

Towards Smarter Everyday objects and structural materials: Integration of Strain and Temperature Sensors via Transfer Printing methods

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Abstract

This paper presents two transfer printing technologies for the integration of sensors on 3D objects with complex geometries, and materials exhibiting complex properties, such as composite. The main objective is to maximize sensor conformability while minimizing intrusiveness during the measurement of physical parameters, including temperature and strain. The first approach combines screen printing of sensors on a water-soluble polyvinyl alcohol (PVA) film to water transfer printing (WTP) method. The second approach relies on the direct transfer of printed sensors on glass fiber-reinforced epoxy composites.

By integrating low-cost, large-area screen-printing technique with transfer printing strategies, the proposed approaches open new opportunities for sensor integration on natural, composite, and bio-based substrates paving the way for new functionalities that are better adapted to environmental and industrial applications, and ultimately contributing to the development of sustainable systems.

Keywords: Smart composites, Smart 3D Objects, Screen-printing, Sensors, Transfer printing.

1. Introduction and background

The ambition to make electronic devices adaptable to all shapes and types of installation environments continues to grow. This trend is driven by the emergence of new applications such as 3D-printed sensors and antennas(Adams et al. 2011), electronic skin enabling electronic films to conform to the shape of human skin(Jeong et al. 2013), advances in robotics, sensors embedded in plants for growth monitoring(Jiang et al. 2020), and smart medical prostheses. These applications have been enabled by the development of innovative manufacturing processes, including direct 3D printing, laser structuring, holographic lithography, and aerosol jet printing on 3D objects. However, these techniques remain poorly suited for industrial-scale production due to slow fabrication speeds, high costs, and limited production volumes. In parallel, other emerging technologies, commonly referred to as transfer printing, combine subtractive fabrication techniques, which are traditionally complex and costly but provide high resolution over small areas, with simpler and more environmentally friendly additive processes that enable large-scale production, albeit with lower resolution. These approaches rely either on the patterning of conventional rigid materials, such as deposited semiconductor and metallic layers(Linghu et al. 2018), or on the printing of intrinsically stretchable materials(Wang et al. 2021), organic materials, nanocomposite inks, or hydrogels.

Transfer printing methods now represent a key approach for the development of 3D electronic devices. Their principle relies on fabricating electronic components on planar or flexible substrates, followed by their transfer onto complex shapes, whether onto 3D objects or irregular surface materials. This approach makes it possible to overcome the limitations associated with directly fabricating electronic devices on 3D geometries without degrading the electrical or mechanical performance of the sensors.

This study demonstrates the capability of two transfer printing technologies developed at the IETR laboratory to functionalize complex materials and substrates with sensors for application-oriented purposes compatible with industrial processes.

The paper begins with a presentation of the materials and methods, followed by a discussion of the results to demonstrating the adaptability of sensor integration through the two aforementioned approaches. Then, it concludes with a conclusion and perspectives on future industrial and everyday applications.

2. Materials and methods

Screen-printing machine ATMAOE MF44 shown in Figure 1a is used in this study to enable patterning over large-area surfaces, A3 format as illustrated in Figure 1b.

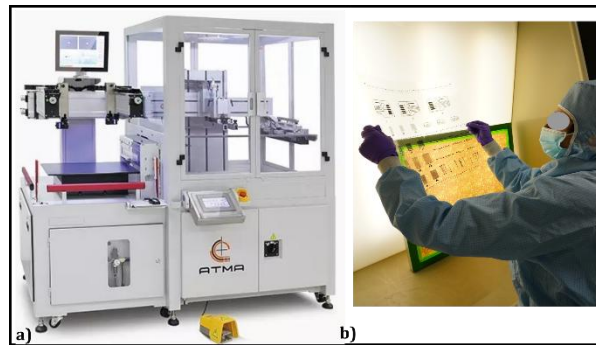


Figure 1: a) Screen-printing machine ATMAOE MF44, b) Large area processing on PVA film.

Two types of inks are used, carbon ink (Carbon Electron RV160222) based on graphite and carbon black and silver ink (Silver Electron Speedy HR) purchased from VFP ink technologies. Printing is performed using a nylon mesh screen with a mesh density of 90 threads cm^{-1} for carbon, and 120 threads cm^{-1} for silver. Depending on the viscosity of each ink, the printing speed was adjusted to ensure controlled and homogeneous deposition. For the silver-based ink, which is more fluid (viscosity of 1.69 Pa·s at 50 rpm), a printing speed of 150 mm/s was applied. In contrast, for the carbon ink, which is more viscous (viscosity of 5.50 Pa·s at 12 rpm), the printing speed was reduced to 100 mm/s. The average thickness of the printed ink layers was approximately 8 μm , as measured using a DektakXT surface profilometer (Bruker).

To enable smart 3D objects and materials, screen printing is combined with two different transfer technologies. The first is WTP using a 50 μm thick PVA film purchased from Mitsubishi Chemical Group. The second is a direct transfer process that allows sensors to be transferred on composite materials. Further details are presented, respectively, into the two subsections 3.1 and 3.2.

3. Results and discussion

3.1 WTP process towards smart 3D Objects

The WTP process is widely used in the decorative coatings industry (Zhang et al. 2015), and as shown in Figure 2a-d, the process steps are relying on a water-soluble PVA film coated with ink, which, once dissolved in water, leaves the printed patterns floating at the air-water interface, allowing conformal transfer on the target object by immersion (Le Borgne et al. 2017; Le Bihan et al. 2024)

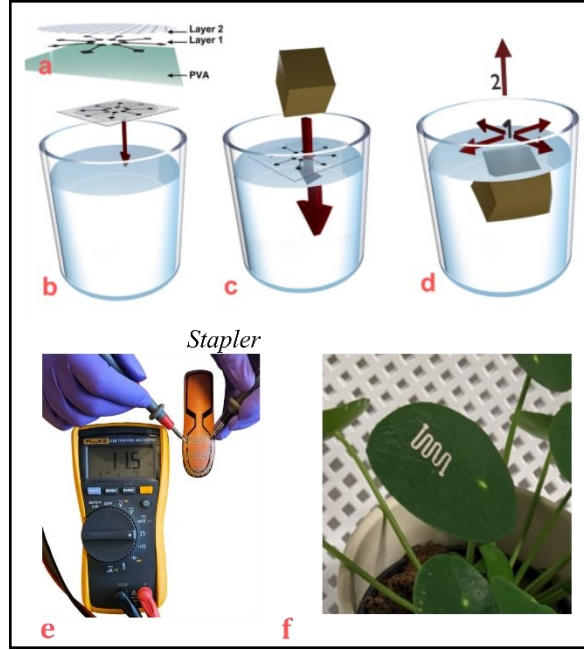


Figure 2: a) Multilayered films patterned on PVA, b) PVA deposited on top of the water-filled dip tank, c) 3D object is dipped through the patterns after PVA dissolution, d) 3D object is gently shaken into the water, after a few seconds the object can be withdrawn from water, e) Conformal transfer of screen-printed silver sensors on 3D Stapler f) on natural plant, highlighting the potential for biosourced substrates.

Note that, as the transfer is mediated by a liquid interface, the sensor layer can accommodate complex surface topographies, including fine recesses, while avoiding stress-induced wrinkling. The proposed approach formed the basis of the pioneering work conducted at IETR and led to the filing of a patent (Harnois et al. 2022). Herein, we demonstrate that the technology is compatible with large-area additive manufacturing processes. This compatibility highlights its potential for scalable surface functionalization. Given that WTP process was originally developed for large-area graphic applications, its combination with printed electronics technologies appears particularly relevant and offering greater advantages than conventional small-area microelectronic processes.

Previous results were limited to the transfer of conductive lines (Le Borgne et al. 2017). However, we propose a new application of this method for the transfer of screen-printed sensors. Figure 2e shows a stapler equipped with serpentine lines of silver ink, exhibiting good mechanical properties after the transfer. The measured resistance of the silver-based temperature sensor transferred onto the stapler is $11.3 \, \Omega$ at $20 \, ^\circ\text{C}$. As shown in Figure 2f, a reliable transfer is also demonstrated, through the integration of the sensor on natural plants. Note that, the sensor presented on the plant, can be used as a temperature sensor. The sensor geometry consists of a serpentine line design, which was specifically chosen to provide greater flexibility and stretchability to the device. In other words, as the plant grows over time, this geometry allows the sensor to adapt and extend without breaking. These results open new perspectives for the deployment of such sensors on biological, living, and bio-sourced surfaces.

The advantage of the screen-printing lies in the deposition of thick, homogeneous layers of conductive inks, ensuring good conductivity and mechanical stability suitable for sensors subjected to strain. These features are considered major strengths of this work and are demonstrated both optically and electrically in Figures 3a–3d. A carbon layer, patterned in a serpentine shape to act as a $2 \times 2 \, \text{cm}$ strain sensor and favor longitudinal strain, is first printed on a PVA film and then deposited onto the water surface. The PVA dissolution process is performed without any negative impact or breakage of the ink tracks throughout the steps. The process is as

follows: Figure 3a shows water diffusing into the hydrophilic polymer network of the PVA, causing heterogeneous swelling and wrinkles on the surface. In Figure 3b, the PVA matrix swells more uniformly.

The Figure 3c shows complete dissolution of the PVA, creating a fully aqueous interface ready for immersion of the target object, with the patterns floating on the surface. Finally, Figure 3d highlights the successful transfer of a 3×4 cm carbon-based strain sensor, after complete dissolution of the PVA layer, onto a PET plastic film, without mechanical degradation or cracking, while maintaining good mechanical integrity of the sensor after transfer.

The carbon-based sensors were evaluated under static strain (Figure 3e), showing comparable performances for both directly printed and transferred sensors (Selmi et al. 2023), with gauge factors (GF) of 15 and 18, respectively. The GF is defined as the ratio between the relative change in the electrical resistance of the sensor ($\Delta R/R_0$) and the applied mechanical strain ϵ :

$$GF = \frac{\frac{\Delta R}{R}(\%)}{\epsilon(\%)} \quad [1]$$

The characterization of the sensors consists of determining their GF (sensitivity). To this end, bending and compression strains (ϵ) are applied.

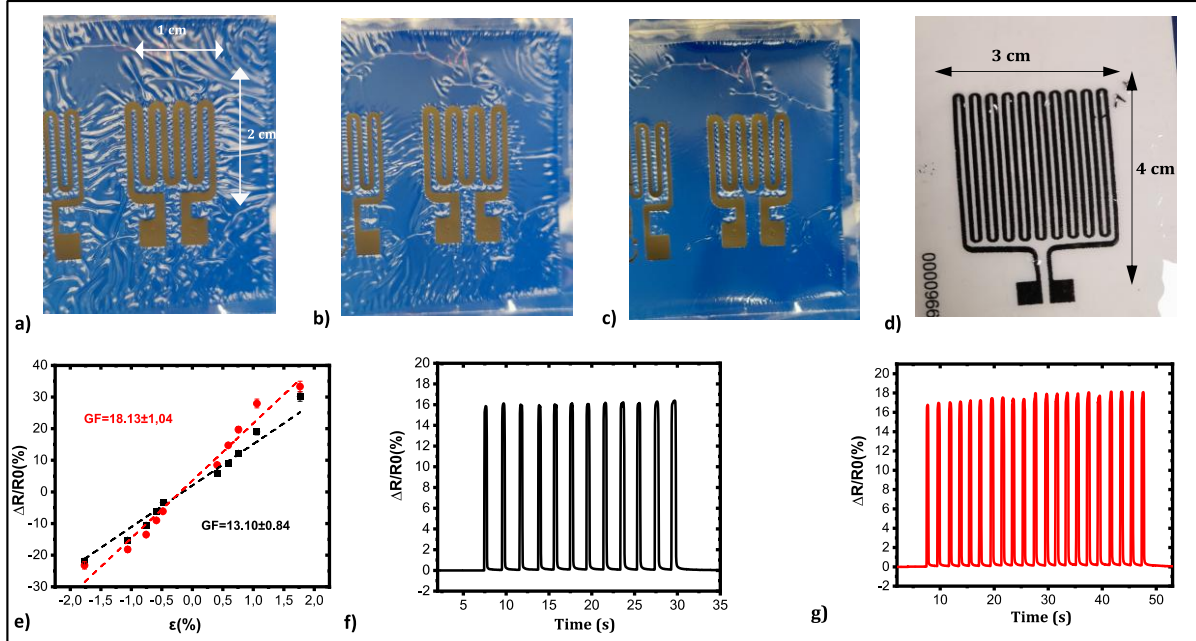


Figure 3: a–c) Dissolution stages of the PVA film during the WTP process: water uptake via hydrogen bonding (swelling and wrinkle formation), weakening of interchain interactions, ultimately resulting in complete dissolution and the availability of floating patterns for conformal transfer, d) Carbon-based strain sensor conformally transferred onto a planar plastic film, e) Electromechanical static response of the sensor directly screen-printed on PET (black signal) and transferred onto PET via the WTP process (red signal) under tensile and compressive strain, f) and g) Electromechanical dynamic response of these sensors showing similar dynamic behavior under 1% strain, and no memory effect and controlled hysteresis are observed.

The strain values are calculated using the following equation:

$$\epsilon = \pm \frac{d_s + d_f}{2R_c} \quad [2]$$

where d_s and d_f correspond to the thicknesses of the ink layer and the substrate, respectively, and R_c is the radius of curvature.

The sensors demonstrate excellent long-term durability, maintaining electrical conductivity and functionality for up to four years after transfer. This confirms that the WTP process does not degrade sensor performance or induce oxidation. Furthermore, the robustness and durability of screen printing, with its thick, mechanically resistant layers, ensure that the sensors withstand wear and abrasion.

Figures 3f and 3g present the dynamic responses as a function of time. The black curve in Figure 3f (screen-printed sensor) and the red curve in Figure 3g (transferred sensor) exhibit nearly identical behavior, with no memory effect and low hysteresis.

3.2 Direct transfer printing towards smart materials

This section describes a second fabrication process that also combines screen printing as the primary method for sensor patterning with a direct transfer process, enabling the printed sensors to be transferred from a temporary donor substrate to a receiver substrate, as shown in Figure 4a and 4b. The receiver substrate serves as the target for the desired electronic function and is typically a complex material, a composite (Selmi et al. 2025).

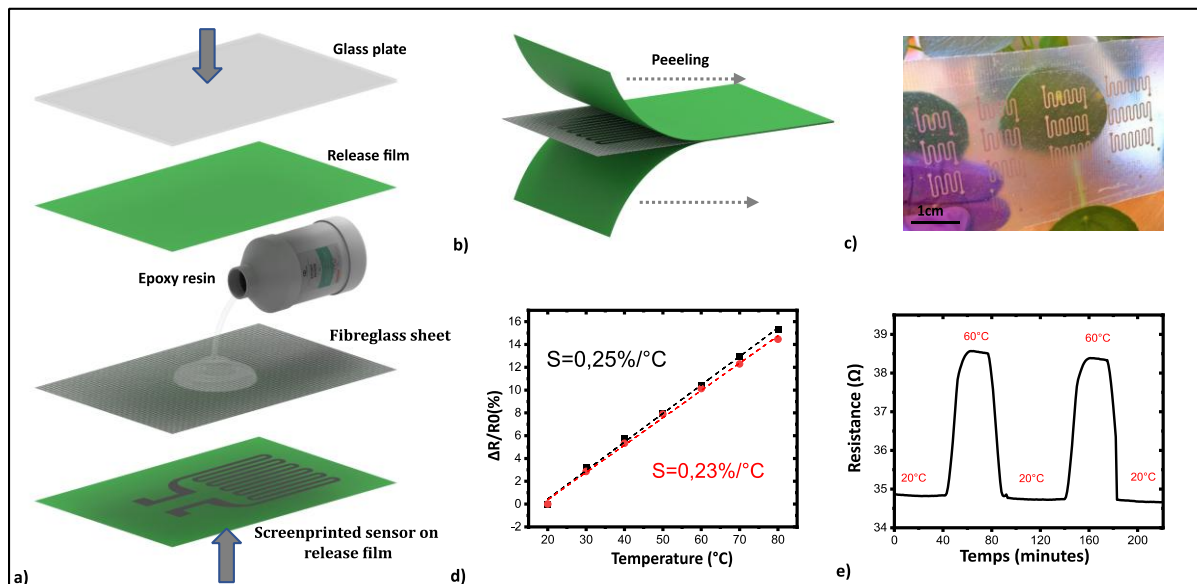


Figure 4: a) Principle of the direct transfer process : sensors are first screen-printed on a donor substrate, followed by the deposition of glass fibers impregnated with epoxy resin, b) Peeling step : After 10 h of curing, the composite hardens, enabling sensor transfer after removal of the initial donor film, c) Examples of silver-ink temperature sensors with serpentine geometries and different lengths transferred onto a composite ply, d) Electrical response $\Delta R/R_0$ (%) to temperature of screen-printed sensors on PET (black curve) and sensors transferred onto PET via the WTP process (red curves). The nearly identical sensitivities confirm the preservation of the thermal properties after transfer and demonstrate that the transfer process does not affect sensor performance, e) Electrical resistance variation of the sensor transferred onto a PET film at two temperature levels (20 °C and 60 °C) over 40 min for each plateau, showing good reproducibility of the electrical response.

The composite material is instrumented in a planar 2D form, referred to as a composite ply. It corresponds, as shown in Figure 4a, to a single layer of reinforcement, which in this case is glass fiber impregnated with a polymer matrix. The ply is fabricated using a contact deposition method, consisting of locally applying an epoxy resin (a mixture of Sicomin SR InfuGreen 810 and Sicomin SD 802 hardener) on the reinforcement fabric. The resin impregnates the fibers and polymerizes to form a solid ply. In the active area corresponding to the sensor location on a release film (industrial grade Nylex S2), the resin is deposited in a controlled manner, creating a localized zone that ensures proper integration of the device while maintaining homogeneous resin diffusion and

the continuity of the ply. After approximately 10 hours, the curing of the composite is completed, and the intrinsically adhesive nature of the epoxy causes the sensors to be pulled from the donor film onto the composite ply. After the detachment step shown in Figure 4b, the sensors are found adhered to the surface of the composite ply without mechanical degradation, cracking, or delamination.

The Figure 4c present a type of sensors fabricated using the silver-based ink consist of a single serpentine silver line transferred onto a composite ply. These sensors share the same design as those transferred by WTP on the 3D object shown in Figure 3d, demonstrating the feasibility of using both transfer processes for the fabrication of temperature sensors on 3D objects as well as on materials with complex composition and nature, such as composite materials.

In terms of electrical performance, the silver-ink temperature sensors transferred onto a composite ply via the direct transfer method exhibit a thermal sensitivity of 0.23%/°C (red signal in Figure 4d), which is comparable to the sensitivity of sensors printed on a standard thermoplastic film (0.25%/°C for the black signal). For both types of sensors, the electrical resistance increases with temperature, which is consistent with the literature and is attributed to the increase in electrical resistivity caused by enhanced thermal agitation of charge carriers at elevated temperatures.

Note That, the relationship between electrical resistance and temperature for metallic materials generally follows the equation below for temperatures above 0 °C:

$$R(T) = R_0[1 + \alpha(T - T_0) + \beta(T - T_0)^2] \quad [3]$$

where $R(T)$ represents the electrical resistance of the material at temperature T , R_0 is the reference resistance (20 °C), α is the linear temperature coefficient, and β is the quadratic temperature coefficient.

When the variation of resistance with temperature is approximately linear over a limited temperature range as shown in Figure 4d, this equation can be simplified as follows :

$$R(T) = R_0[1 + \alpha(T - T_0)] \quad [4]$$

The slope of the electrical resistance variation curve shown in Figure 4d corresponds to the sensor sensitivity, expressed in %/°C. This coefficient, denoted as α , corresponds to the TCR (Temperature Coefficient of Resistivity), which reflects the dependence of electrical resistance on temperature.

$$\alpha = \frac{1}{R(T_0)} \times \frac{R(T) - R(T_0)}{T - T_0} \quad [5]$$

The TCR values reported in Figure 4d are in good agreement with the values reported in the literature for printed temperature sensors (Le Goupil et al. 2023).

Beyond preserving electrical, mechanical, and thermal properties after direct transfer into the composite ply, the sensors also demonstrate good reproducibility and electrical stability at two temperature levels, as shown in Figure 4e. The electrical resistance alternates between two stable values, 34.9 Ω and 38.5 Ω , corresponding to temperatures of 20 °C and 60 °C, respectively, maintained for 40 minutes at each plateau.

4. Conclusions

This work demonstrates the transfer of strain and temperature sensors on complex environments, including irregular 3D geometries, natural living surfaces, and heterogeneous composite materials. Two reliable transfer strategies are employed, WTP process based on PVA

dissolution enabling intimate and substrate-free conformal contact with the target surface, and direct transfer into glass-fiber/epoxy composite plies. Both approaches provide lightweight, thin, and mechanically robust sensors with preserved electrical performance. The results are divided into two sections. The first section focuses on enabling smart 3D objects by equipping them with sensors such as mechanical strain sensors, or temperature sensors, with potential future applications. The second section focuses on making materials themselves smarter, particularly structural composite materials.

Using the presented process, these materials can integrate sensors, such as strain or temperature sensors, during their fabrication, enabling effective monitoring of their structural health. These results enable accurate monitoring of advanced composite structures and open new opportunities for sensing on bio-sourced, living, and multifunctional surfaces.

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