GOSPER SPACE-FILLING RADIOFREQUENCY-SKIN FOR THE DETECTION AND IDENTIFICATION OF SURFACE CRACKS

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Abstract

The aging of polymer-based objects (tires, cable harness, paints, gaskets) may appear as the formation of surface defects like cracks and scratches. An early detection of such signs may support the Predictive Maintenance in the Industry 4.0 paradigm of critical polymeric devices before the occurrence of a severe damage. Inkjet printed Space Filling Curves (SFC) are here proposed as an artificial electric skin, suitable to be integrated with an RFID tag, at the purpose to detect and remotely transmit the presence of small aging signs of a surface. Thanks to the particular properties of the Gosper SFC, the size and space resolution of the skin can be easily controlled by few parameters.

Index Terms – Electronic Skin, Material Aging, Printed Electronics, RFID technology.

I. INTRODUCTION

Polymers are increasingly being used in a wide variety of applications where reliability in long-term service in harsh environments is required. These materials are usually greatly involved in aerospace and automotive industries, including civil buildings and infrastructures. The main cause that can lead to a failure during the service is the physical or chemical aging of the materials that could compromise its integrity with catastrophic results. One of the major aging effect [1] [2] is the generation of superficial cracks on the polymer. Accordingly, a regular and hopefully automatic monitoring of the object's health status could extend its lifetime preventing unexpected faults. Currently, there are several cracks detection techniques that usually require cumbersome measure methods and a highly trained operator to collect and interpret data.

This contribution introduces a new idea for the wireless identification of aging signs over plastic surfaces and some preliminary experimental examples. The method is based on an ink-jet printed electronics skin, enveloping the object like a tattoo and connected to an integrated RFID antenna. The alteration of such a skin, due to aging of the surface, will be detected by the RFID microchip transponder and then backscattered to the reader.

II. GOSPER SKIN CIRCUITS

Without loss of generality, the defect to be detected are here modeled as a linear crack, of length *l*, over the object surface (assumed, for the sake of simplicity, to be planar). A possible family of electrodes to achieve a detection skin is that of Space-filling curves (SFC) [3] [4], that map a multi-dimensional space into the one-dimensional domain. A space-filling curve acts like a thread that passes through portions of the space so that every point is visited only once. The filling density on the surface can be controlled by the selection of the iteration (order) parameter. It can be proved that the minimum length of the detectable crack can be defined as space resolution *S(N)* and expressed as:

$$S(N) = \frac{4r\sqrt{3}}{\sqrt{7^{N+1}}} \quad (1)$$

where r is the radius of the circle enveloping the Gosper island. We consider here the Peano-Gosper curves (Fig. 1) as possible detectors of surface defects since, thanks to their rotational construction, they have the property to uniformly and quickly improve the spatial resolution with respect to the Hilbert curve. The Gosper SFC also possesses the capability of surface tessellation so that several Gosper Islands can be placed one close to another (Fig. 2) in order to widen the area to be monitored. The interrogation of the resulting skin is implemented by connecting the two terminals of each island to the anti-tampering port of an RFID tag. The occurrence of a crack (or more in general of a defect) will not only be identified, by even localized in a macro-region depending on the responding tag with the altered anti-tamper bit.

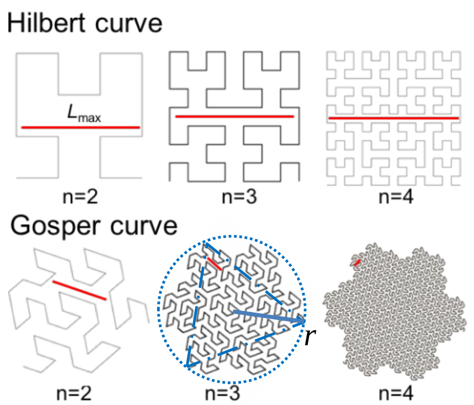

FIG. 1 Hilbert and Gosper Space-Filling Curves of some orders. The red lines indicate the maximum segment that is not crossed by the curves; such segment can be considered as the lower-bound length of a crack that would not interrupt the line. The blue segment is the radius of the circle enveloping the SFC.

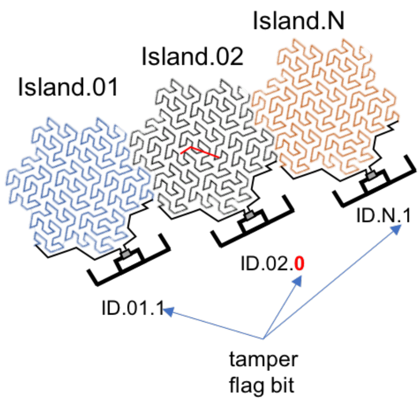

FIG. 2 Pictorial example of how several Gosper Islands can be mutually displaced in order to fill a large surface. The red '0' indicates the anti-tamper bit in the response of the second tag detecting the occurrence of a damage in the island n.2; in other words, the condition $l_{crack}>S(N)$ has occurred for that island.

III. GOSPER SKIN RESISTANCE

A possible fabrication of the space-filling RFID skin involves the conducting inkjet printing process thanks to its capability to produce complex shapes and to deposit ink even onto non planar surfaces. The DC conductivity of the self-sintering ink is $\sigma^{DC} \simeq 1 \cdot 10^7$S/m [5]. In a preliminary test the printing substrate is the PVA coated PET Mitsubishi Paper Mills (Thickness 135µm). Fig. 3 shows some single-pass printed Gosper curves of increasing order such to be limited within 8.5cmX8.5cm square. The critical issue is the non-uniform spread of the deposited ink droplets inside and outside the main trace so that, in high order SFC (closes lines), they may produce a change of the input DC resistance of the curve, measured at the two terminals. Tab. 1 resumes the measured DC input resistance, by a Fluke meter, in case of a continuous line (R^{SC}) as well as in case it was interrupted in the middle (R^{OC}) by a small cut. Due to the intrinsic ink loss, the short-circuit resistance increases (nearly doubles) along with the order of the curve, i.e. for overall longer traces. With reference to the NXP UCODE G2iM+ chip, the tampering circuit is considered closed (alarm flag = 0) when the port resistance is R^{SC}<2MΩ, while instead the circuit is considered interrupted (alarm flag = 1) when R^{SC}>20MΩ. Accordingly, the measured resistances in Tab. 1 show that all the considered Gosper curves can be suitable to interconnection with an RFID tag.

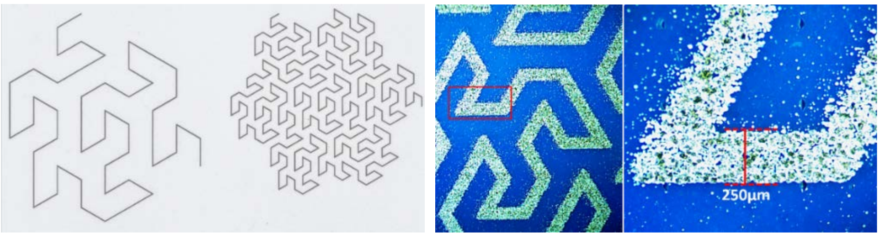

FIG. 3 Some inkjet-printed Gosper SFCs, with a trace 250µm of increasing orders, over a PET substrate (left). Magnified photo of the n=4 curve (right).

TABLE I – MEASURED DC INPUT RESISTANCE AT THE GOSPER SFC IN CASE OF SHORT-CIRCUIT CURVE AND OPEN-CIRCUIT LINE.

Order (n)	Length [m]	R^{SC} [kΩ]	R^{OC}[MΩ]
2	0.60	0.7	>2000
3	1.40	1.6	>2000
4	3.86	3.6	>2000

IV. EXPERIMENTAL VALIDATION

The overall wireless sensing skin (order n=3), is finally integrated (Fig. 4) with a meander line dipole, made by a thin wire conductor, embedding the anti-tamper chip NXP UCODE G2iM+. Fig. 4 shows also the realized gain of the skin (in two operative conditions). The SFC acts as a parasitic element that electromagnetically interacts with the MLA antenna depending on its status thus affecting its impedance and radiation pattern. The resonant frequency of the tag shifts from 921MHz, in absence of the skin, to 899MHz when the skin is connected to the anti-tampering port of the chip, and the peak of the gain decreases of 0.5dB. Finally, when the Gosper curve is broken in the middle by a 86µm scratch, the induced current reshapes and the resonance frequency of the tag moves to 903MHz. Overall, being P_C=-17.5dBm the power sensitivity of the chip, the status of the skin might be read up to 10m in case of an interrogation power EIRP=3.2W at the peak condition.

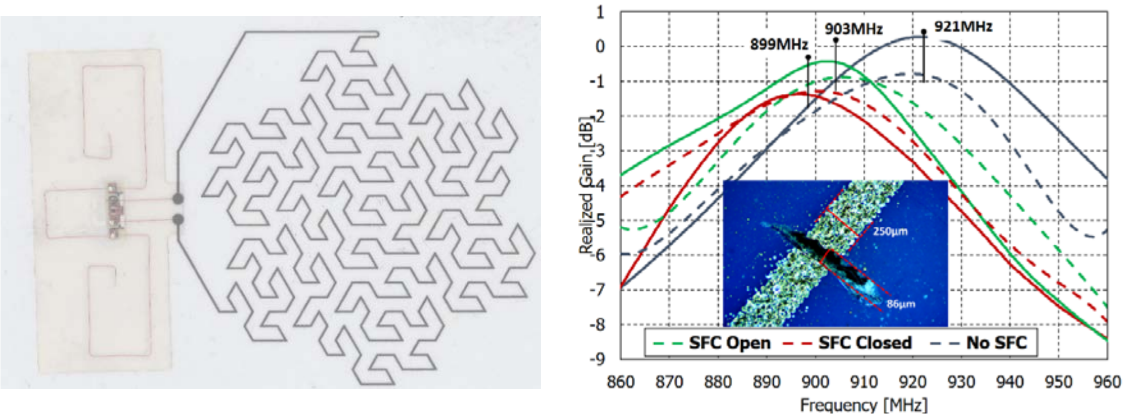

FIG. 4 Inkjet-printed third-order Gosper skin integrated with an RFID MLA tag (on the left). Measured (dashed) and simulated (solid) realized gain in absence of damage and in case of an interruption of the skin in the middle (on the right).

V. CONCLUSION

We have presented the idea and a preliminary experimentation of a defect-detecting printed skin to monitor the aging of surface by means of the RFID platform. The Gosper curve looks an interesting option to control the size and the space-sensitivity of the skin by means of few parameters. Despite of the modest quality of the used low-cost inkjet printing, the achieved resistance of the printed trace is low enough to let the anti-tamper chip to discriminate an open circuit skin (a surface defect) from a short circuit case (healthy surface).

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