Conformal Space-Filling Electromagnetic Skins for the Wireless Monitoring of 3D Object Integrity

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***Abstract*—The widespread use of polymer-based objects such as pipes, cables, tiles, gaskets in a wide range of applications demands for large scale a regular monitoring of their health status in order to prevent potential failures during service. Indeed, the exposure of these objects to mechanical or chemical stressing agents may accelerate their aging process thus decreasing their natural lifetime. A non-invasive and early monitoring of these aging signs (such as surface defects) may enable a predictive maintenance in order to avoid, or at least to minimize, unexpected failures.**

This paper describes a wireless crack detection method based on space-filling curves working like an electromagnetic second-skin enveloping the object. The conformal sensor permits to remotely transmit the presence of small defects over the object by using Radio Frequency Identification antennas and microchip transponders provided with anti-tampering features. The proposed idea is corroborated by numerical modeling and by some experimentations with a plastic pipe joint coated by a three-cells sensing skin made by silver conductive paint that is suitable to enable a wireless robust crack detection system up to 1.5m distance.

***Index Terms*—Radio Frequency Identification, Object integrity, Sensors, 3D Print, Flexible Electronics, Electronic Skin.**

I. Introduction

Polymeric mechanical devices are being increasingly used in automotive or aerospace industries, as well as in buildings and medical applications. In every case, they undergo non-negligible mechanical, thermal or chemical stress that could accelerate their natural aging process, up to a severe damage and even failure. In order to prevent catastrophic events, a predictive maintenance may play a key role.

Generally, aging process produces a breakage of the chain in the polymer structure thus generating surface cracks that make the object more susceptible to fracture [1]. This relentless process may be delayed by advanced manufacturing techniques, such as self-healing procedures or by means of scheduled maintenance. Common crack detection procedures for a regular monitoring are currently based on non-destructive methods [2]. They span from high-resolution techniques such as X-Ray, micro-tomography or scanning electron microscopy (SEM) that allow to detect defect up to nano-metric scale, down to low-medium resolution (milli-metric scale) acoustic or electric impedance techniques. These approaches usually involve bulky measurement equipments, wired probes and highly trained operators. Accordingly, these crack detection methods are not suitable to a large scale adoption, i.e. to enable an efficient and automatic monitoring of the health status of a large surface or of multitude of products in the emerging framework of Internet of Things.

A more modern diagnostic approach involves the electromagnetic backscattering-based monitoring through the Radio Frequency Identification (RFID) technology. The remote sensing rationale [3], [4], [5] relies on the presence of a surface defect that perturbs the electromagnetic behavior of an antenna placed onto or close to the defect. The main limitation is that the sensing antenna must be placed in the proximity of the crack. Thus, monitoring wide surfaces may require the deployment of a dense cluster of tags. Also, the implementation of this architecture is hence impractical when the detection of small cracks is requested over a large surface.

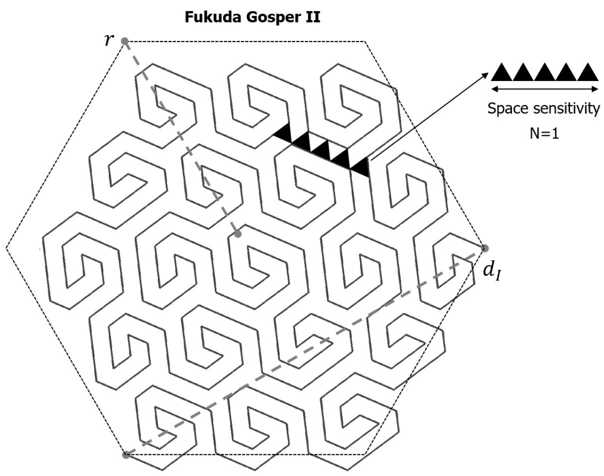

Figure 1. First-order *Fukuda Gosper II* space-filling curve for defect detection. Black triangles indicate the maximum free space path non intercepted by a defect defining the *space sensitivity* of the the cell.

A *distributed* approach has been recently proposed by the authors [7], where a tunable ink-jet printed electrode acts as a *second skin* (or even as a nervous system) of the object to be monitored. The electrode can be ideally printed over the surface like a tattoo and the early aging signs (micro-cracks, wearings) can be easily contactless monitoring by using ad-hoc designed RFID antennas with distributed loads. The leading idea involves a space-filling electrode connected to the anti-tamper port of an UHF-RFID microchip transponder. The breakage of the electrode, following the appearance of a surface defect, will force the microchip transponder to flag an integrity bit and this information can be wireless recovered by a remote reader unit through backscattering modulation.

In this work, this detection method is further extended to non-planar objects and a first prototype is presented where three sensing cells are wrapped around a pipe joint. The resulting system is a multi-port sensing skin that is here numerically modeled and then fabricated by 3D inkjet printing and finally experimentally characterized with and without the presence of cracks.

II. Space Filling Skins

The considered crack-detecting technique is based on *Space Filling Curves* (SFC), such as Hilbert, Gosper, Koch, Moore, and Fukuda families [6]. A SFC can be considered as the mapping of a multi-dimensional domain (surfaces, volumes) onto a one-dimensional dense path. The filling density can be increased by rising the iteration order of the curve. Moreover, the one-dimensional path never intersects itself and therefore the SFC can be used as a probing closed-circuit. As originally introduced in [7], SFC-based sensors comprise a distributed electrode, forming a 2D sensing cell, made by conducting paint and coupled with an RFID tag. The SFC electrode is thus connected to the anti-tamper port of the tag IC. If a crack occurs within the detection area of the cell, the tamper flag will be set to the logic value '1' ('0' otherwise). The resolution of the sensor, i.e. the smallest crack size that can be detected is related to the external size of the sensing cell (the side r if the enveloping hexagon) and to the iteration order N of the curve. We consider hereafter the Fukuda Gosper II space filling curve [8] (Fig. 1). In this case, the space sensitivity is given by:

$$S\left(N\right) = \frac{5\sqrt{3}}{\sqrt{19^{N+1}}}r \qquad (1)$$

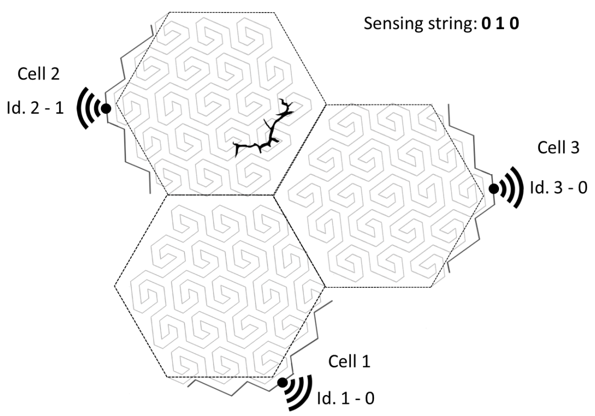

Figure 2. Space tessellation with some Fukuda Gosper II cells to localize a defect onto a large surface.

A single cell allows detecting a crack occurrence, but it does not provide any information about its localization on a large surface. By taking benefit of the tessellation property of the Gosper-Fukuda curves, several sensing cells can be arranged together in order to monitor a wider area (Fig. 2) with a space resolution equal to the hexagon side r. The string formed by the integrity binary digits, returned by the sensing grid to the reader, following a wireless interrogation, will therefore indicate the presence of one or more defects of size larger than $S(N)$ in the nth cell, being n the position of the digit '1' within the string.

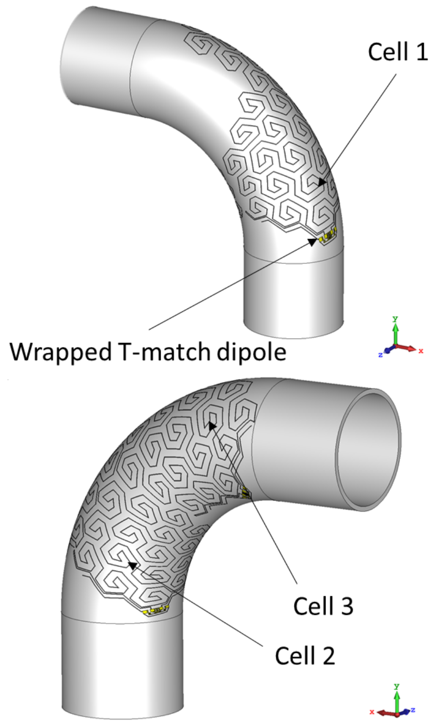

Figure 3. Example of a conformal placement of a three-cells sensing skin over a pipe elbow.

III. Electromagnetic Modeling of the Conformal SF Skin

The surface tessellation generates a close displacement of loaded RFID tags that can be considered as a coupled electromagnetic multi-port system. For the sake of the simplicity, a first-order electromagnetic model is here adopted: the nth port is sourced and other ports are connected to the input impedance of the microchip in harvesting mode. Accordingly the realized gain $\tilde{G}_n = G_n \tau_n$ will be numerically computed, being G_n and τ_n the embedded gain and embedded power transfer coefficient referred to nth port. A more accurate modeling based on RFID grids [9], [10], fully accounting for the inter-tag coupling, will be also presented at the conference for a more advanced comprehension of the electromagnetic phenomena.

IV. Conformal SFC Skin

Fig. 3 shows a possible application of the SFC Skin to the monitoring of a curved surface, here a bent pipe of radius

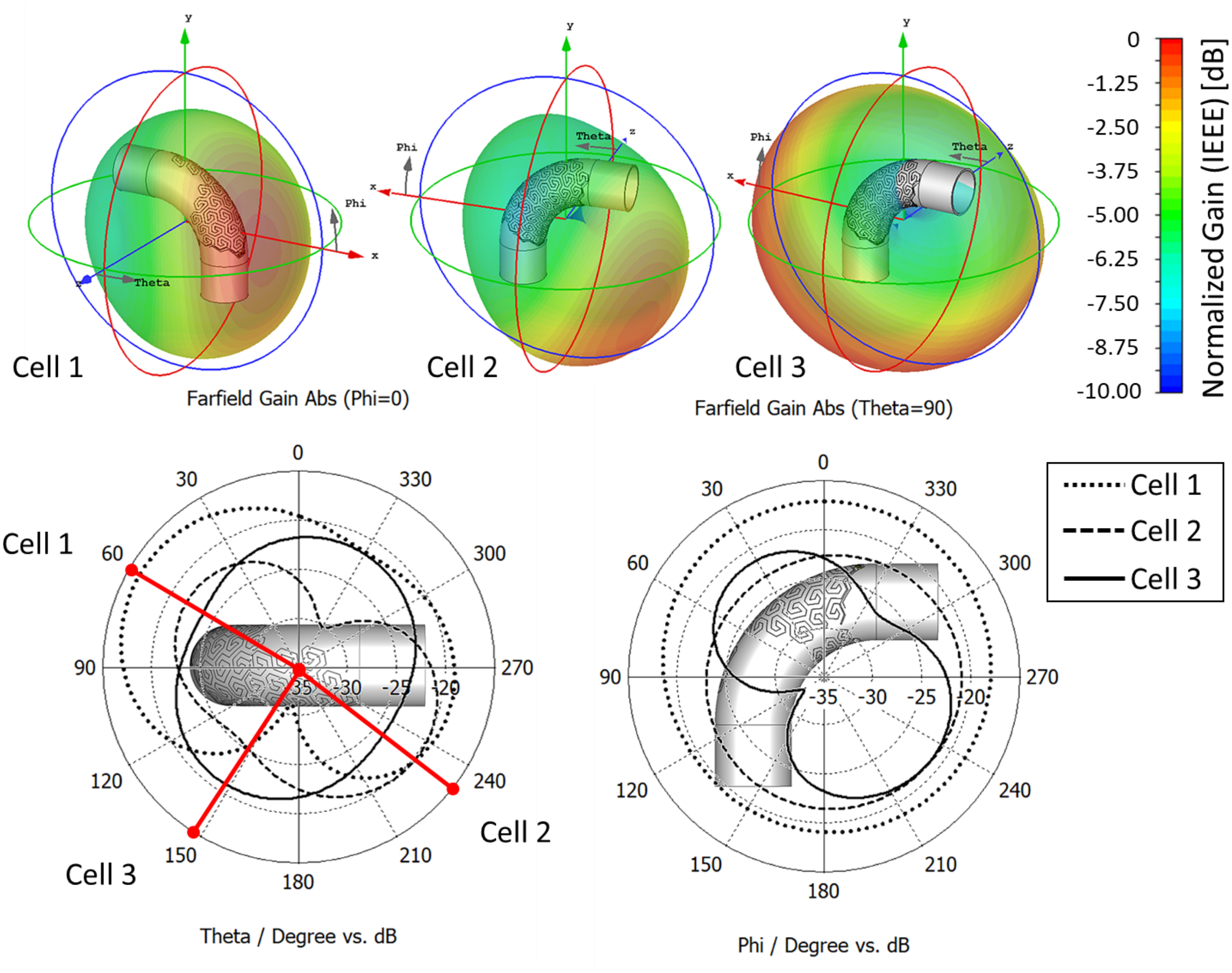

Figure 4. Up) Simulated 3D embedded gain (normalized scale) of the three space-filling cells over the pipe elbow. Bottom) Some 2D cuts of the embedded gain (absolute scale); red markers indicate the direction of the main lobe of the sensors.

$R = 25mm$. The pipe is coated by three adjacent sensing cells (order $N = 1$, enveloping hexagon side $r = 45mm$), wrapped over the curved surface. Each cell is hence potentially capable to detect cracks longer than $S(N) \geq 20mm$. The radiating part of each sensor is a T-match dipole optimized by the help of CST Microwave Studio solver and suitable to adhere as much as possible to the external boundary of the sensing cell. Simulations revealed that the conformal co-location of the Space Filling cells over the pipe will produce different and non isotropic radiation patterns (Fig. 4) that will require to move the reader around the pipe.

V. Prototype and Measurements

A prototype of the pipe (wall thickness: $2mm$) was 3D printed with ABS ($\varepsilon_{ABS} = 1.8$, $\sigma_{ABS} = 0.001S/m$ [11]) by the Zortrax M200 printer (Fig. 5). In the same process, the Space Filling skin was impressed on the pipe by means of $0.4mm$ deep grooves. The grooves were then filled with conductive silver paint (resistivity $\rho = 0.001\Omega - cm$), sintered at room temperature. The RFID microchip transponder (NXP G2iM+, power sensitivity $P_{chip} = -17.5dBm$, input impedance at 915MHz $Z_{chip} = 21.2 - 119j\ \Omega$) was finally mounted on the pipe by means of silver conductive epoxy glue.

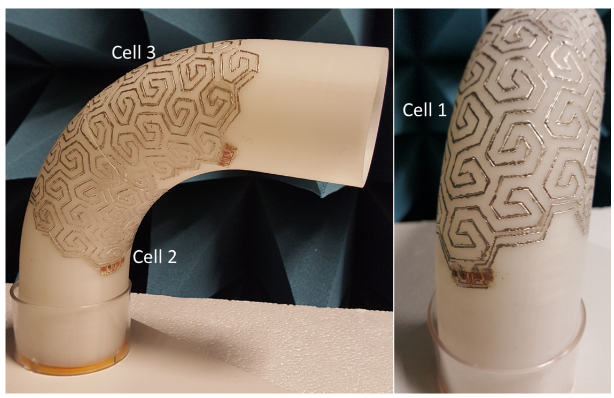

Figure 5. 3D printed pipe with the implementation of three-cell Fukuda-Gosper tessellation made by conducting paint filling $0.4mm$ deep grooves.

The resulting multi-tag sensing skin was electromagnetically characterized by means of Voyantic Tagformance station. Two configurations were considered: integer pipe (no defect over the surface) and damaged pipe (having scratched the cell #2). In both cases, the embedded realized gains Fig. 6 were evaluated by interrogating each sensor along the direction of its maximum embedded gain.

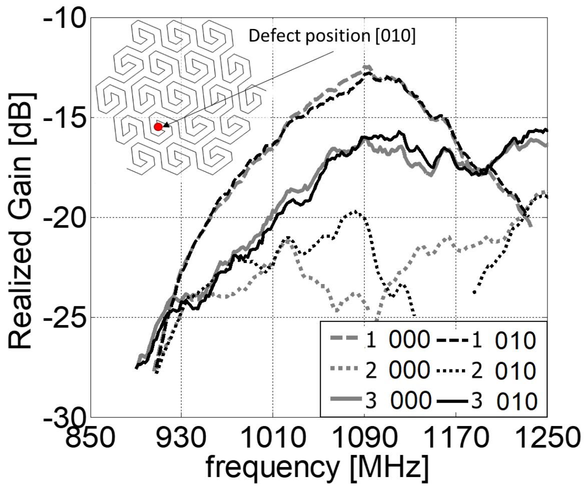

Figure 6. Measured embedded realized gains of the three sensing cells in two conditions: integer pipe (black, string *000*) and damaged pipe (grey, string *010*) inside the cell #2.

Due to the poor conductivity of the painted traces of both the SFC and the wrapped antennas, the values of the realized gain are rather low (of the order of $-20 \div -12dB$, comparable with simulations). The theoretical read distances, corresponding to $3.2W\,EIRP$ power emitted from the reader (the maximum one allowed by European Regulation) are of the order of $1.5m$ in the best conditions. It is worth observing that the presence of a defect (trace interruption) in the *n*th cell only (slightly) modifies the *n*th radiation pattern, while leaving the remainings unchanged.

VI. Conclusions

We have presented and demonstrated the feasibility of a defect-detecting printed conformal skin to monitor the health status of a curved plastic object by means of painted space-filling curve electrodes, wrapped antennas and RFID communication. The laboratory experimentation with a 3D printed mockup proved that a crack detection monitoring can be achieved from remote by a typical Internet of Thing infrastructure. Despite of the skin was fabricated by hand and the conductivity of the silver paint is rather poor, the contrast between the input impedances of the SFC electrodes in integer and damaged cases is high enough to allows the anti-tamper chip detecting the occurrence of a pipe defect that interrupts the distributed electrode.

Overall, the sensing skin is suitable to localize the portion of the tessellation where the defect appears from a distance (1.5 m) which is compatible with an on-the-fly monitoring procedure in a real environment. Improved read range could be achieved by fabricating the wrapped dipole with a thin copper wire replacing a painted trace. Additional modeling, test cases and experimental results will be shown at the Conference.

Conflict of Interest

The authors declare that they have no conflict of interest

Ackowledgements

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