Fabrication challenges in embedding of components and embroidered conductors into 3D-printed textile electronics structures

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Abstract**—***The challenging unobtrusive implementation of electronics structures into clothing, with low cost and high reliability, can be achieved via utilising and adapting a novel structural additive manufacturing method. Our goal is to utilize 3D-printed flexible and washable wireless platforms, where electronics, embroidered antennas and interconnections are embedded mid-printing, created directly on textiles. During the fabrication process, several challenges were encountered. The most important challenges related to the embroidery process were repeated thread breakages, thread cluster formation at the opposite side of the embroidered patter, and non-precise positioning of the thread at different embroidery rounds. Further, during 3D printing, positioning of the starting point of the printing, resulting as misaligned 3D-printed layers, was a major challenge. This paper describes in detail the challenges encountered during the fabrication process of clothing-integrated basic wireless components, passive UHF RFID tags. Despite the introduced challenges, the ready-made textile-integrated tags showed excellent wireless performance and read ranges of around 6 meters.*

Keywords—Antennas; 3D printing; NinjaFlex; embroidery; passive UHF RFID; textile electronics.

1. INTRODUCTION

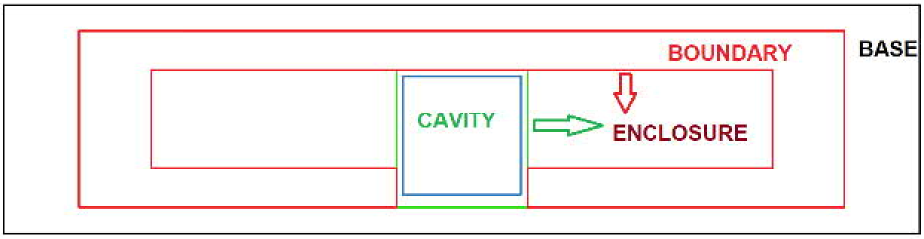
The possibility of bendability and flexibility, as well as the ability to roll and wear electronics has already significantly impacted the way electronics can be used. The development of new materials and novel manufacturing methods has resulted in widespread applications of flexible electronics, some of which are bendable displays, wearable biomedical devices and health monitors, and flexible photovoltaic devices [1]-[3]. Further, flexibility of electronics has benefitted significantly fabrication of clothing-integrated electronics, where the solutions need to be robust towards mechanical stresses. The challenging unobtrusive implementation of electronics structures into clothing, with low cost and high reliability, can be achieved via utilizing and adapting a novel structural additive manufacturing method: Our goal is to utilize 3D-printed flexible and washable wireless platforms, where electronics, embroidered antennas and interconnections are embedded mid-printing, created directly on textiles.

Embroidery with conductive yarn is a relatively simple process but is very useful in development of antenna patterns on non-conductive textiles. The sewing process parameters, such as stitch type and density, can be modified to control the antenna performance parameters. Previous studies have widely analyzed the performance of embroidered antenna patterns [4]-[7]. 3D printing is a process where digital models are used to develop physical objects layer-by-layer [8][9]. The process involves depositing several two-dimensional layers on top of one another, and as the deposition proceeds, the layers solidify. This process is repeated until the entire three-dimensional model is prepared [8]. NinjaFlex is a relatively new flexible 3D printing material introduced in 2014. It is a thermoplastic polyurethane (TPE) material, a combination of thermoplastic and rubber [10][11]. NinjaFlex has already gained interest in the field of wearable antennas [10]-[12], and as a substrate material of passive ultra-high frequency (UHF) radiofrequency identification (RFID) tags [13][14].

In this study, our novel manufacturing approach is used to integrate wireless platforms into textiles. However, during the fabrication process, several challenges were encountered. This paper describes in detail the challenges encountered during the fabrication process of clothing-integrated basic wireless components, passive UHF RFID tags.

2. TAG FABRICATION

Initially, using AutoCAD 2017, a model for the substrate pattern to be 3D printed was developed, as shown in Figure 1. The model comprised of two patterns: a simple rectangular base pattern and an enclosure pattern. The enclosure pattern consisted of an outer boundary and a cavity, the latter being used for the protection of the matching part of the antenna pattern and the RFID microchip. The combined height of the base and enclosure parts was 0.9 mm, in which the base pattern was 0.2 mm and the enclosure pattern was 0.7 mm. The AutoCAD models were then exported to Simplify3D, which is a slicer software for 3D printing. The printer used for this experiment was Prenta Duo 3D printer and the printed material was NinjaFlex. The base pattern and 0.2 mm of the enclosure pattern without the cavity part were first printed on the used stretchable cotton-based textile. The printing parameters are illustrated in Table 1 (referred as “pre-embroidery”). The cavity part was not printed for this layer, in order to give space for the needed RFID microchip component, which was going to be embedded inside the 3D-printed structure.



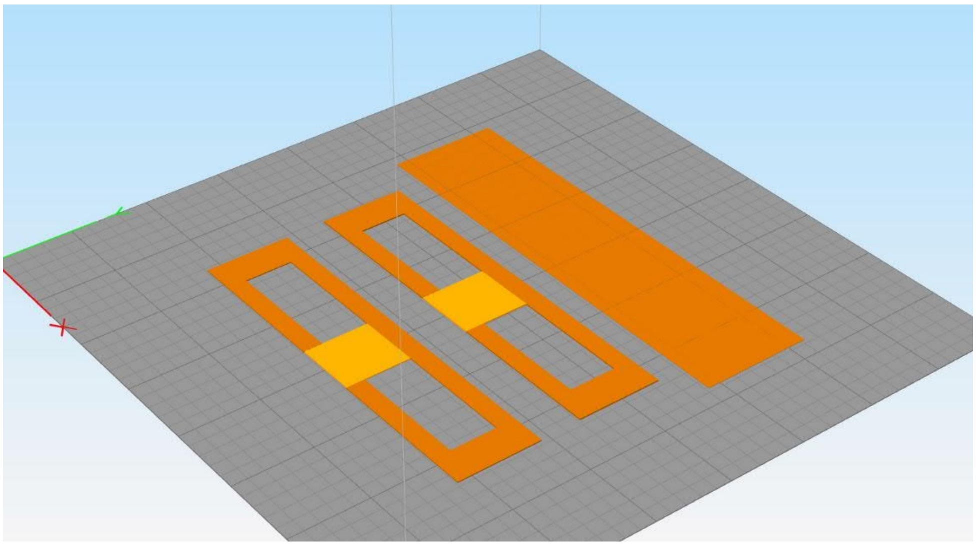


Figure 1. The designed parts of the 3D-printed structure.

Table 1. The used printing parameters.

	Layer Height	Infill Pattern	Infill Percentage
Pre-embroidery	0.1 mm	Rectilinear (-10^{o} and +10^{o})	80 %
Post-embroidery	0.1 mm	Rectilinear (-90^{o} and +90^{o})	100 %

The base pattern served as a support for the embroidery process, without which the textile fabric, which was quite flexible, bent due to the thread tension during the embroidery process. The antenna pattern was then embroidered on the 3D-printed base pattern. The used antenna pattern is as shown in Figure 2. It has been previously used in several studies, e.g. [5][14], and was thus selected due to the known excellent wireless performance.

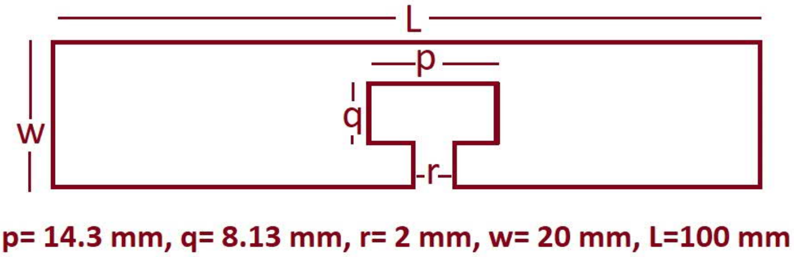


Figure 2. The used antenna design.

The embroidery of the antenna pattern was done using Husqvarna Viking Ruby Royale embroidery machine, which is a normal household embroidery device. The used conductive thread was Shieldex Filament 110f32 2-ply HC, with a DC linear resistivity of 500+-100 Ω/m. Four rounds of the antenna pattern were embroidered, as presented in Figure 3. After the embroidery process, NXP UCODE 2GiL RFID ICs (integrated circuits) were attached to the antenna pattern by embroidery, where the two copper pads of the IC component were sewn on the antenna pattern. Figure 3 presents the embroidered antenna pattern and attached IC component on the 3D-printed structure.

Figure 3. Embroidered antenna pattern and attached IC component on a 3D-printed structure.

After the above process, the top enclosure pattern, comprising of both the boundary and the cavity parts, were printed on both sides of the textile, i.e., on the top of the embroidered pattern and on its opposite side. The printing parameters are presented in Table 1 (referred as "post-embroidery"). Examples of ready-made wireless platforms integrated into textiles are presented in Figure 4.

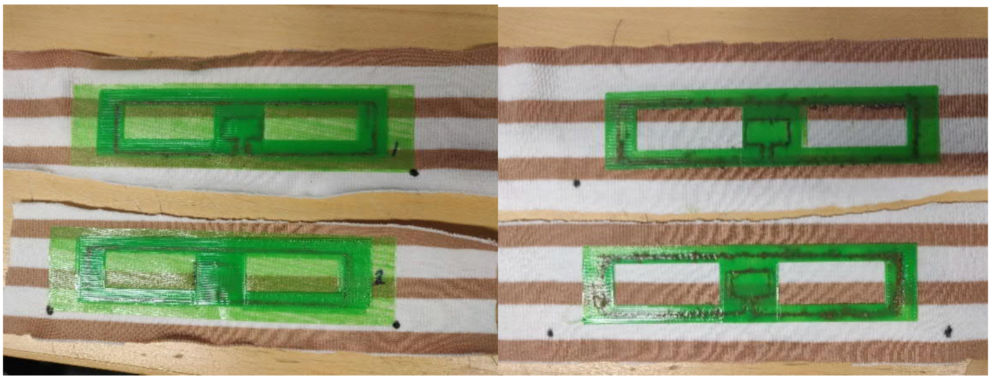


Figure 4. Top (left) and bottom (right) views of ready-made wireless platforms integrated into textiles.

3. CHALLENGES ENCOUNTERED DURING PLATFORM PREPARATION

The most important challenges related to the embroidery process were repeated thread breakages, thread cluster formation at the backside of the embroidered patter, and non-precise positioning of the thread at different embroidery rounds. Further, during 3D printing, positioning of the starting point of the printing, resulting as misaligned 3D-printed layers, was a major challenge.

Firstly, the conductive thread that was used in the embroidery process was relatively soft, resulting in repeated thread breakages after several steps of the embroidery process. It occurred at random instances, and after every breakage, the entire embroidery setup had to be remade. Another challenge was the formation of thread clusters at the opposite side of the textile fabric. This occurred due to improper knotting of the bobbin thread with the topside thread at several instances. An illustration of the cluster formation is depicted in Figure 5. The cluster of thread had to be manually trimmed out using scissors after the embroidery process. Further, at some instances, bending of the textile fabric during the embroidery process resulted in the misalignment of the antenna pattern, as shown in Figure 5. This occurred when the bend caused the embroidered pattern to shift to a different position.

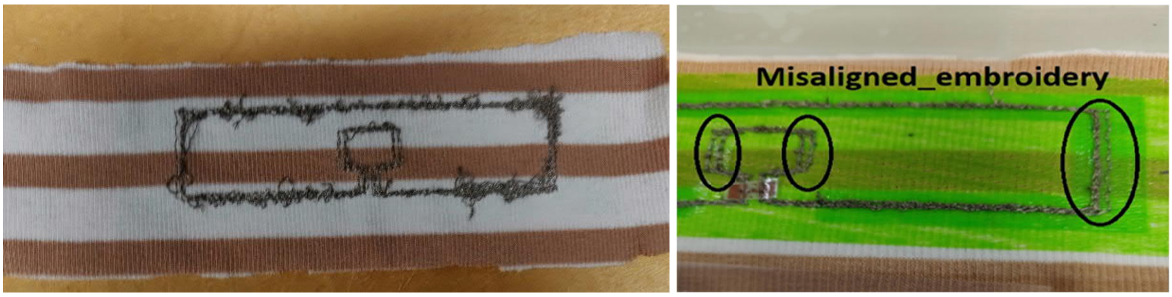


Figure 5. Encountered embroidery challenges: Thread clusters (left) and misaligned embroidery rounds (right).

Further, for the antenna pattern to be embroidered on the NinjaFlex substrate, the textile had to be removed from the printing plate of the printing machine, after the printing of the base and lower enclosure pattern. After the embroidery process, the top enclosure pattern had to be printed on top of the embroidered antenna pattern. The main challenge was the precise positioning of the embroidery hoop (and thus the platform on it) to its original position before removal, which resulted in misalignment of the top and bottom enclosure pattern printing. This resulted in exposed thread segments, which were not completely enclosed within the substrate. This challenge is presented in Figure 6.

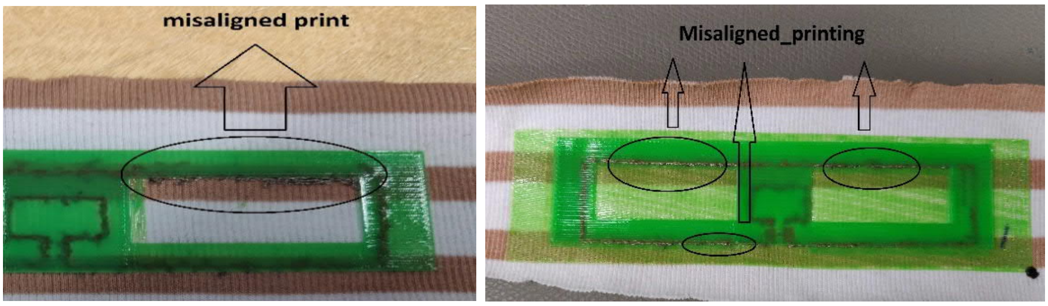


Figure 6. Encountered 3D printing challenge: Misaligned printed layers.

4. WIRELESS TESTING

The wireless performance of the platforms was evaluated using Voyantic Tagformance RFID measurement system. It contains an RFID reader with an adjustable transmission frequency (800–1000 MHz) and output power (up to 30 dBm) and provides the recording of the backscattered signal strength (down to −80 dBm) from the tag under test. We conducted all the measurements with the tag suspended on a foam fixture in an anechoic chamber. During the test, we recorded the lowest continuous-wave transmission power (threshold power) at which the tag remained responsive. The wireless channel from the reader antenna to the location of the tag under test was characterized using a system reference tag with known properties, which enabled us to estimate the attainable read range of the tag versus frequency from

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

where λ is the wavelength of the transmitted wave from the reader antenna, EIRP is the Effective Isotropic Radiated Power, P_{TS} and L_{fwd} are the threshold power and forward losses respectively. The results presented in this study are based on the European regulations of EIRP, which is 3.28 W. The read range results are presented in Figure 7.

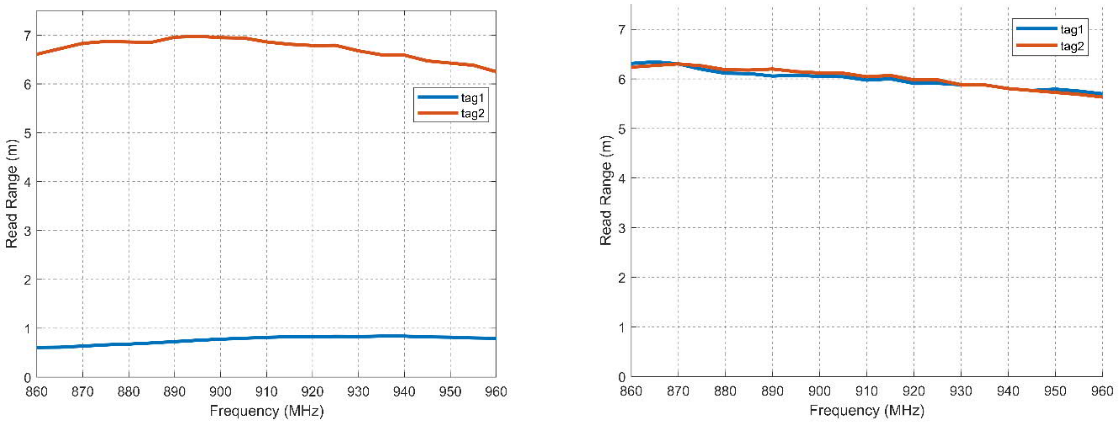


Figure 7. Read range results of the wireless platforms after embroidery (left) and after printing of enclosure patterns on top and bottom (right).

Figure 7 presents the read range results of the developed wireless platforms after the embroidery stage (meaning prior to the top and bottom enclosure printing stage), as well as when the platforms are fully ready. As shown, these wireless platforms showed read ranges of around 6 meters, which can be considered very promising. It can also be seen, that due to embroidery challenges, the RFID IC of tag 1 was not properly attached to the antenna pattern during the embroidery stage, which resulted in short read range. However, during the printing stage, the tag IC was fixated on the matching part, because of the 3D-printed layer printed of top of it. The relative dielectric permittivity and loss tangent of NinjaFlex have been measured to be within the ranges of 2.75 to 2.94 and 0.05 to 0.08, respectively [13]. However, as can be seen, the application of NinjaFlex on the top and bottom sides of the embroidered antenna affected the read range values only slightly.

The wireless performance and reliability of the platforms can be sufficiently improved, if the observed challenges can be rectified. Most of the challenges are caused by human error. For instance, the user is positioning the textile on the embroidery hoop and the embroidery hoop into the 3D printing device. If the process is made less dependent on the user, these challenges can be solved. Further, use of a stronger conductive thread, with similar suitable electrical features, to avoid the repeated breakages during the embroidery stage, could be helpful in developing a better performing wireless platform.

NinjaFlex is both waterproof and flexible, and the purpose of embroidering the antenna pattern and placing the IC component inside a 3D-printed NinjaFlex structure is to protect them from external factors, such as dust, mechanical stresses, and moisture. Hence, solving the encountered challenges is very important for the development of properly functioning and reliable textile-integrated wireless platforms.

5. CONCLUSIONS

This paper described a new type of fabrication process of clothing-integrated basic wireless components, passive UHF RFID tags, by utilizing 3D-printed flexible and washable wireless platforms, where electronics, embroidered antennas and interconnections were embedded mid-printing, created directly on textiles. During the fabrication process, several challenges were encountered, and this paper presented some of the major challenges in detail. Despite the introduced challenges, the ready-made textile-integrated tags showed read ranges of 6 meters, which is already very promising. If the challenges of the fabrication method can be resolved, we can expect high reliability an even better wireless performance.

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