). A radio-mechanical model was derived, allowing the design of epidermal antennas which are robust and duly insensitive to fatigue.

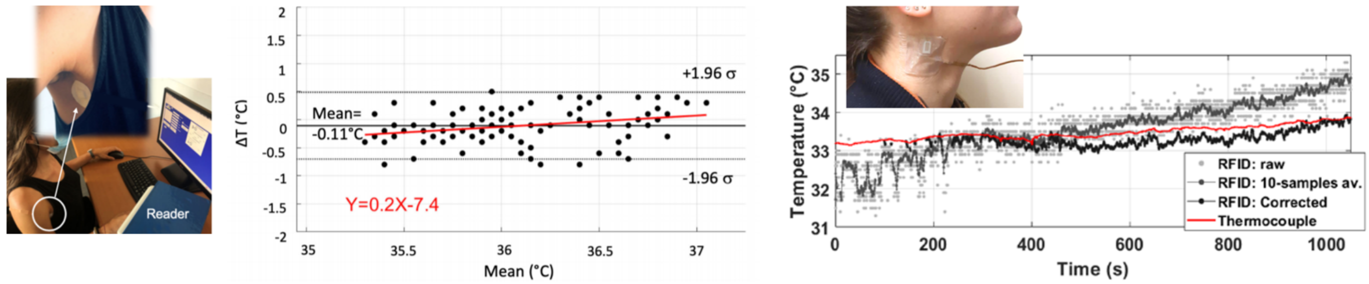
B. Configurable Epidermal Data-Logger: Human Variability Issue

To overcome the possible shift of the working frequency of an epidermal device when attached on different individuals or on different body regions, a battery-assisted-passive (BAP) version of epidermal device [15] has been implemented over a flexible Kapton substrate including a tuning mechanism to adapt the working frequency in the European or American UHF band (Fig. 3).

Thanks to the presence of the on-board battery, the device also acts as a data-logger able to continuously record biophysical parameters (such as temperature [16] and pH [17]) over time, even in the absence of the RF interrogation signal.

C. Accuracy of Epidermal Thermometers: Experimental Evaluation and Thermal Correction Algorithm

The developed epidermal sensors have been primarily employed for the monitoring of body temperature. An experimental campaign (Fig. 4.a) involving 10 healthy volunteers was carried out [4] in order to evaluate the agreement of the temperature measurements retrieved by an axillary epidermal thermometer (Fig. 1.f) with those obtained with a conventional electronic thermometer. Following an initial calibration, the average deviation between the two measuring instruments is about $0.5°C$ in 95% of cases (Fig. 4.b). Moreover, a correction algorithm has been implemented [18] to obtain a robust measurement of the body temperature (Fig. 4.c) regardless the reading modalities. In particular, the measurement outcomes should be independent on the distance between the reader and the sensor, and independent on the power at stake.



(a) (b) (c)

Fig. 4. (a) Measurement set-up with the epidermal thermometer placed in the armpit. (b) Bland–Altman diagram with an indication of 95% limit of agreement [4]. (c) Temperature measurement at the neck. Comparison between raw data without and with correction [18].

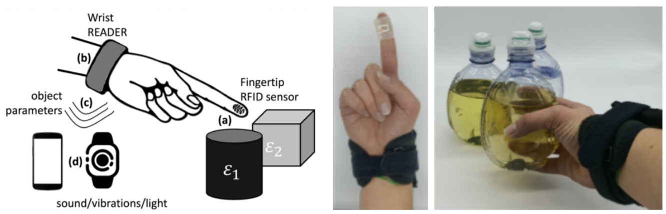
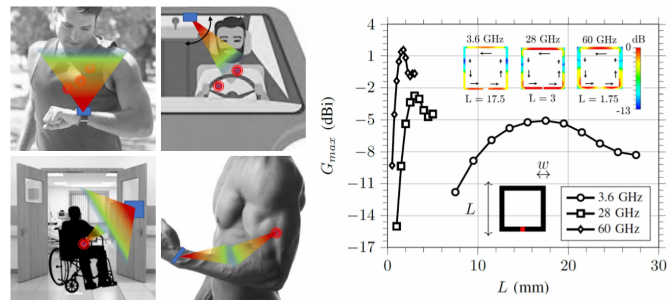
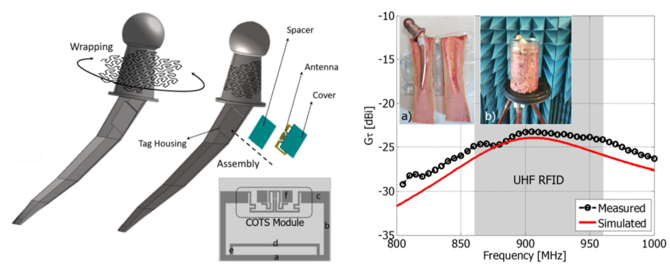


Fig. 5. RFAD system for sensing of the dielectric constants [20].



(a) (b)

Fig. 6. (a) Possible scenarios of epidermal sensor networks at 5G frequencies. (b) Optimal gains of 5G epidermal loops as function of the length [23].



(a) (b)

Fig. 7. (a) CAD model of the RFID-powered prosthesis with space-filling-curve sensor of crack. (b) Measurement of the prosthesis in the limb mock-up [24].

D. Radio Finger Augmentation Devices (RFADs)

Another kind of epidermal sensor has been designed for fingertip applications [19] with a twofold purpose: the re-generation of impaired sensory functions at the hand level, and the enabling of sensory *ultrability*. Also the wrist-fingers communication link has been numerically and experimentally characterized [5]. These new fingertip sensors, namely Radio Finger Augmentation Devices (RFADs), are able to measure the temperature of touched objects as well as to estimate their materials (e.g., the content of a bottle and the liquid level [20], Fig. 5). Moreover, the possible application of these RFADs to the cognitive remapping of lost sensorial functionality was also evaluated [21]. Therefore, this technology can enable the emerging paradigm of *Tactile Internet*, with positive impact in support of users with tactile disabilities and as an interface for remote-controlled robotics.

IV. Side Results

In this section, the scientific side-results issued by the SECOND SKIN project are reported.

A. Future 5G-RFID Epidermal Sensors

Epidermal RFID devices were also investigated to integrate with the emerging 5G framework to foster healthcare applications (Fig. 6.a) such as patient monitoring, tele-surgery, and augmented sensorial abilities (both for humans and robots). Indeed, developing a 5G-RFID system based on backscattering communication will help reducing the power consumption and lowering the electronic complexity. Through simulations and preliminary experiments, the feasibility of an epidermal 5G-RFIDs sensing architecture has been demonstrated, at both microwave and mmWave frequencies [22]. In particular, the optimal sizes, the maximum gains, the achievable read ranges, and the possible data-rates of passive 5G-RFID links have been identified [23] (Fig. 6.b).

B. Surface Electromagnetic Skins

Finally, as a scientific side-result of the SECOND SKIN project, not only epidermal but also implantable RFID applications were investigated to envisage new-generation cyber prostheses. Sensorized membranes (i.e. *skins*) can be printed with conductive ink in the form of conformal space filling curves over dielectric and metal surfaces to monitor their integrity and surfaces defects [25]. If printed over a hip prosthesis (Fig. 7), the detection of micro-cracks in orthopedic implants becomes feasible [24].

V. CONCLUSION

SECOND SKIN project definitely boosted the implementation of flexible and elastic electronics for applications on the human skin by exploiting the UHF RFID communication link [26]. This new technology is useful for the measurement of a variety of biophysical markers on the skin interface to reveal the state of health of a person, or to enable sensory functionality. The collected data can be used for personalized diagnostics, or recently for the containment of epidemics [27].

The developed methodologies and fabrication procedures could shorten the path to a real-life adoption, that in some cases has already been demonstrated during the project. Additional tests on data processing procedures should be addressed to improve robustness and precision. Indeed, the epidermal sensors can be interrogated remotely through fixed and/or wearable readers that should be combined with interrogation softwares for data processing and representation.

The outcomes of the project are currently undergoing further refinements within the DUAL-SKIN project, funded by *Italian Ministry of University and Research* (FISR 2020 COVID, Ref. FISR2020IP_00227), which resorts to multi-chip devices [28] at the purpose to simultaneously collect more parameters and improve accuracy.

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http://pervasive.ing.uniroma2.it/secondskin.htm.

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