RFID-BASED STRESS PREDICTIVE ENGINEERING

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Abstract

The aging of materials is one of the main causes of failure of instruments and devices. Availability of early detection tools can improve the Predictive Maintenance process to extend the lifetime of devices, saving on costs and time. We here introduce the new paradigm of wireless monitoring of surface integrity based on Space Filling Curves (SFC). It acts as an artificial electric skin suitable to envelope a surface to detect from remote the presence of small aging signs. In particular, the occurrence of an even small surface crack is detected in a binary form and transmitted remotely, following a standard RFID interrogation. The feasibility of the idea is supported by numerical analysis and experimental outcomes on 2D and curved thin, flexible and stretchable surfaces and metallic objects, such as an orthopedic prosthesis.

Index Terms – RFID, crack detection, electronic skin, predictive maintenance.

I. INTRODUCTION

Any industrial and biomedical manufactured device is affected by aging that represents one of the main causes of failure. The aging process can also be accelerated by critical operating conditions, such as non-negligible mechanical or chemical stress. A recognized approach to prevent severe events due to aging of materials is the Predictive Maintenance. To work properly, it requires a massive spread of sensors over the objects. By focusing on the aging signs of materials, the main symptom is the generation of surface cracks due to the massive breakage in the lattice of the material [1]. Current crack detection techniques, based on scanning electron microscopy, X-rays and acoustic emission, are invasive and not easy to implement, overall, these are not suitable to fast diagnosis during operative conditions.

This contribution proposes a scalable crack monitoring framework, relying on Radiofrequency Identification (RFID) system that is suitable to devices made by any kind of material, from plastic to metal, and from rigid to stretchable texture. The method is based on the concept of Space Filling Curves (SFC) that are engineered to act as a distributed electrode for small crack detection over a surface [2]. This sensor together with the transponder antenna can be printed or painted by a conductive ink directly on the surface of the object for a total integration. Data gathering concerning the occurrence of cracks is achieved by an RFID IC with anti-tamper capability that is connected to the sensor.

II. A DISTRIBUTED CRACK DETECTOR

A Space Filling Curve maps a multi-dimensional space into a one-dimensional domain. Among the various option of SFCs, Peano/Hilbert's and Fukuda/Gosper's ones represent the most suitable families due to their self-avoidance characteristic. This feature allows them to act like a thread passing only once for every point of the target surface. By modelling the crack as a linear segment L, the smallest detectable crack, $S(N)$, is given by (1): $S(N) = m\frac{\sqrt{3}\,r}{s^{N+1}}$, Where r is related to the area of the SFC, while N is the iteration order, that determines the electrode density (Fig. 1.1). Any crack of $L_{crack} > S(N)$ will surely cause the interruption of the curve. By considering the random nature of the crack occurrence, the practical resolution of crack detection, estimated by the *Montecarlo analysis*, is $0.5S(N)$ with a probability of detection more than 75% (Fig. 1.2). For large surfaces multiple cells can be arranged to tesselate the plane according to a hexagonal grid (Fig. 1.3). In this way it is possible to limit the portion of the damaged surface. To remotely convey the information about the crack occurrence, the SFC is connected to the anti-tamper port of an RFID IC. This information is transduced in a digital way, namely to an anti-tamper bit having two logic symbols, '0' (absence of crack) or '1' in presence of crack. The further connection to an UHF antenna enables the wireless data exchanging between the sensor and the reader unit.

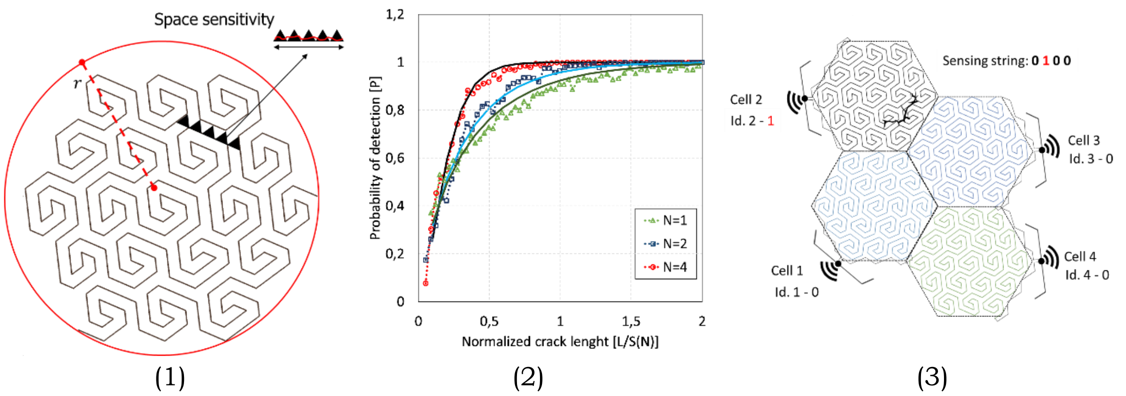


FIG. 1 – *1)* Fukuda-Gosper curve, $N = 1$. Space sensitivity in the worst case is the smallest segment that touches the SFC. Each curve can be bounded by a circular detection area. *2)* Probability of detection of the curve for several iteration orders (N). Increasing in curve density increases the detection probability also for smaller cracks that space sensitivity. *3)* Concept of the surface tessellation. Each cell comprises an SFC connected to an RFID transponder. The crack location is related to the sensing string through the unique identification number of each IC.

III. ANTENNA DESIGN AND TECHNOLOGIC CHALLENGES

To successfully applying this crack detection technique, the first constraint is represented by the electrical insulation between the SFC electrode and the surface to monitor in case it was metallic. This is necessary to avoid a permanent short circuit condition (Fig. 2.1). Indeed, the anti-tamper port of the RFID transponder NXP UCODE G2iM+ (Fig. 2.2) allows to distinguish among two resistance values, namely short circuit when the $R_{SC}^{IC} < 2M\Omega$ (or healthy condition) and open circuit condition if $R_{SC}^{IC} > 20M\Omega$ (crack occurred). To make the sensor working properly, the metal surface under monitoring needs to be treated with an insulating layer, afterward the SFC sensor can be applied.

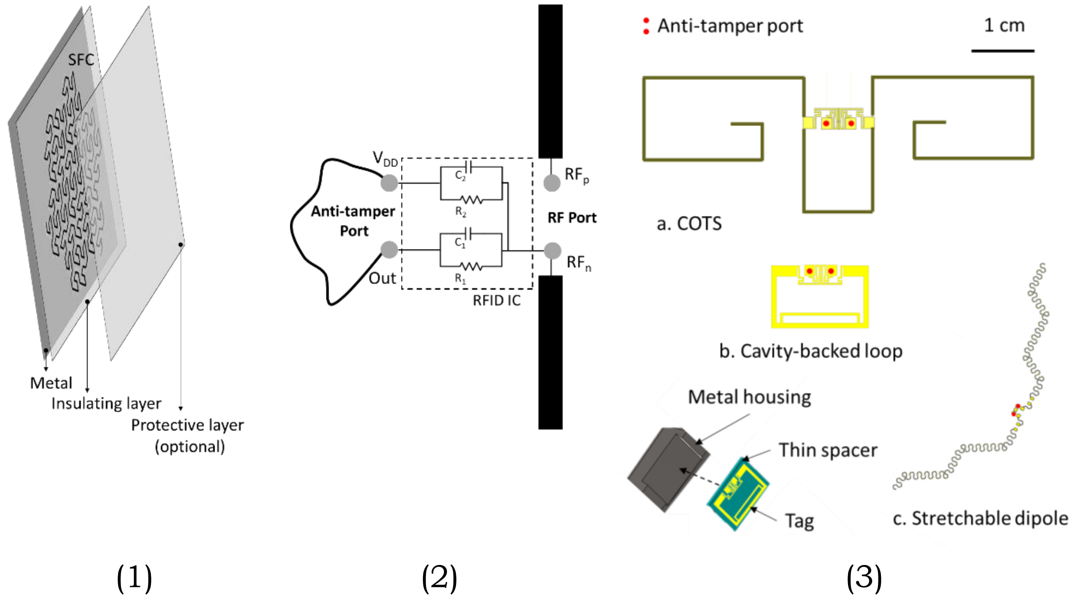


FIG. 2 – *1)* Arrangement of SFC over a metal surface by means of insulated layer. 2) Equivalent circuit to account for the RF coupling between the antenna and the anti-tamper port of the IC. 3) Modularity of the proposed approach. Depending on the environment, it can be a) a COTS module, b) a cavity-backed loop optimized for metal surface proximity or a c) stretchable dipole, for elastomeric surfaces.

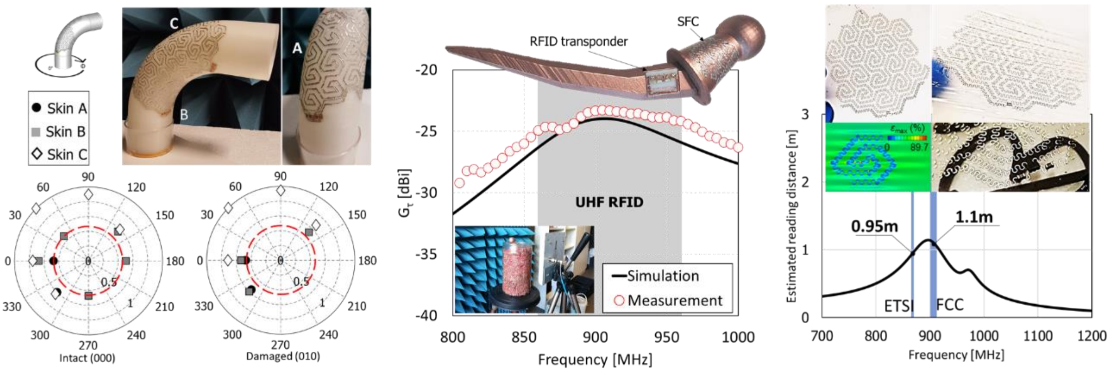
This detection method allows to independently design the electrode and the antenna to achieve the best performance for both, namely in terms of crack sensitivity and reading distance. For instance, the same SFC can be used for 2D dielectric surfaces or for metallic object, provided that the proper antenna geometry is selected (Fig. 2.3), moving from a dipole antenna (dielectric objects) to a cavity backed-loop configuration (metal objects).

IV. EXAMPLES OF APPLICATION

The application of the presented crack detection technique was investigated on different objects with increasing manufacturing complexity. Starting from a planar and flexible substrate, where the SFC was easily printed by means of a conductive silver ink [2], other applications include:

i. *Dielectric objects: pipe joint*

   A prototype of the pipe joint was 3D printed with ABS by the Zortrax M200 printer (Fig. 3.1). In the same process, a three-cells



(1) (2) (3)

FIG. 3 – *1)* Interruption of SFC due to cracks has an impact over the reading distance. In any case, a $0.5\,m$ reading distance is achieved. *2)* Comparison between the simulated and measured realized gain of the prosthesis in the limb mock-up. *3)* Prototype of the elastic space filling wireless sensor under two stretch conditions. Numerical mechanical analysis under 35% x-direction stretching and simulated reading range with $3.28\,W\ EIRP$.

Space Filling skin and wrapped dipole antennas were impressed on the pipe by means of 0:4mm deep grooves, then filled with conductive silver paint. Finally, ICs were glued by conductive epoxy glue By interrogating the pipe joint along its horizontal plane, all three tags provided a response in the range $0.5\,m$ to $1\,m$ depending on them position and crack occurrence.

ii. *Metallic objects: hip prostheses*
A prototype of hip prosthesis (Fig. 3.2) was made by following the same manufacturing process previously described. Before filling the SFC thread with conductive ink, the prototype was metallized by means of a metallic silver-plated copper spray and then coated by a thin insulating enamel layer to achieve the electric insulation between the metal surface and the SFC [3]. The RFID loop antenna was fabricated by a carved adhesive copper trace on a PET substrate, that was housed in the stem of the hip prosthesis. The connection between the anti-tamper port of the IC and the Skin was obtained by using thin copper wires, running inside the prosthesis through a hole. Electromagnetic characterization on a mock-up shown that the implanted systems allows to achieve a reading distance of $60\,cm$ in case of a fixed reader emitting $3.28\,W\ EIRP$ that is fully compliant with a fixed reader for non-collaborative diagnosis.

iii. *Stretchable objects: planar surface*
Fabrication of both, SFC and antenna (Fig. 3.3), starts with spin casting (poly)methyl methacrylate as a sacrificial layer on a 4-inch silicon wafer followed by spin casting a $3\,\mu m$ layer of polyimide (PI).

Then the Cr/Au thin film was patterned by electron beam deposition to the desired geometry ($10/100\,nm$). A second layer of polyimide ($3\,\mu m$) completely encapsulated the device. Afterwards, O_2 plasma reactive ion etching was used to pattern both PI layers into suitable geometry and create openings for external electrical connections. After removing the PMMA, the resulting device was transferred to cellulose-based water-soluble tape. On another side, the elastomer (Ecoflex 00-30, Smooth-On Inc., $20\,\mu m$) was prepared on a PMMA treated glass slide ($75\,mm\,\times\,50\,mm$) and then exposed to ozone in a UV-O cleaner for 5 minutes to generate -OH group at the surface. Water was finally used to dissolve the water-soluble tape and form the SFC device on Ecoflex. The IC was soldered by standard soldering techniques. It is worth noticing that, thanks to the properties of the micro-serpentine of the conductor lines [4], the electrode and antenna are strongly tolerant to deformation as the form factor of the SFC pattern remains unchanged also for a moderate 35% strain, with an estimated reading distance of $95cm$ in ETSI band with $3.28W\ EIRP$.

V. Conclusion

The proposed synergy between an RFID platform and the Space Filling Curve is a promising and key-enabling approach to early localize a defect on a surface. With few parameters, such as external size and iteration order, it is possible to define the crack sensitivity of the SFC. Through different manufacturing technologies, this approach becomes suitable for strongly different materials, from metal to elastomers and, thanks to its modularity, the performance of the radiating element can be optimized in relation to the surface of application.

Acknowledgement

Work partially funded by Lazio Innova, project SECOND SKIN. Ref. 85-2017-14774.

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