Strain Reliability of Embroidered Passive UHF RFID Tags on 3D-printed Substrates

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***Abstract*—Flexible electronics is an emerging field where the electronic components, antennas, and interconnections can endure significant mechanical stresses. This paper presents the fabrication and strain reliability evaluation of embroidered passive UHF RFID tags on 3D-printed (NinjaFlex) substrates. Based on the achieved results, these wireless platforms can withstand increases up to 14 % in length and remain functional. These preliminary results are promising, considering the current trend towards flexible and stretchable electronics structures.**

***Index terms*—3D Printing, embroidery, flexible electronics, NinjaFlex, passive RFID, strain reliability, stretchable electronics.**

I. INTRODUCTION

For years, research and development of electronics was primarily focused on making electronic devices smaller and faster, with most of these devices being silicon-based devices, which are rigid and hard. However, an emerging field in electronics is the development of flexible and stretchable structures, where the goal is to obtain an optimal performance of the electronic device also under challenging mechanical conditions [1][2].

Recently, there has been significant progress in the fields of mechanical science as well as advanced materials and manufacturing processes, which has led to the development of materials that can be incorporated in the manufacture of flexible and stretchable electronics [3]. Due to their flexibility and lightweight properties, flexible and stretchable electronics are ideal for various applications, for example in robotics, wearable and implantable biomedical devices, and sensors. Many of these materials are compatible with textiles and fabrics, and in some cases, organs and tissues [4].

3D printing (one form of additive manufacturing) is a process in which objects are manufactured in a layer upon layer sequence [5]. Initially used for prototyping, these processes have since provided several advantages for product development at every step, from concept realization to the finished product [6]. 3D printing processes have gained popularity due to the increasing availability of 3D printable materials and their reducing costs. Recently, additive manufacturing has been used for example in manufacturing of electronic devices, biomedical technologies, devices which store energy (like batteries), and various kinds of sensors [7].

Among the various materials available for 3D printing, thermoplastic polyurethane materials, such as NinjaFlex, have recently gained a lot of interest. They are lightweight, yet strong and flexible, and have thus been used in RF applications, for example as substrates for wearable antennas [8]-[10] and passive Ultra-High Frequency (UHF) Radio-Frequency Identification (RFID) tags [11][12].

Now, in this study, substrates with different mechanical properties were fabricated using 3D printing of NinjaFlex, and passive UHF RFID tag antennas were developed on these substrates, by embroidering the antenna patterns with conductive thread. The wireless performance of these wireless platforms was evaluated initially, as well as when they were being stretched, in order to study their strain reliability.

II. MANUFACTURING OF WIRELESS PLATFORMS

A. *3D printing and substrate preparation*

The substrates were 3D printed from NinjaFlex material, using Prenta Duo 3D printer. Using a nozzle temperature of 230-235 ˚C and a printing speed of 35 mm/s, substrates of 140 mm x 30 mm were printed. A sample of a 3D-printed substrate is shown in Fig. 1. In 3D printing, it is possible to modify the mechanical and electrical properties of the printed structure, simply by modifying the printing parameters. Two types of samples were fabricated, which were rectilinearly printed substrates and substrates printed with horizontal lines. Fig. 1 presents these two types of substrates. The 0.2 mm thick bottom and top layers (2 of each) of the substrates were printed with 100 % infill patterns and one 0.2 mm layer with 25 % infill pattern was printed in the middle of the structure.

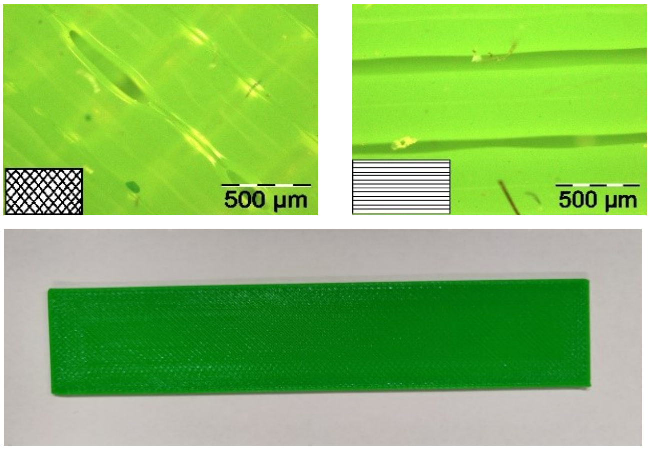

Fig. 1. Microscopic view of a rectilinear substrate (top-left) and a horizontal substrate (top-right), and a sample substrate (bottom)

B. *RFID tag fabrication*

The tag antennas were fabricated on the 3D-printed substrates by embroidering the outer boundaries of the antenna pattern as shown in Fig. 2. The antenna pattern used in this experiment has been previously successfully embroidered on a 3D-printed substrate [11]. The antennas were embroidered using Husqvarna Viking Ruby Royale embroidering machine. The conductive thread used for the embroidery process was Shieldex Filament 110f32 2-ply HC, with a DC linear resistivity of 500 Ω/m ±100 Ω/m.

After the embroidery process, NXP UCODE G2iL RFID ICs (integrated circuits), were attached onto the antenna patterns, using conductive silver epoxy. A ready tag on the 3D-printed substrate is shown in Fig. 3. Two RFID tags were fabricated on horizontally printed substrates and two RFID tags on rectilinearly printed substrates.

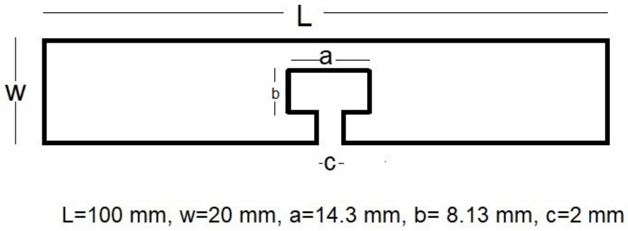

Fig. 2. The used antenna design.

Fig 3. A ready-made wireless platform.

There were some major challenges encountered during the tag antenna manufacturing process. In general, embroidery of the antenna patterns on the horizontal substrates was easier, compared to the rectilinear substrates. Rectilinear substrates occupy more space compared to the horizontal substrates, hence the conductive thread had to encounter more infill material during the embroidery process. The conductive thread used for the embroidery process was weak, resulting in repeated breakages during the embroidery process. Thus, a non-conductive nylon thread, which was stronger and less susceptible to breakage, was selected as the bobbin thread, in order to ease the formation of knots underneath the substrate. The thread tension value in the embroidery machine was increased to reduce the clusters that formed easily during the embroidery process, as shown in Fig. 4.

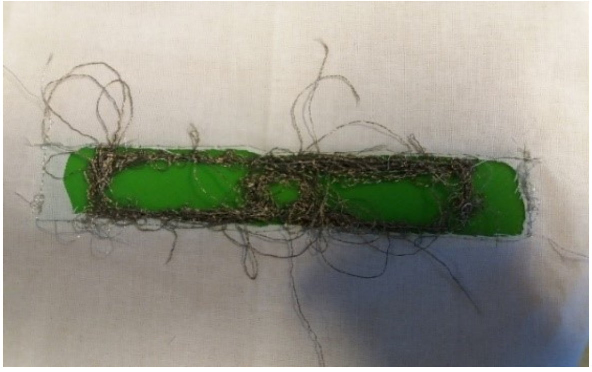

Fig. 4. Cluster formation from bobbin thread.

III. MEASUREMENT SETUP

The strain reliability of the platforms was evaluated using Instron 4411 tensile strength tester, as shown in Fig. 5, by placing the two ends of the substrates at the two arms of the tester. The load attached to the tester was 5 kN and the arms of the tester were made to move apart at a speed of 20 mm/min.

Fig. 5. The used tensile strength tester.

The wireless performance of the fabricated platforms was first studied in an anechoic chamber, using Voyantic Tagformance RFID measurement system, as shown in Fig 6. The system is calibrated firstly using a reference tag to characterize the properties of the wireless channel from the reader antenna to the tag. The theoretical read range between the tag and the reader antenna is based on the measured path loss and threshold power, as given in (1),

$$d_{Tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{P_{TS}\,L_{fwd}}} \qquad (1)$$

where EIRP is the emission limit of an RFID reader, given as equivalent isotropic radiated power. In this study, EIRP = 3.28 W, which is the emission limit in European countries. λ is the wavelength transmitted from the reader antenna, P_{TS} and L_{fwd} are the measured threshold power and forward losses, correspondingly.

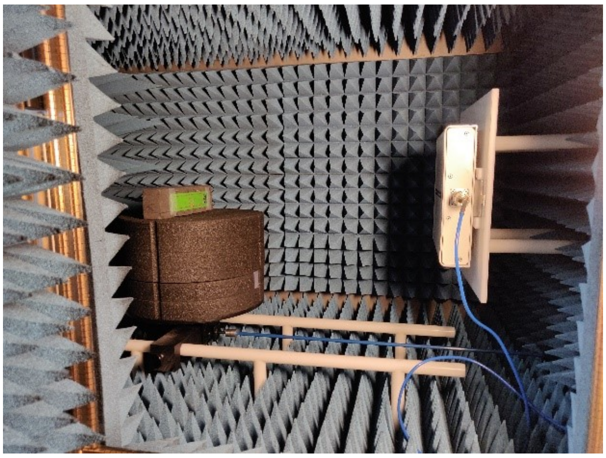

Fig. 6. Measurement set-up in an anechoic chamber.

In order to test the wireless performance of the platforms in real-life conditions, they were then tested in a normal office environment, as shown in Fig 7. Finally, the platforms were subjected to the strain reliability test, as shown in Fig 5. The wireless measurements during stretching were made at one-minute intervals and the platforms were stretched at a rate of 5.00 mm/min.

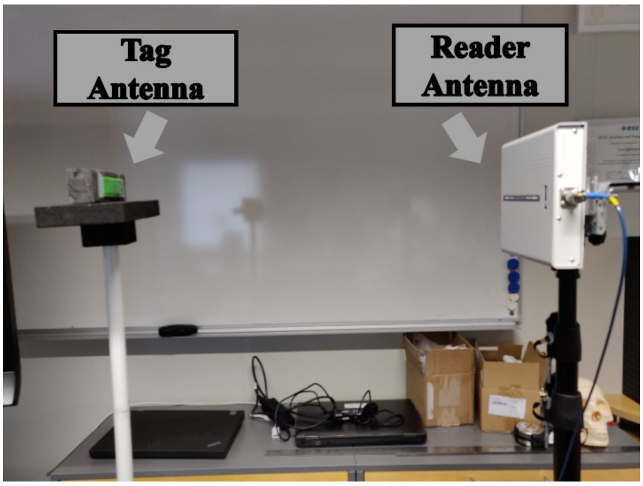

Fig. 7. Measurement set-up in an office.

IV. RESULTS AND DISCUSSION

The initial wireless measurement results (before any testing) from the anechoic chamber are shown in Fig. 8 and the initial measurement results from the set-up in an office are shown in Fig. 9. As can be seen, there are significant variations in the read range results of the RFID tags on horizontal and rectilinear substrates, as well as major differences between the read ranges of the tags on similar substrates. These variations are caused by the unstable embroidery method, which means the embroidery process clearly needs to be developed further. The variations in the free-space measurements compared to the measurements done in the anechoic chamber are caused by the unstable measurement environment. However, in all situations, all of the tags showed read ranges of more than 2.5 meters, throughout the global UHF RFID frequency band. Thus, these platforms can be considered very promising for versatile wireless applications, after the challenges in their manufacturing process have been fixed.

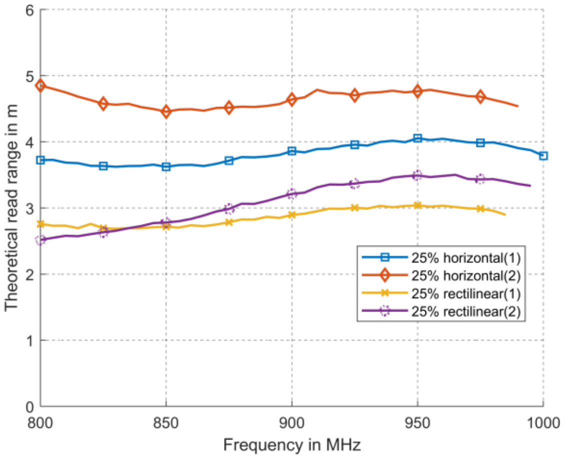

Fig. 8. Read range measurement results from the anechoic chamber.

Fig. 10 represents the read range values during the stretch tests of the horizontal and rectilinear platforms at every one-minute interval. Firstly, it was noticed that the metallic parts of the stretching test device affected the wireless performance of the platforms. This was evident, when comparing the measurement results from the office environment to those achieved initially inside the stretch test device. During testing, the performance of the rectilinear tags decreased significantly already after 3 minutes, while it was observed that the tags in the horizontal platforms responded in a quite stable way for the first 6 minutes of the testing, i.e., when the platform was stretched by less than 14 % from its original length. After 6 minutes, none of the tags responded. Based on these results, the horizontally printed structures seem to be a better choice for applications that require electronics to be embedded into stretchable platforms.

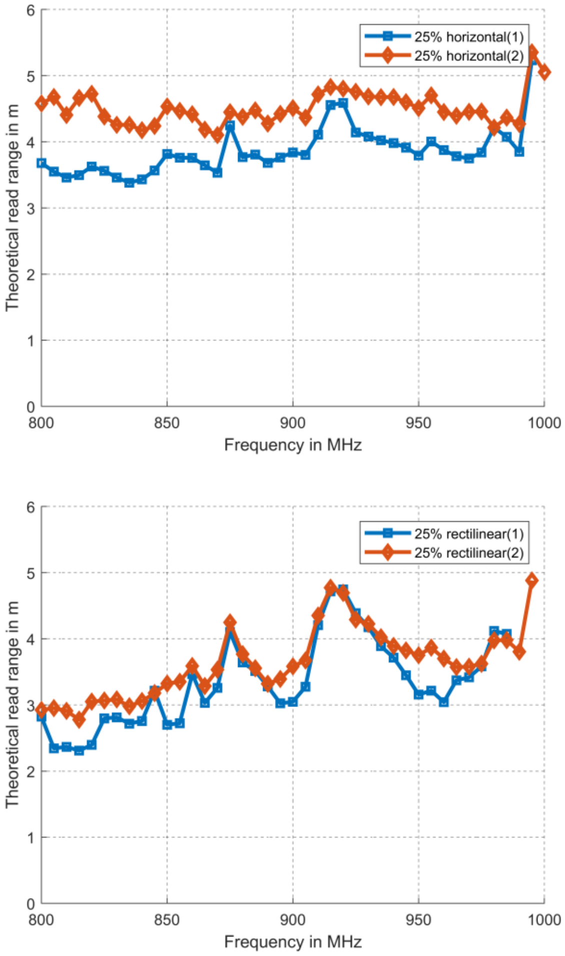

Fig. 9. Read range measurement results from the office set-up: Tags on horizontal substrates (top) and tags on rectilinear substrates (bottom).

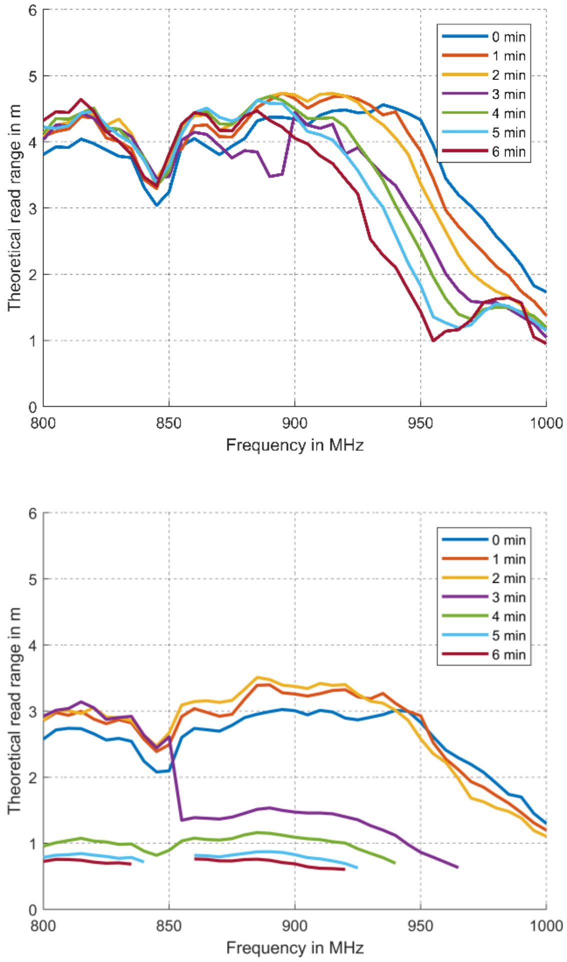

Fig. 10. Read range measurement results during the stretching test for horizontal (top) and rectilinear (bottom) platforms.

V. CONCLUSIONS

We studied the wireless performance of embroidered passive UHF RFID tags on 3D-printed polyurethane substrates. The measurement results showed that the platforms were able to maintain suitable wireless performance, and read ranges of several meters, despite being subjected to a 14 % change in their initial length. It was discovered that horizontally printed substrates could offer a more convenient solution for stretchable electronics structures, compared to rectilinear printing. These results were obtained despite the challenges encountered during the development of the tags, especially during the embroidery process of the antennas. The next step is to solve the challenges related to the embroidery process and make more accurate measurements with a larger amount of samples.

ACKNOWLEDGEMENT

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VI. REFERENCES

[1] J. Song, "Mechanics of stretchable electronics," *Current Opinion in Solid State & Materials Science,* vol. 19, *(3),* pp. 160-170, 2015.

[2] J. Ahn and J. H. Je, "Stretchable electronics: materials, architectures and integrations," *J. Phys. D,* vol. 45, *(10),* pp. 103001, 2012.

[3] Y. Ma *et al*, "Design of Strain-Limiting Substrate Materials for Stretchable and Flexible Electronics," *Advanced Functional Materials,* vol. 26, *(29),* pp. 5345-5351, 2016.

[4] B. Wang *et al*, "High- k Gate Dielectrics for Emerging Flexible and Stretchable Electronics," *Chem. Rev.,* vol. 118, *(11),* pp. 5690-5754, 2018.

[5] W. Zhou. (). *3D printing.* Available: https://www.accessscience.com:443/content/3d-printing/694300. DOI: 10.1036/1097-8542.694300.

[6] R. Noorani, *3D Printing : Technology, Applications, and Selection.* 2017Available: http://ebookcentral.proquest.com/lib/tut/detail.action?docID=4986151.

[7] C. Liu *et al*, "3D Printing Technologies for Flexible Tactile Sensors toward Wearable Electronics and Electronic Skin," *Polymers,* vol. 10, *(6),* pp. 629, 2018.

[8] M. Rizwan *et al*, "Flexible and Stretchable Brush-Painted Wearable Antenna on a Three-Dimensional (3-D) Printed Substrate," *IEEE Antennas and Wireless Propagation Letters,* vol. 16, pp. 3108-3112, 2017.

[9] K. Nate and M. M. Tentzeris, "A novel 3-D printed loop antenna using flexible NinjaFlex material for wearable and IoT applications," 2015.

[10] S. Moscato *et al*, "Infill-Dependent 3-D-Printed Material Based on NinjaFlex Filament for Antenna Applications," *IEEE Antennas and Wireless Propagation Letters,* vol. 15, pp. 1506-1509, 2016.

[11] M. Rizwan *et al*, "Embroidered passive UHF RFID tag on flexible 3D printed substrate," in 2017, . DOI: 10.1109/PIERS-FALL.2017.8293247.

[12] M. Rizwan *et al*, "Flexible and stretchable 3D printed passive UHF RFID tag," *Electron. Lett.,* 2017.