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Inkjet-printed RFID-Skins for the Detection of Surface Defects

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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 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. The idea is corroborated by preliminary experimentations with low-cost inkjet printed traces that easily enable to monitor the presence of a defect from a distance of 10 m and more.

1 Introduction

In the last years, polymers are 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. In each scenario, they can suffer from non-negligible stress factors (mechanical, thermal or chemical) that could compromise their integrity with catastrophic results. The main cause that can lead to a failure during the service is the physical or chemical aging of the materials. The aging of an object is a natural phenomenon that can't be stopped but can be delayed by resorting to advanced manufacturing processes, using self-healing techniques, or to predictive maintenance procedures. One of the major aging effect [2, 3] is the generation of superficial cracks on the polymer. These macroscopic damages are due to massive chain break in the polymer structure and makes the object brittle and therefore much more susceptible to fracture. 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 [4, 5] based on non-destructive methods. Some of them provide a very high resolution (up to nm scale) such as X-ray microtomography or scanning electron microscopy (SEM). Other techniques are acoustic-based with a low-to-medium resolution (from cm up to mm scale). Finally there are some cracks detection methods based on electric impedance and thermography (up to mm scale). All these techniques usually require cumbersome instruments of measure and, in some cases, a highly trained operator to collect and interpret data. Hence, applying these cracks detection techniques over a large scale is not straightforward.

In the last five years some potential applications of Radiofrequency Identification (RFID) technology to the wireless monitoring of cracks have been investigated. In most of the papers [6, 7], the leading idea is that the occurrence of a crack produces a modification of the tag's antenna electromagnetic behavior that is detectable remotely by processing the backscattered signals (amplitude and/or phase) emitted by the tag. The common requirement is that the antenna body has to be placed exactly where the crack is going to occur, or at most, at a very close distance from it. Thus, to monitor a large surface wherein the future presence of a crack is unknown, a dense grid of tags have to be used. This approach becomes of difficult implementation in case of very small cracks have to be detected within a large surface.

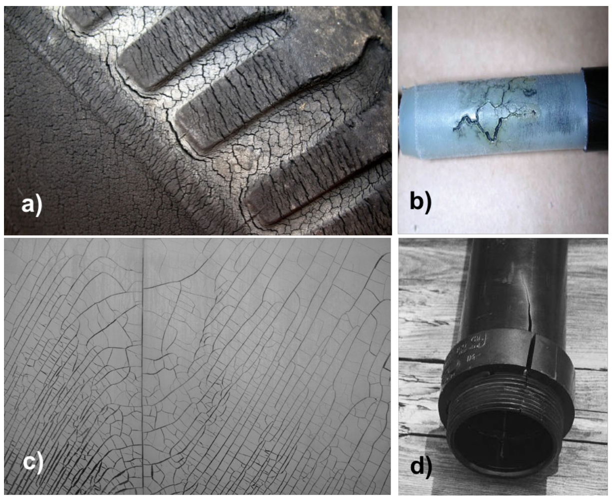


Figure 1. Examples of micro and macro cracks onto polymeric materials: s) tire, b) cable harness, c) paint, d) gasket.

In this paper, we propose a scalable and easily applicable technology, still involving RFID communications, for the wireless identification of aging signs over plastic surfaces. The method is based on the fabrication of an ink-jet printed electronics skin, enveloping the object like a tattoo, that has the advantage to be easily tunable in size and density in order to monitor large areas with a programmable space sensitivity. The alteration of such a skin, due to aging of the surface, can be identified from remote by using RFID. The idea consists of a space-filling curve circuit connected to the anti-tamper port of an UHF-RFID tag that, once damaged in some points will set a tampering bit in the tag response.

This contribution introduces the selection of the most appropriate space filling curve and some preliminary experimental example with inkjet printed prototypes.

2 Space-filling curves for defect detection

Without loss of generality, the defect to be detected are here modeled as a linear crack, of length L, over the object surface. For the sake of simplicity, we moreover assume the object's surface to be planar. A possible family of lines to achieve a detection skin is that of Space-filling curves (SFC), originally introduced by the mathematician Giuseppe Peano (1890) [1] that map a multi-dimensional space (even volumes) 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. As space-filling curves do not self-intersect (Self-Avoidance property), they can be used as an electric circuit. Finally, space-filling curves are Self-similar, that means it is possible to control the filling density on the surface by the selection of the iteration (order) parameter. Among the various options of SFCs, some of them have been already investigated for antenna applications to miniaturize dipoles and patches [8, 9, 10]. We consider here the Peano-Hilbert and the Peano-Gosper curves (Fig. 2) as possible detectors of surface defects.

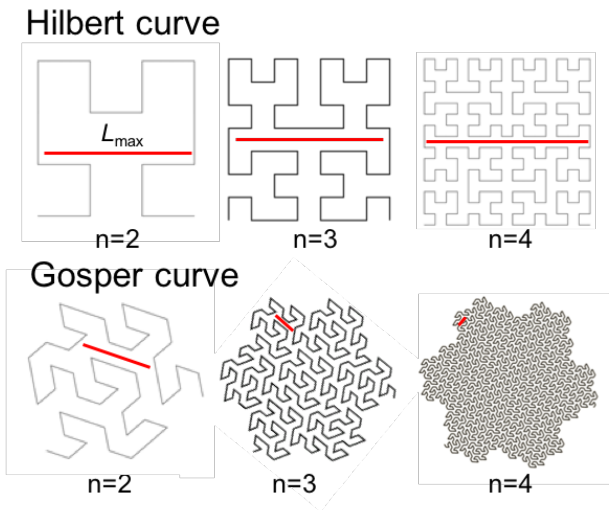


Figure 2. Hilbert and Gosper Space-Filling Curves (first iterations) of some orders, for application to surface defect detection. The red lines indicate the maximum segment that is not crossed by the curves .

It is useful to compare the behavior of the two curves for the specific application. Let's denote with L_{max} the longest segment that can be placed along portions of the surface that are not filled by the lines. Such segment can be considered as the lower-bound length of a crack that would not interrupt the line and accordingly it determines the spatial resolution of the skin detector. While both Hilbert and Gosper curves increase the filling density by rising the iteration order, it is clear that the Gosper curve, thanks to its rotational construction, has the property to uniformly and quickly improve the spatial resolution with respect to the Hilbert curve, This, preserves instead, in some part of its geometry, the same maximum "white" surface tile of the first iterations even in much denser patterns. Thus Gosper SFC is the only configuration hereafter investigated.

Even though not regular as 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. 3) 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.

3 Inkjet Printed Gosper skins

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. A low-cost printer with self-sintering ink [11] is adopted in preliminary experimentations. The advantage is that post-manufacturing curing is not required as the ink will spontaneously sinter at ambient temperature. The DC conductivity of the ink is $\sigma_{DC} \simeq 1 \cdot 10^7 S/m$. The printing substrate is the PVA coated PET Mitsubishi Paper Mills (Thickness 135 μm). Fig.4 shows some single-pass printed Gosper curves of increasing order such to be limited within $8.5\,cm \times 8.5\,cm$ 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 (closer 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

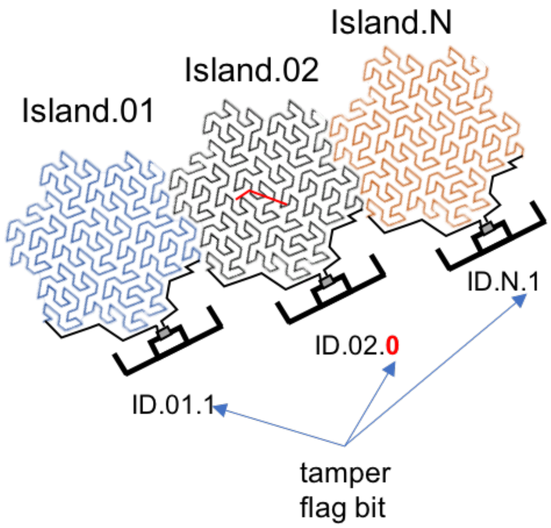


Figure 3. Pictorial example of how several Gasper Islands, each connected to an RFID tag provided with an ante-tampering port, can be mutually displaced in order to fill a large surface. The red '0' indicates the anti-tamper bit in the response of the second tag detecting the occurrence of a damage in the Island n.2.

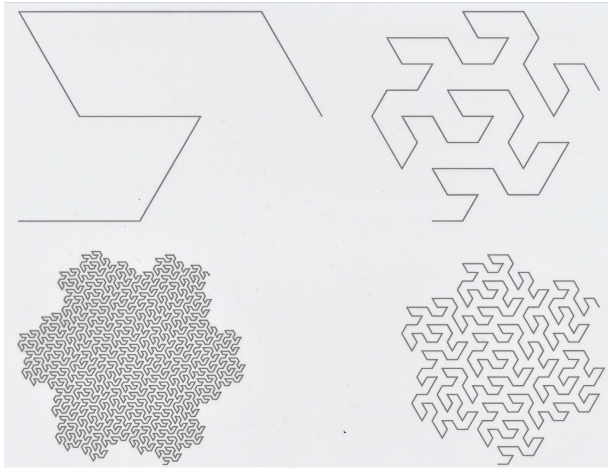
Fluke meter, in case of a continuous line (R^{SC}) as well as in case it was interrupted in the middle (R^{OC}) by a small cut. Due to the intrinsic ink loss, the short-circuit resistance increases (nearly doubles) along with the order of the curve, i.e. for overall longer traces. These values have to be compared with the threshold resistance of the anti-tampering port (VDD and OUT pins) of the RFID chip. With reference to the NXP UCODE G2iM+ chip, the tampering circuit is considered closed (alarm flag = 0) when the port resistance is $R^{SC} < 2\,M\Omega$, while instead the circuit is considered interrupted (alarm flag = 1) when $R^{SC} > 20\,M\Omega$. Accordingly, the measured resistances in Tab.1 show that all the considered Gosper curves can be suitable to interconnection with an RFID tag.

Table 1. Measured DC input resistance at the Gosper SFC in Fig.4 in case of short-circuit curve and open-circuit line (interrupted in the middle by a cut). The second set of measurements saturated to the meter upper-bound range.

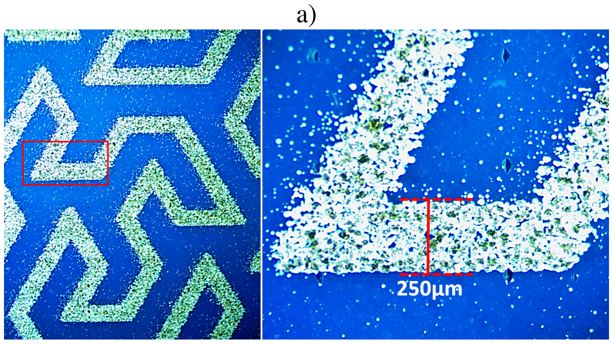
n	**length [m]**	R^{SC} [$k\Omega$]	R^{OC}[MΩ]
2	0.60	0.7	>2000
3	1.40	1.6	>2000
4	3.86	3.6	>2000

4 The integrated RFID skin

The overall wireless sensing skin (order n=3), is finally integrated (Fig. 5.a) with a meander line dipole, made by a thin wire conductor, embedding the anti-tamper chip NXP UCODE G2iM+. Fig. 5.b shows the realized gain of the skin (in some two operative conditions) that have been measured in the world-wide RFID band by means our custom setup employing the ThingMagic M5e reader.



a)



b)

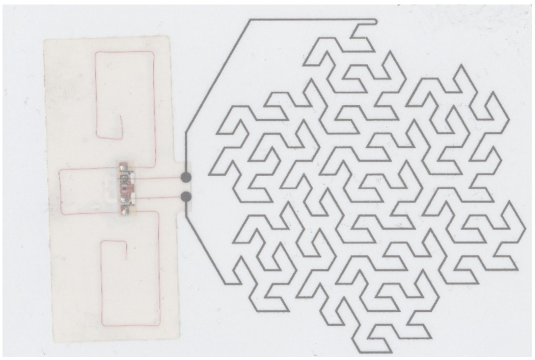
Figure 4. a) Some inkjet-printed Gosper SFCs, with a trace 250 µm of increasing orders, over a PET substrate. b) Magnified photo of the n=4 curve.

The SFC acts as a parasitic element that electromagnetically interacts with the MLA antenna depending on its status thus affecting its impedance and radiation patter. The resonant frequency of the tag shifts from 921 MHz, in absence of the skin, to 899 MHz when the skin is connected to the anti tampering port of the chip, and the peak of the gain decrease of half dB.

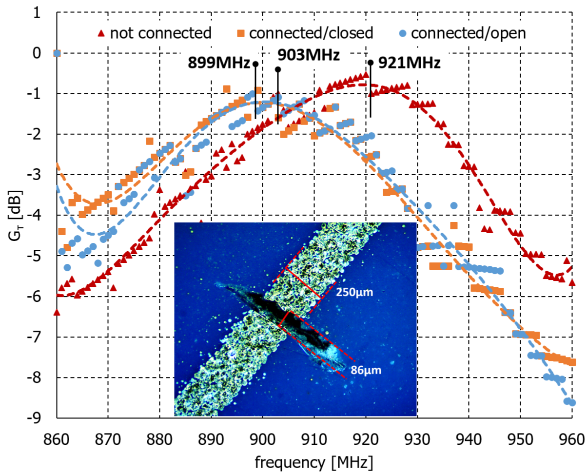
Finally, when the Gosper curve is broken in the middle by a 86 µm scratch, the induced current reshapes and the resonance frequency of the tag moves to 903 MHz.

Overall, being P_C=-17.5 dBm the power sensitivity of the chip, the status of the skin might be read up to 10 m in case of an interrogation power EIRP=3.2 W at the peak condition.

However, the design of more complex configurations demands for an accurate electromagnetic modeling to find the



a)



b)

Figure 5. a) Third-order Gosper skin integrated with an RFID MLA tag. b) Measured realized gain in absence of damage and in case of an interruption of the skin in the middle.

optimal shape of the antenna and of the interconnection to the skin, in order to make the working frequency as more insensitive as possible to the occurrence of possible defects.

5 Conclusions

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 ink-let 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).

At the Symposium, we will moreover present a detailed numerical analysis of several relevant configurations in order to earn a better insight into the electromagnetic interaction phenomena when multiple Gosper islands are involved.

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