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Best practices for hybridization and injection moulding of rigid control units on in-mould flexible devices

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Contents

Page

European foreword

This CEN/CENELEC Workshop Agreement (CWA 18002:2023) has been developed in accordance with the CEN-CENELEC Guide 29 “CEN/CENELEC Workshop Agreements – A rapid prototyping to standardization” and with the relevant provisions of CEN/CENELEC Internal Regulations - Part 2. It was approved by a Workshop of representatives of interested parties on 2022-11-01, the constitution of which was supported by CEN /CENELEC following the public call for participation made on 2022-10-03. However, this CEN/CENELEC Workshop Agreement does not necessarily include all relevant stakeholders.

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Introduction

This document presents a study for the construction of an in-mould smart tag as a robust flexible and battery-free label with a radiofrequency energy harvesting sub-system and enhanced geolocation features. Conventional tags based on Printed Circuit Board (PCB) with a protective casing limit the type of objects to be tracked according to their shape and surface material. The proposed tag is intended to be attached to objects such as tools, vehicles, and parts in assembly lines compatible with curved surfaces for their geolocation.

The key innovation of the tag is that it is obtained by In-mould electronics (IME) which combines the functional printing of electronics and the hybridisation of electronic components with traditional plastic transformation processes, such as injection. In the case under study, IME processing is applied over printed antennas with a directly hybridized rigid control module and both elements protected by an over-moulded flexible superstrate.

IME is prompted as a high-speed and competitive manufacturing methodology to ensure robustness and conformability of the tag. IME combines two dissimilar manufacturing processes, which are printed electronics and plastic processing, an already established high-volume production technology based on plastic injection and thermoforming [1]. Polymer embedded antennas have been proven advantageous due to the enhanced protection towards harsh environments, temperatures, wetness and the low-permittivity of polymers which make them a suitable option for higher-frequency applications [2]. Other advanced materials such as nanocellulose-based substrates and highly conductive inks based on silver nanoparticles (Ag NP) are used.

The geotracking tag will consist in a flexible foil based on nanocellulose with a combination of printed antennas (Ultra High Frequency and Ultra Wide Band), a small rigid multipoint control unit part (MCU). Both parts will be fully integrated into a flexible plastic piece through an overmoulding process. Therefore, TPU or related flexible thermoplastic will be the preferred choice.

1 Scope

Establish best practices for hybridization and injection moulding of rigid control units on in-mould flexible devices, in the case of study, an in-mould battery-free geolocation tag, a FR4-based control unit which has the function of enabling energy harvesting and communication of dedicated printed antennas, is directly hybridised on a flexible substrate which is ultimately integrated in a plastic part through injection moulding.

This document aims to develop the processing of hybridization of rigid control unit on printed functional foils and the subsequent incorporation into plastic pieces, The specific objectives are:

1) Design and assembly of components by Pick & Place of the rigid control unit.

2) Integration into a plastic piece through injection moulding.

Procedures for the accurate attachment, alignment of the control unit on substrate with the injection mould and for reliable plastic over-moulding process are defined.

2 Normative references

There are not normative references in this document.

3 Terms and definitions

No terms and definitions are lister in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp/ui

— IEC Electropedia: available at https://www.electropedia.org/

4 Symbols and abbreviations

For the purpose of this document, the following symbols and abbreviations have been used:

CNF	Cellulose Nano-Fibrils
FR 4	Flame Resistant 4
IME	In-mould electronics
MCU	Multipoint control unit
NC	Nanocellulose
NP	Nanoparticles
OLAE	Organic and large area electronics
PCB	Printed Circuit Board
PU	Polyurethane
Rs	Sheet resistance
SMD	Surface mount device
TPU	Thermoplastic Polyurethane
UHF	Ultra-High Frequency
UWB	Ultra-Wide Band

5 Manufacturing process of a geotracking tag

5.1 General

This section provides a detailed overview of the manufacturing process of the in-mould geotracking tag, including a description of the materials and equipment used in each of its phases: printing, hybridization, cutting, and over-injection.

The concept idea is to assemble a miniaturized rigid control unit based on conventional Flame Resistant 4 (FR4) fibre glass directly hybridized on an electronic flexible substrate with printed antennas. Interconnection between antennas and the rigid module are achieve by single step hybridization process. The encapsulation of the assembly is implemented by injection moulding with the objective of enhancing robustness and durability and protecting the active components and circuit elements. Accurate alignment of the module on substrate and the injection mould and tooling is achieve through automatized Pick&Place and shape-cutting four precise mould fitting.

5.2 Printing process

In aim of the printing process is producing functional films containing thin layers of circuits and electronic devices. There are two primary types of screen printers: i) flatbed screen printers that have a bed where the substrate is placed sheet to sheet, and the screen is moved over it for printing and ii) rotary screen printers that have a cylindrical screen that rotates and allow continuous printing on roll-to-roll. The choice of the screen printing methos depend on the needs and requirements. Flatbed screen printers are generally better suited for lower to medium volume printing, as they require manual placement of each substrate. Roll-to-roll screen printers excel in high-volume production since they can continuously feed and print on a roll of material.

In this case of study, the equipment used is a flatbed screen printer ARMA AT-60P available at the Eurecat and the functional circuit is the combination of two antennas, one Ultra High Frequency and one Ultra Wide Band, which have been designed for the prototype. The selected substrate and ink are cellulose nano-fibrils (CNF) A4 foil and highly conductive Ag NP ink.

5.3 Hybridization process

The hybridization process consists in placing electronic components, normally surface-mount devices (SMDs), onto a functional film using Pick& Place equipment. The combination of printed electronics and SMD components is known as hybrid electronics.

Figure 1 — Essemtec PUMA Pick&Place equipment

The hybridization procedure detailed in this document is realized with a Puma Pick&Place equipment from Essemtec. It consists in 3 main processes:

1) Dispensing of conductive adhesive on the connection points.

2) Dispensing of structural adhesive, around or below the component.

3) Pick and Place of the components.

The order of step 2 and 3 can be interchanged depending on the component type. For the placing of the document, a CAD file must be generated, which provides the exact component placement points. Additionally, a specific recipe is created containing all the information needed for component hybridization: PCB size definition, offset definition, component package definition, among others.

5.4 Cutting process

After printing and hybridization, functional films are subsequently cut into a preform to be used as inserts in the injection process. It is important to obtain a good definition of the cut contours since this setting influences the holding and handling of the foil inside the injection mould.

There are several types of CNC-based (Computer Numerical Control) machines that can be used for cutting purposes. Two common types of machines are die cutting machines and laser cutting machines.

Die cutting machines are equipped with a cutting tool, while laser machines use an intensive laser beam. Laser cutting is a non-contact process where the laser beam is focused through lens and can vaporize or melt the materials along the cutting path. However, it is important to note that not all materials are compatible with laser cutting, as some may be sensitive to heat or have reflective surfaces that can affect the cutting process.

Die cutting machines are suitable for a wide range of materials, while laser cutting machines provide high precision and the ability to create intricate designs. The choice between the two depends on the specific requirements of the project and the characteristics of the materials being cut.

For this document case, where the substrate is based on nanocellulose foil, a LaserPro Mercury CO_2 laser-based cutting machine is used.

5.5 Injection moulding

Injection moulding is a manufacturing process in which a molten thermoplastic material is injected into a closed and pressurized mould. In the IME framework it allows protective encapsulation for electronics, achieving a functionalized plastic part. It can be divided into six steps: closing of the mould, injection, back pressure, dosing, cooling, and expulsion of the piece. Certain parameters can also affect the resulting piece, like melting temperature, back pressure, and cooling time. Controlling the process is key to generate quality IME pieces with components susceptible to damage.

The machine used in this project for the injection process is the Engel E-motion 200/55 full electric (Figure 2). This machine has a spindle with a diameter of 25 mm with a maximum injection volume of 59 cm^3 and a clamping force of 550 kN.

Figure 2 — Detail of injector ENGEl E-Motion 55

Regarding the injected resin, both flexible and rigid materials are commonly used, depending on the specific requirements of the application. Some examples of rigid thermoplastics are Polycarbonate (PC), Poly(methyl methacrylate (PMMA) or Acrylonitril Butadiele Styrene (ABS). In the case of flexible materials, the most standard thermoplastics used for injection moulding are Thermoplastic Polyurethane (TPU) or thermoplastic elastomer (TPE).

6 Case of study: in-mould geotracking tag

6.1 Tag printed circuit design and hybridization concept

The proposed tag consists in a flexible foil based on nanocellulose with a combination of printed antennas (UHF and UWB), a small rigid multipoint control unit part (MCU).

The hybridization process involves the placement and adhesion of the electronic module on a printed foil with the functional antennas. As shown in Figure 3, the MCU is a 15 x 15 mm all-in–one board and embeds the harvester chip (for UHF), the microcontroller and the transmission unit (for UWB).

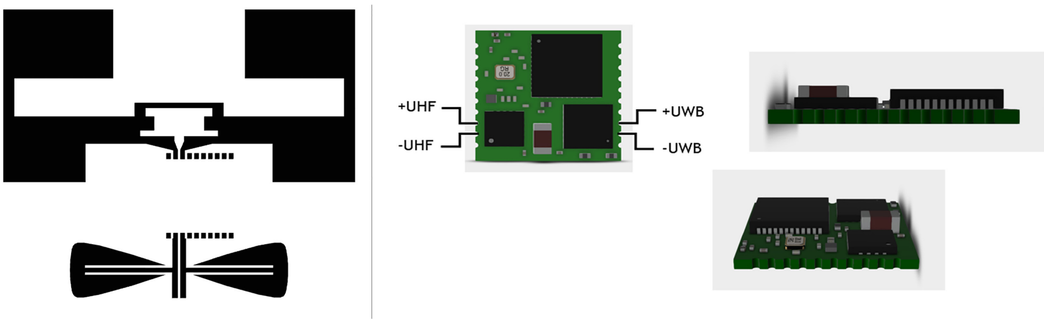

Figure 3 — (Left) Complex conjugate printing design composed by a UHF (upper) and a UWB (lower) antennas. (Right) 3D model of the control electronic module

6.2 Materials and sample preparation

The antenna design is screen printed using highly conductive silver nanoparticle ink. Silver nanoparticle (Ag NP) ink for screen printing is used due to its outstanding electrical properties compared to standard Ag µflakes inks [6, 7].

The selected substrate for this application is nanocellulose foil. To ensure optimum structural integrity, there must be good adhesion between substrate containing the integrated device and the overmoulding material. The most preferred option is to use TPU as the injected resin and PU coating on substrate to achieve maximum adhesion. Hence, a PU coating of 4 g/m^2 per side is applied on a 60 µm-thick CNF foil. Adhesion injected TPU and good sintering of printed Ag NP layer has been validated. Several iterations for the improvement of PU-coating were done to obtain Ag NP layer with conductivity between 20-50 mOhm/sq.

Injected tags with 2-side PU coated CNF gave the best results in term of: i) adhesion to TPU, ii) processability of the substrate (less pronounced rolling up of sample after curing); iii) elasticity upon bending and iii) protection to humidity.

In the next table (Table 1) materials and processes used for the manufacturing of the printed foil are shown:

Table 1 — Specifications of the materials and printing process for the printed antennas

SPECIFICATION	VALUE	Details
Substrate material	PU coated CNF foil	60 µm-thick CNF foil with PU coating of 4 g/m^2 per side
Printed materials	Ag NPs based ink	Rs = 22 ± 8 mops; Thickness = 2.3 ± 0.3 µm; resistivity =4.8 ± 0.8 µOhm.cm. 4 B adhesion to PU coated NCF
Moulding material	TPU	Flexible material. Pure ether grade with increased resistance to humidity
Printing	Screen printing	Flatbed semi-automatic screen printer; Screen mesh = 140 T; speed = 175 mm/s, 2 passes
Curing	Thermal curing	Precuring of 110 °C for 10 minutes plus a 140 °C treatment for 15 minutes at a reflow oven

After printing, MCU hybridization is conducted using a positioning design based of 4 fiducial points as shown in Figure 9-left. More details about the hybridization process can be found in section 6.3.2. Subsequently samples are laser cut into the shape fitting the specific mould (Figure 9-right). The injection moulding process is detailed in section 6.4.

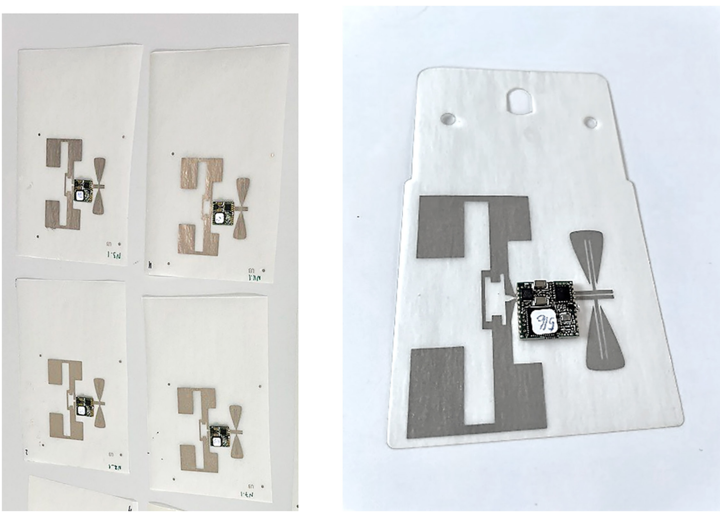

Figure 4 — Complex conjugate of UHF and UWB antennas printed on PU-coated CNF-foil. (Left) samples used with positioning design based on 4 fiducial points. (Right) Mould shape cut sample

6.3 Hybridization of pads for characterization and multipoint control units

6.3.1 Through-substrate vias and hybridized pads for characterisation of in-mould mould devices

As shown in Figure 3, the MCU features two differential input pads for the antennas. Prior to MCU hybridization, another hybridization strategy is developed to be able to test antennas after injection moulding. The strategy consists in hybridizing interconnecting pads that connect the two sides of the antennas, so the moulded side with the backside of the substrate. The machinery used allows automatized processes: an LPKF circuit board plotter is used for drilling micro-holes and the Pick&Place equipment for dispensing de conductive and structural adhesives and placing of the SMD contact pads.

The procedure is depicted in Figure 4 and consists in:

1) Drilling micro-holes on antennas contact pads using a LPKF circuit board plotter.

2) Filling of the micro-holes and surrounding with conductive epoxy resin (EPO-TEK H20E) to allow an interconnection from the backside and adhere pads to antennas' footprint.

3) Placing of the SMD contact pads using fiducial positioning and curing at 90 °C for 1 h.

4) Application of structural adhesive on pads to reinforce the hybridized pads on the injected side and curing at 90 °C for 1 h.

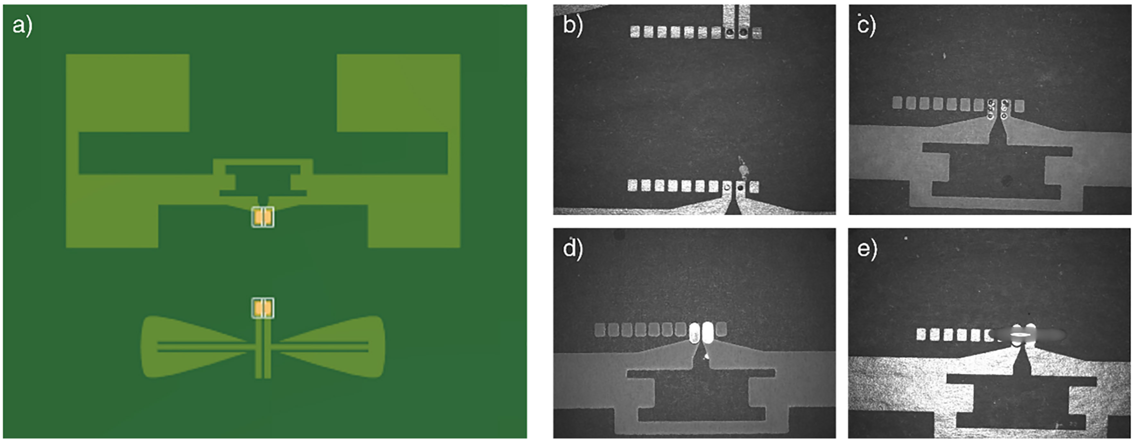

Figure 5 — Hybridization procedure for characterization of IM-antennas. Interconnecting pads (d) are hybridized on antenna through perforations (b) using conductive (c) and structural adhesive (e)

In Figure 5, an example of the strategy used to characterize individual antennas that have been encapsulated in the injection process and cannot be accessed. This is done in order to study the effect of the overmoulded superstrate on the design antennas prior to testing hybridization of the control unit.

For a radiation test of the complex conjugate antenna, a board with matching elements, balun (balanced to unbalanced convertor) and connectors can be used so the antenna can be measured through a SMA connector.

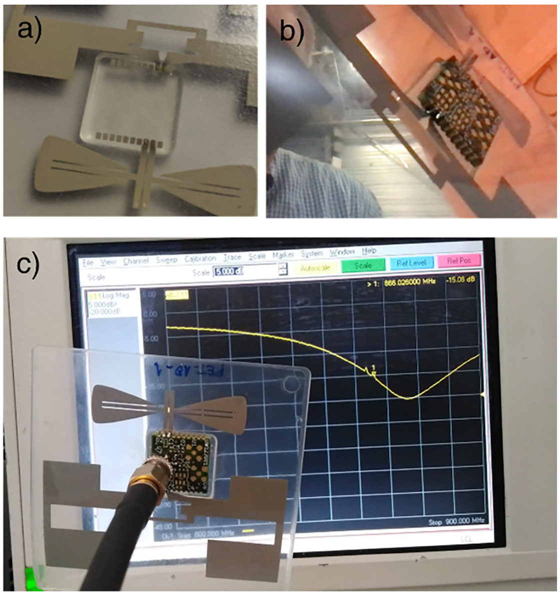

Figure 6 — Characterisation procedure for in-mould antennas. Antennas with hybridised pads are inject moulded (a), then an external PCB is soldered on pads (b) A balun is soldered on the PCB so return loss characterisation can be performed through a coaxial cable

6.3.2 Multipoint control unit hybridization procedure

With the design of the complex conjugate of the two antennas the final position of the MCU was establish and Pick&Place procedure for the MCU defined. As shown in Figure 6, a fiducial system was included to hybridize the MCU on the defined position on the tag: four 2-mm dots were included in the surroundings of each tag in the screen printing design so the Pick&Place software could read to precisely dispense the adhesives and place of the component.

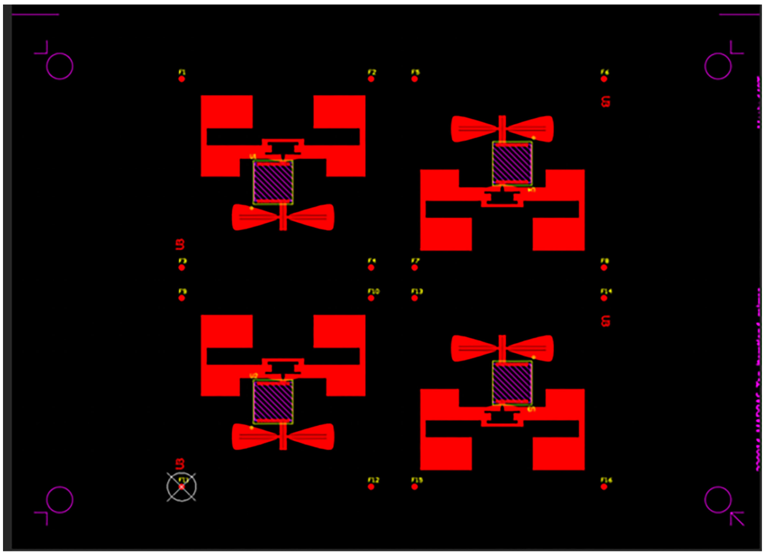

Figure 7 — Altium Designer screenshot of the screen-printing tag layout with fiducials (in red) and a schematic of the 15 x 15 mm UMD on top (in violet)

In the case of hybridisation of PCBs, the dispensing of the structural and conductive adhesive on the footprint area is done in the same dispensing step as depicted in Figure 7. Structural adhesive is dispensed on the centre of the area where there are no pads while conductive adhesive (EPO-TEK H20E®) is dispensed on the defined pads for each antenna.

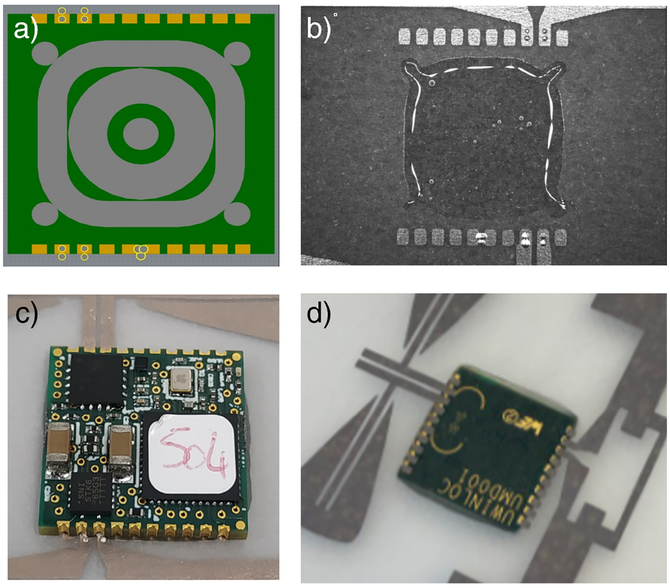

Figure 8 — Structural and conductive adhesive dispensing design for Pick and Place of the control unit (a). Photos after dispensing (b) and after hybridization, from top (c) and bottom (d)

Regarding structural adhesives, two types of adhesives can be used:

— Thermal-curable adhesive: it is advantageous we can reduce the curing stept to one and cure conductive and structural adhesive at the same time. Thermal-curable adhesives are not transparent. The adhesive tested for this case is Structalit® 8805 from Panacol.

— UV-curable adhesive: it is transparent and can be fastly cured in a UV-oven. In this case we use Loctite 3525AA which spreads much smoothly than the thermal-curable adhesive tested.

Thermally-cured adhesive | UV-cured adhesive

Figure 9 — Comparison of the appearance of a glued PCB on top of a printed tag with two different structural adhesives: Thermally and UV cured

The thermally curable adhesive shows a non-homogenous distribution while the UV-curable adhesive spread much smoothly (Figure 9).

Additionally, for this specific control unit, which has distribution of components with different height, we had to fabricate a subjecting lid using a 3D printed mask and glue it on the components with removable adhesive to allow the P&P to pick the MCU correctly (Figure 8).

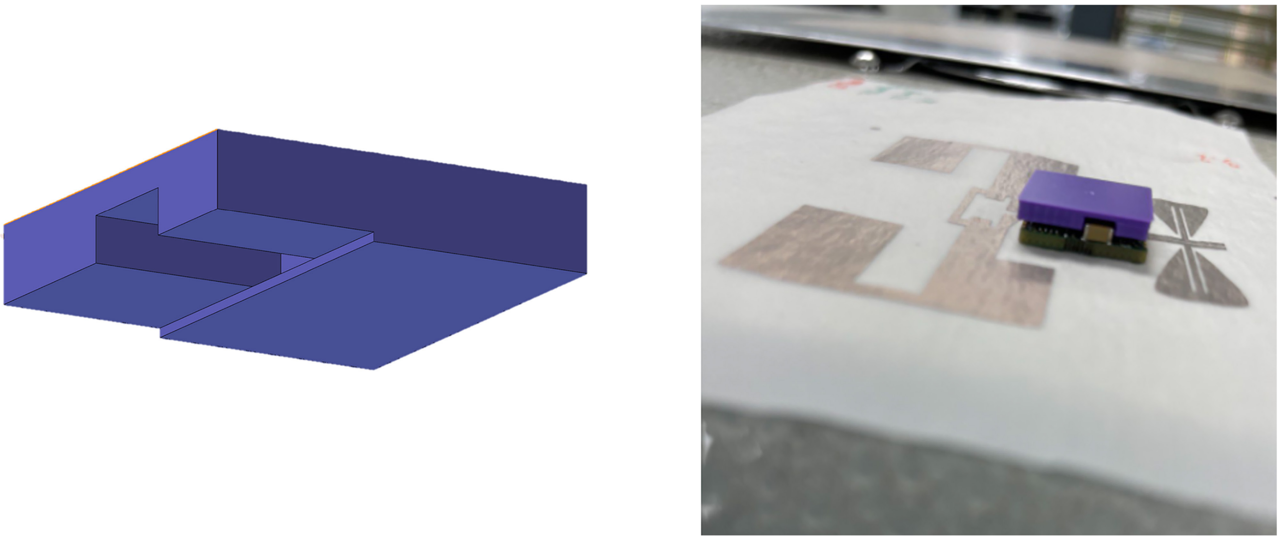

Figure 10 — 3D printed mask design and sample with 3D printed purple lid fabricated to match the height of MCU components to allow correct picking of the MCU with Pick and Place equipment

Finally, the curing procedures that enables fixing the MCU and sinter the conductive paste to have appropriate electrical contact consisted of:

1) Curing the structural adhesive through a reflow UV oven with 3 passes at 15 Hz (144" under UV) with a light intensity of 1 752 mJ/cm^2. First pass through the UV overs is done with the MCU facing up and a transparent support and the two next passes are done with the PCB facing down and the UV light passing through the NCF which has a 80 % of transparent.

2) Curing the conductive adhesive through the reflow oven with top and bottom hot air heating, 5 minutes at 140 °C.

6.4 Injection moulding processing

6.4.1 General

To manufacture a plastic embedded tag, the film to be overmoulded needs to be placed inside a mould cavity. In the present injector system, this is done by subjecting it mechanically via pins in the injection side of the machine. The molten polymer goes through a hole cut in the film to the other side, covering a square 70x70 mm area, which is the mould geometry chosen. Therefore, functional foils must be cut into the shape shown in Figure 10-left, with three holes, two for subjection and one to allow the molten polymer to enter the cavity.

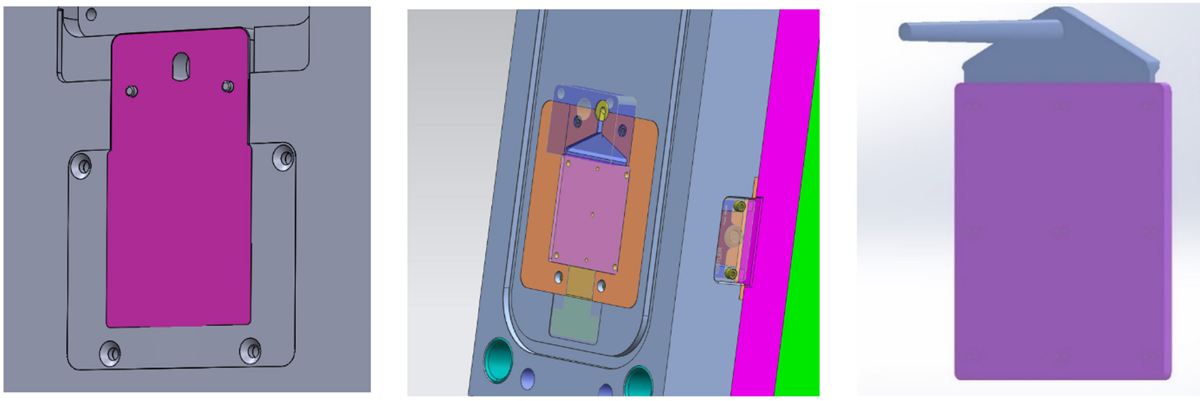

Figure 11 — Schematics of the plastic injection system. (Left) Mechanical subjection of the film (purple) in the mould cavity (grey). (Middle) Mould schematic. By using interchangeable inserts (orange region) different thicknesses can be injected varying from 1.25 to 4 mm. (Right) Injected part

The shape of the design is based on the antenna presented in [3, 4, 5]. It was simulated considering the presence of a TPU layer to predict the effect of the materials on the return loss and the radiation efficiency. Simulation studies showed that the radiation efficiency of the UHF antenna decreases with a thicker TPU layer due to the dielectric losses of the TPU. To address this, a mould with a cavity to host a MCU with components was manufactured. As shown in Figure 11, the design of the in-mould cavity considers a thickness of 1.25 mm on top of the printed elements and a 4 mm-thick housing for the PCB. The cavity section is only bigger around the control unit area. In that way TPU thickness surrounding the MCU could be reduced to 1.25 mm to prevent the antennas to lose transmission quality. Additionally, it has also been proved that a reduction of the thickness of the TPU layer avoid cracking of the nanocellulose foil upon bending due to a closer location of the foil to the neutral axis.

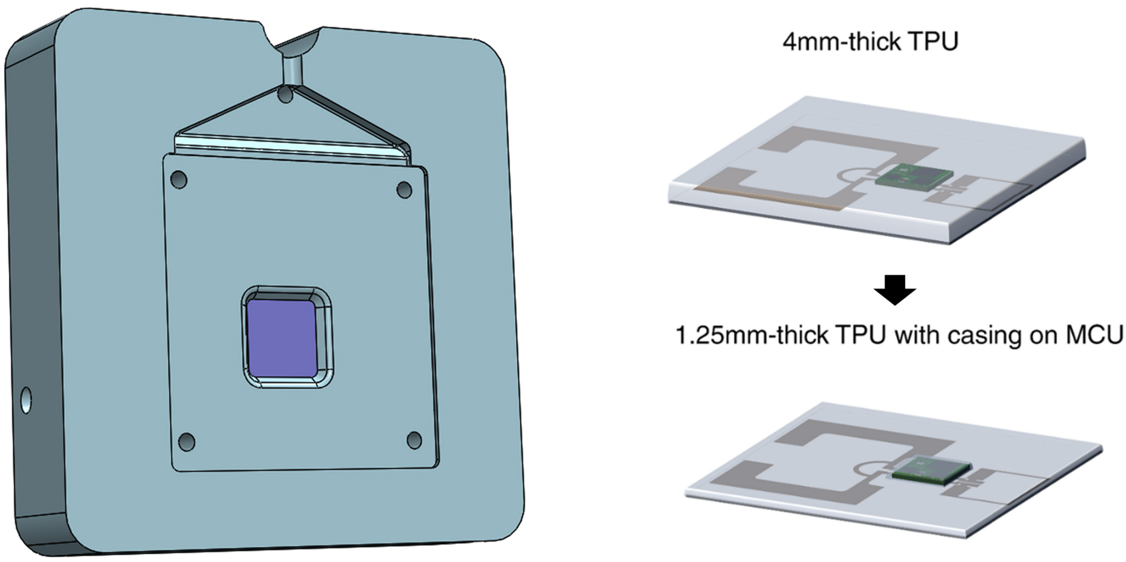

Figure 12 — Schematic of the mould with a cavity used for injection experiment on hybridized PCB. The design considers the optimal section thickness of 1.25 mm over the printed antennas

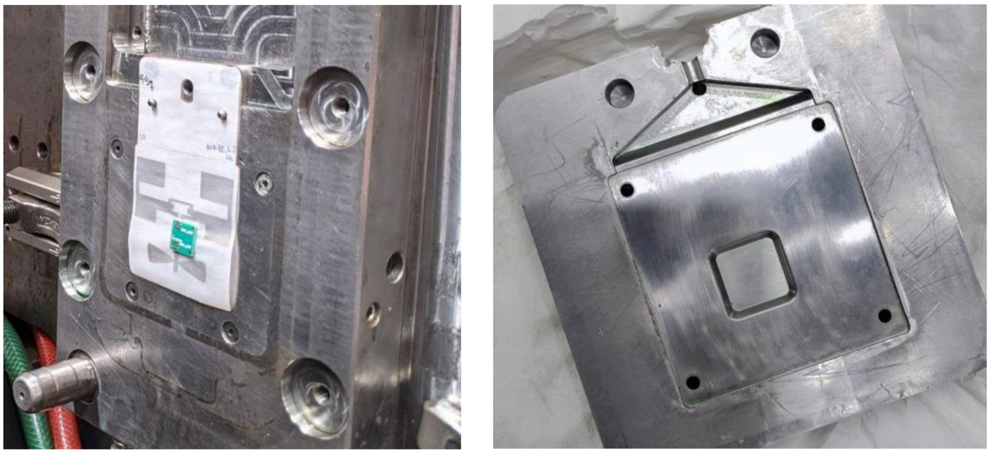

Figure 13 — (Left) Injection side where functional foil holds mechanically via pins. (Right) Ejection side that defines the injection thickness and control unit housing

6.4.2 Injection moulding parameters

The chosen thermoplastic for injection of the tag was TPU Estane Clear 15N80 manufactured by Lubrizol. This TPU is a clear grade with 80 as shore A hardness value.

On first injection tests ripping of the CNF substrate was observed and so optimization injection parameters needed to be conducted.

In this optimization phase it was concluded that a higher melting temperature along with a higher injection speed provided the best results and prevented the substrate from ripping. Higher injection temperatures made the polymer more fluid and thus produced less shear stress on the surface of the substrate. Higher injection speed caused the cavity to fill faster and reduced the time the polymer applies shear stress. Finally, a lower back pressure allowed the tag to sit flag instead of warping. It is believed that the previous value compacted the part too much, which produced combing.

Table 2 shows the parameters applied for the injection moulding experiment.

Table 2 — Parameters for TPU injection moulding process

	Parameters	Value
Barrel temp	Nozzle [°C]	180
	Metering zone [°C]	220
	compression zone [°C]	215
	feeding zone [°C]	210
Molud temp	Injection side temp [°C]	23
	Ejection side temp [°C]	23
Injection unit	Metering stroke [mm]	50
	Pressure Limit. [bar]	1300
	Peak Inj. Pressure[bar]	1000
	Injection speed [mm/s]	150
	Holding Pressure [bar]	500
	Holding Time [s]	5
	Cooling time [s]	25
	Cut off position [mm]	19
	Cushion [mm]	18,97
	Suck back [mm]	3
	Backpressure [Bar]	150
	Screw rotation speed [rpm]	150

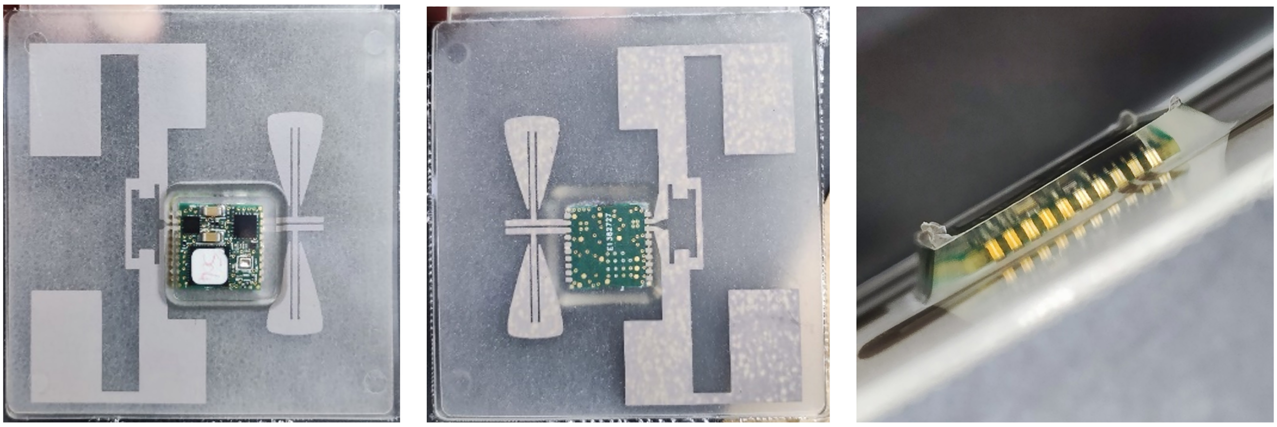

Figure 14 — Geo-tracking tag injected with hybridized control unit, front (left) and back (middle).(Right) Detail of the cross-section of the cavity with embedded MCU

6.5 Constraints on electronic components on PCB circuits for injection moulding process

Obtaining functional in-mould tags proved challenging due to the deformation of a component during the injection process. As shown in Figure 15, the component experiencing deformation was a 25 MHz quartz crystal. This crystal is a component that provides a stable and precise frequency, commonly used as a timing reference in electronic circuits.

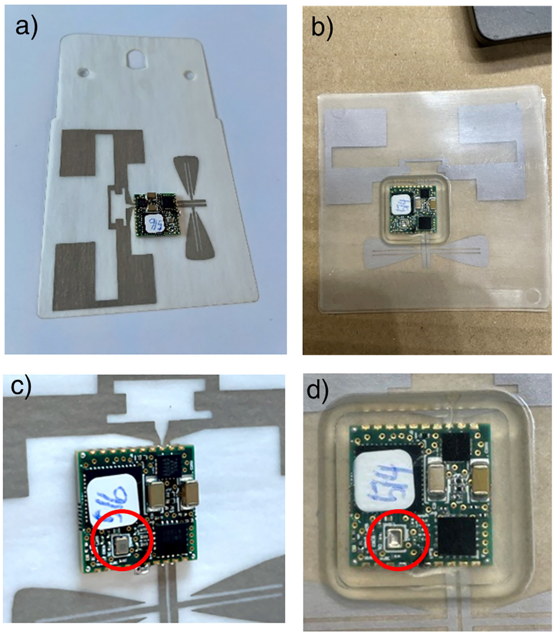

Figure 15 — Photo of samples before (a, c) and after injection (b, d). The quartz crystal (small metal box located in the bottom right corner) is deformed after injection due to injection pressure

The damage of the components was attributed to injection pressure that could reach the 1000 bar. To determine the critical step in the process causing the damage, either the initial peak pressure or the holding pressure for compression, we conducted experiments with the injection parameters (Table 3).

Some samples injected without applying any holding pressure where functional, indicating that the initial peak pressure (injection pressure) was already capable of damaging the control units.

The first peak pressure is determined by various variables, such as:

1) Material viscosity and temperature: higher viscosity requires more pressure to be injected. Higher material and mould temperatures reduce the material's viscosity, requiring less pressure.

2) Injection speed: higher injection speeds require higher pressure to maintain the flow of material into the mould cavity.

3) Mould design, such as wall thickness.

4) Material volume: larger volumes require more pressure to fill the mould.

Therefore, one set of injection parameters involved reducing the injection pressure by decreasing material volume and eliminating the holding pressure. However, this resulted in visually unappealing tags due to the presence of bubbles caused by insufficient material compaction.

In the following table we summarized three conditions that could lead to functional tags:

Table 3 — Initial condition parameters (Condition 1) optimized to avoid substrate ripping, followed by Condition 2 with lower injection speed to lower peak pressure and finally Condition 3 where injection pressure is eliminated

INJECTION PARAMETERS	Condition 1	Condition 2	Condition 3
Temperature nozzle (°C)	220	220	230
Temperature front (°C)	215	215	225
Temperature middle (°C)	210	210	220
Temperature rear (°C)	200	200	210
Injection speed (mm/s)	150	60	Null
Switch-over position (mm)	20	22	40
Injection dosing (mm)	40	40	40
Injection pressure (bar)	590	368	Null
Holding pressure (bar)	150	150	150
Holding pressure time (s)	10	10	1.5

Simultaneously, protective measures were implemented to safeguard the quartz crystal in the MCU. Either the whole control unit or the single components was encapsulated using structural adhesives with high Shore hardness. Examples of such adhesives included DELO Katiobond GE 680, DELO Katiobond OB 678, and Structalit 5604.

These steps indeed play a critical role in improving the overall quality of the injected samples. However, it is worth considering a more straightforward solution, which involves avoiding the use of fragile components such as quartz crystals.

By selecting alternative components that are more robust and less prone to damage during the injection process, the need for extensive protective measures and complex optimization techniques can be mitigated.

7 Lessons learned and guidelines for injection moulding of rigid control units

The present document sets a methodology to manufacture devices through IME incorporating Miniaturized FR4-based control units in an automatized approach through hybridisation by Pick&Place and injection moulding process.

We have effectively established the feasibility of producing functional in-mould tags. Nonetheless, additional research is needed to assess the compatibility of crucial components like quartz crystals with the injection moulding process. If incompatibility issues arise, it will be necessary to explore alternative circuit designs and components to ensure successful production of in-mould tags.

Critical points for improvement and guidelines to help ensure successful manufacturing of in-mould tags have been identified. These are:

1) Encapsulation of components: Encapsulation is essential provide adequate protection of fragile components like quartz crystals, which are particularly vulnerable to damage during the injection process.

2) Injection parameters: injection parameters should be optimized to minimize injection pressure, which can damage the control unit assembly components, particularly the quartz crystal.

3) MCU design: MCU design should be optimized to ensure proper alignment and contact of the MCU pads with the printed antennas, preferably using SMD pads instead of side vias channels.

4) MCU components selection: fragile components like the quartz crystal should be avoided whenever possible to reduce the risk of failure during injection process.

By following these guidelines, manufacturers can improve the yield of in-mould tag production, resulting in more functional and reliable products.

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