DRS 2018 Design Research Society 2018 Catalyst

University of Limerick
25th-28th June 2018

ICS Materials. Towards a Re-Interpretation of Material Qualities Through Interactive, Connected, and Smart Materials.

PARISI Stefano[a*]; ROGNOLI Valentina[a]; SPALLAZZO Davide and PETRELLI Daniela[b]

[a] Politecnico di Milano, Department of Design
[b] Sheffield Hallam University, Art and Design Research Centre, C3RI
* Corresponding author e-mail: stefano.parisi@polimi.it
doi: 10.21606/dma.2017.521

The domain of materials for design is changing under the influence of an increased technological advancement. Materials are becoming connected, augmented, computational, interactive, active, responsive, and dynamic. These are ICS Materials, an acronym that stands for Interactive, Connected and Smart. While labs around the world are experimenting with these new materials, there is the need to reflect on their potentials and impact on design. This paper is a first step in this direction: to interpret and describe the qualities of ICS materials, considering their experiential pattern, their expressive-sensorial dimension, and their aesthetic of interaction. Through case studies, we analyse and classify these emerging ICS Materials and identified common characteristics, and challenges, e.g. the ability to change over time or their programmability by the designers and users. On that basis, we argue there is the need to reframe and redesign existing models to describe ICS materials, making their qualities emerge.

ICS materials; expressive-sensorial dimension; aesthetic of interaction; materials experience.

Introducing ICS Materials

The materiality of the world where we live is changing under the influence of technological advancement that feeds miniaturization and a continuous democratization processes. Fuelled by the diffusion of the Open source and the spreading of fab labs, workshops, and platforms for experimentation and prototyping, the democratization of technological practices is bringing to easier access to data and technologies both owned, through cheap and flexible tools, and shared, also for non-specialized users. As a result, design is becoming computational and interactive, exploring trans-disciplinary approaches, and merging with computer engineering and biology (Antonelli, 2008; Myers, 2012). Through embedded technology, smart object and systems can interact with people and the environment, sensing and reacting to stimuli or transferring data. Based on these experiences, we can imagine a future where industries develop a new generation of interactive materials to fabricate products. These new materials will be dynamic, augmented, and programmable. We refer to these as ICS Materials, as they are Interactive, Connected, and Smart.

In order to lay down a clear definition of these materials, it is necessary to first unpack the lexicon currently used. In the use of the terms connectivity and smartness, "there is a common misunderstanding that interaction design is concerned fundamentally with the digital medium" (Buchanan, 2001). This is supported by the acknowledged declinations of the terms into materials domain. The concepts of 'Interactive material', and 'Smart Textiles' (Stoppa and Chiolero, 2014) underlines the use of electronic and digital technology, while 'Smart Objects' and 'Connected material' are related to the Internet of Things. In contrast, 'Smart materials' work through analogic means (Addington and Schodek, 2005) such as memory-shape alloys and thermo-chromic inks. Instead of a 'Technology-Centered view' we assumed a 'Behaviorist View' of Interaction (Saffer, 2009) which underpins a broad meaning for those terms by including other applications and means of interaction different from digital and computational and adopting an inclusive approach. Thus, the definition of ICS Materials encompasses materials that are: (i) able to establish a two-way exchange of information with human or non-human entities; (ii) linked to another entity or an external source, not only through the internet and digital network; (iii) able to respond contextually and reversibly to external stimuli, by changing their properties and qualities; (iv) programmable, not only through software (Rognoli et al., 2016; Parisi et al., 2018).

Examples such as DuoSkin and BioLogic by MIT Media Lab (Kao, et al., 2016; Yao, et al., 2015), the Recurring Pattern project by the Swedish School of Textiles (Nilsson, et al., 2011) and Transformative Paper by the Institut für Materialdesign Offenbach show that ICS Materials are not limited to computational, electronic, and digital. Indeed, this definition also encompasses interactive materials using chemical, mechanical, and biological means. Therefore, because of their systemic and networked complexity enabling interactivity and smartness (Ferrara, et al., 2018), we can describe them as hybrid material systems that work by establishing interactions among their constituting components, and with people, objects, and environments, through the combined use of electronic, chemical, mechanical, and biological components.

These materials can be fabricated (Coelho, et al., 2009), tinkered, hacked and programmed by designers (Vallgårda, et al., 2016) according to a self-production practice that extends the definition of DIY-Materials (Rognoli, et al., 2015; Ayala Garcia and Rognoli, 2017). Experiments with these emerging class of materials provide a remarkable contribution to design and research, pushing boundaries and opening up to new questions and issues to explore their expressive-sensorial dimension and their aesthetic qualities of interaction.

Although the range of interactive materials increases (Coelho, et al., 2009; Razzaque, Dobson, and Delaney, 2013; Vallgårda and Sokoler, 2010), their peculiar qualities, challenges, and opportunities, as well their possible applications are still to be fully understood. This paper is the first step in this direction and proposes a framework based on the analysis of a selection of existing projects and experiments, focusing on the experiential pattern of these materials, above all considering their expressive-sensorial dimension and their aesthetic of interaction. This proposal builds upon existing frameworks in the literature by different authors, that we put in relations and to expand, according to ICS Materials characteristics.

ICS Materials Map

We propose an initial map for ICS Materials (fig. 1) as a tool for understanding and framing materials. It is based on the outcome of a workshop involving the project participants and aiming to classify and organize a collection of best examples of materials, systems, components and products (Parisi, et al., 2018). The model is inclusive and encompasses different classes of materials, according to their degree of interactivity, smartness, and connectivity, and their related technological and systemic complexity. The graphical representation is read from the top to the bottom through the categories of: inactive materials, reactive materials, and proactive materials. The systematic classification of materials is an ongoing effort, thus prone to re-categorizations and extensions, considering other criteria and by furthering the collection of case studies.

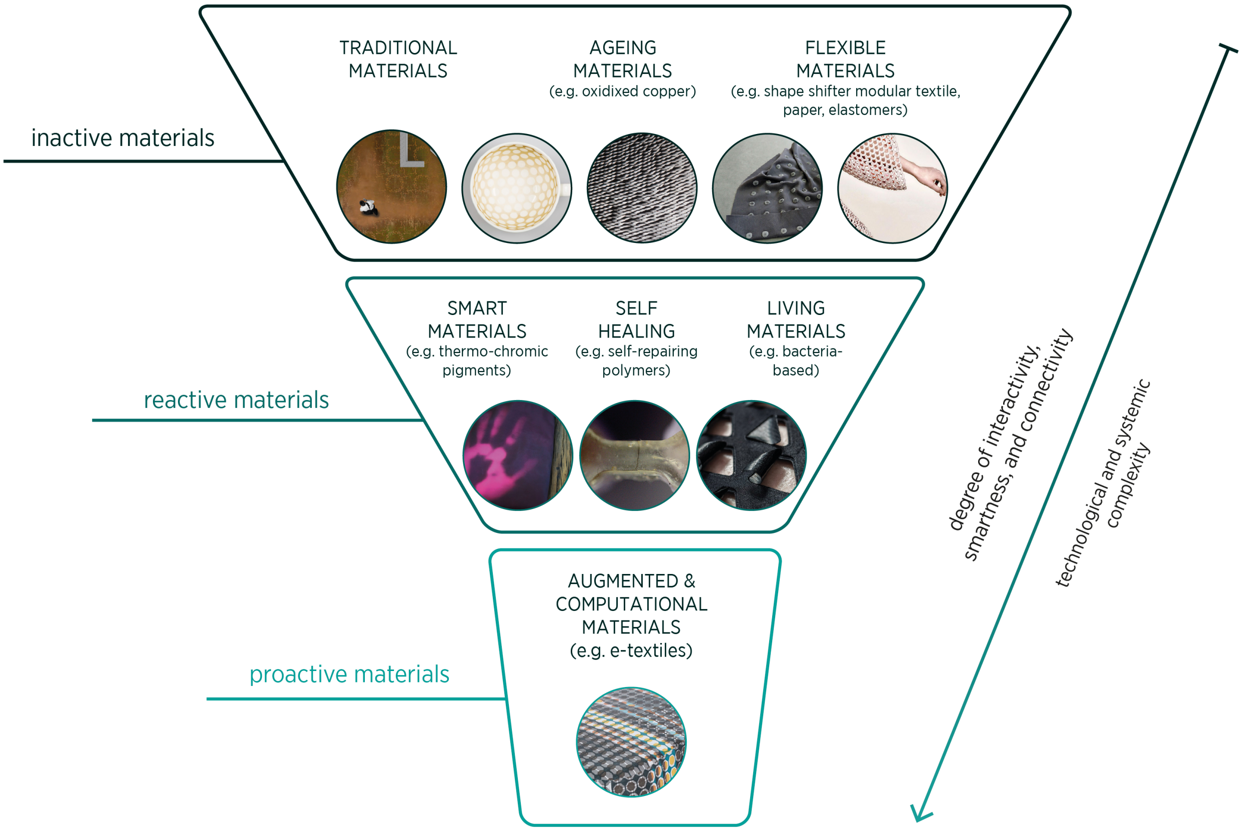

Figure 1. A tentative map of ICS Materials, arranged by their level of systemic and technological complexity, which is related to their degree of interactivity, connectivity, and smartness.

Inactive materials are material with no explicit interaction or allowing interaction at a very low degree and do not show ability to quickly react and connect: in other words, they are mostly behaving in a passive manner. They are mainly traditional materials. Thanks to their chemical or structural characteristics, they are subjected to establish some sorts of interaction with the users and the environment over time. Some materials display such interaction in a more evident or expressive way than other. For example, aging materials, as oxidizing copper, or flexible materials, as paper or elastomers. Their behaviours cannot be designed or programmed, but only exploited in design and can support the following more interactive classes.

Reactive materials include smart materials or combinations of inactive materials with smart materials components, e.g. thermo-chromic inks. They display changeable properties and can reversibly change some features such as colour or shape, in response to an external stimulus, e.g. light, temperature or the application of an electric field. Examples are thermo-chromic and photo-chromic polymers, shape memory alloys and piezo-electric materials. Other examples use living and growing organisms as bio-sensor and bio-activators to sense and react to stimuli, as bacteria. Because they are living organisms, they have a certain degree of intelligence and unpredictability. We might include into this category also self-healing or self-repairing materials, substances with the ability to autonomously repair any damage to themselves without external diagnosis of the damage or human intervention (Bekas, et al., 2016). Reactive materials have a higher degree of interactivity compared with the Inactive materials, but their connectivity is low. They can be seen as *closed materials*, because their performances are designed in the fabrication stage. However, if these materials are combined with other entities in a more complex and intelligent system they can improve their connectivity and smartness. This means that they can be applied "as a critical part of smart systems" (Ferrara and Bengisu, 2013).

Proactive Materials represent complex and intelligent systems of material components based on the combinations of inactive materials or reactive materials with embedded digital, electronic and computational technology in the form of sensors and actuators and connected with external or embedded computers, e.g. many smart textiles. These are also called *augmented materials* (Razzaque, Dobson, and Delaney, 2013) or *computational composites* (Vallgårda and Sokoler, 2010). Proactive materials show a very high degree of interactivity, connective abilities, and smartness. When compared to reactive material, they are more advanced as they can be programmed at every stage of fabrication and use. This acknowledge them as transformable (Ishii, et al. 2012) and open materials, unfolding new scenarios of interaction and a new concept of smartness, as they allow programmers, designers, makers, creatives, and users to operate on them, to obtain results, qualities and expressions. Proactive materials are the ones that best fit the definition of ICS materials. Projects such as Smart Dust (Warneke, et al., 2001) are expected to deliver microelectromechanical systems the size of a cubic millimetre that will take sensing and communication capabilities at the level of the material itself as opposed to the level of the object manufacturing as it is today. Smart materials can then be imagined as becoming an integral part of the future designers' toolbox possibly changing the way design is done.

In the rest of this paper we describe related works, pertaining to the fields of Materials and Design, HCI and Tangible Interaction that deal with the experiential pattern, expressive-sensorial dimension and aesthetic qualities of interaction. We further put forward a proposal to expand the Materials Experience model of a level of interactivity – that we named connective level – and analyse four cases accordingly.

Experiential, Expressive-sensorial and Aesthetic Qualities of Materials

In the last 30 years, research in Materials and Design has shifted its focus from technical properties of materials (e.g. flexibility or strength) to their expressive-sensorial qualities that define and affect the materials experience (Manzini, 1986; Cornish, 1987; Ashby and Johnson, 2002; Rognoli, 2010; Karana, Pedgley, and Rognoli, 2014; 2015). Thus, it is now acknowledged that materials need to have qualities that go beyond the fulfilling of practical demands. They must have intangible properties that captivate appreciation and that affect the experience of an artefact beyond its functional value. These properties were firstly named Intangible Characteristic of Materials (ICM) (Karana, Hekkert, and Kandachar, 2010; Karana, Hekkert, Kandachar, 2007), and later intangible sparks of materials (Karana, Pedgley, and Rognoli, 2015); they are qualitative, non-technical, and intangible characteristics related to emotions, personality, and cultural meanings. These qualities of materials have been explored and classified by different scholars. Here we review the literature including authors' contributions on this topic, and we propose a framework for the analysis of ICS Materials in accordance to their peculiar qualities. The framework we propose builds upon a substantial body of work we have developed over a number of years to better understand the principles of materiality. In proposing this framework, we expand our knowledge to include emerging computational characteristics that will become part of future ICS materials.

Materials Experience

Since materiality contributes to the definition of 'product experience' (Desmet and Hekkert, 2017), the concept of *material experience* arises as "the experience that people have through and with materials" (Karana, Pedgley, and Rognoli, 2014), which is framed into sensorial, affective, interpretive, and performative layers of experience (Giaccardi and Karana, 2015). These levels affect each other in a non-sequential manner:

- the *sensorial experience*, related to how people sense materials. We find materials cold, shiny, etc.
- the *affective experience*, related to emotions elicited by the material, e.g. feeling surprised, bored, etc.
- the *interpretive experience*, related to the meanings evoked by the material and are associated to abstract concepts, e.g. materials are modern, cozy, etc.
- the *performative experience*, acknowledges the active role of materials in shaping ways of doing, physical actions and practices, e.g. to scratch, finger, squeeze, etc.

The material experience is interpreted subjectively; therefore, when defining the qualities, a material should have or using it for an artefact, the role of the designer is key in understanding, envisioning, and creating that specific experience.

In the sub-sections below we are showing other models or concepts of experiential, aesthetics, expressive and sensorial qualities of materials. They are discussed and identified as corresponding or grounding the framework of Materials Experience.

Expressive-Sensorial Dimension of Materials

We define the sensorial, subjective, qualitative, and unquantifiable, profile of materials as their *expressive-sensorial dimension*. This notion looks at design materials as instruments to characterize a product from the points of view of perception, interpretation and emotion. By means of the expressive-sensorial qualities of materials, designers can embody in the product sensorial emotional references that trigger a particular material experience. The Expressive-Sensorial Atlas (Rognoli, 2010) supports designers in their understanding of the material qualities and unfolds their relations with engineering properties. It is a mapping of the technical, objective and measurable profile of materials, into a sensorial, subjective and qualitative one. Examples of these characteristics are texture (smooth/uneven), touch qualities (warm/cold, soft/hard, flowing/stilted, light/heavy), brilliancy (gloss/matte), transparency (transparent/translucent/opaque). These characteristics may be also used to describe the sensorial level of materials experience.

Meanings of Materials

These sensorial-expressive qualities are key in determining the meanings evoked by materials that are embodied in a specific product (Karana, Hekkert, and Kandachar. 2007; 2008). A set of meanings conveyed by the materials of a product have been identified by Karana and Hekkert (2008; 2010), such as cozy, aggressive, feminine, high-quality, toy-like, sober, etc. These meanings are used to describe the interpretative level of materials experience. The relationship between material qualities and elicited meanings is grounded on individual-personal, cultural-contextual, and universal reasons. Therefore, the right combination of materials and qualities to obtain a specific meaning are difficult to determine and are related to several variables.

Performances with Materials

Similarly, a set of performative actions that map ways of doing and practice have been argued as a performative level of materials experience, by Giaccardi and Karana (2015) and further explored in (Karana, et al., 2016). Examples of elements in the performative level are actions such as scratching, fingering, exploring, caressing, squeezing, stroking, etc. These are affected and mediated by the other levels of Materials Experience and inform them in a mutual manner.

As demonstrated by this latter contribution, as experience and interaction have become a matter of concern for material design, so materiality has spilled into in Human-Computer Interaction (HCI). The community around HCI have started to look at interaction and experience with materials as a complement to interaction and digital technology (Petrelli, et al. ,2016), re-valuing the importance of a sensorial engagement of the user with the physical matter and promoting the notion of *material turn* (Robles and Wiberg. 2010), *material move* (Fernaeus and Sundström., 2012) and *material lens* (Wiberg, 2014). This focus on materiality in HCI underpins studies by Vasiliki Tsaknaki and Ylva Fernaeus on the use of raw materials, such as leathers, and the value of imperfection in HCI (Tsaknaki and Fernaeus, 2016; Tsaknaki, Fernaeus, and Schaub, 2014), and those by Daniela Rosner et al. (Rosner, et al., 2013; Rosner and Taylor; 2012) on the topic of ageing and traces.

Thus, in many respects, materials design and interaction design are converging and offering a new interpretation of what we have defined above as interactive, connected and smart materials (ICS). ICS Materials introduce properties and qualities such as interactivity and temporality that in conventional materials do not exist, are irrelevant, unexpressed or complex to identify. Computational composites, as discussed by Vallgårda and Sokoler (2010), bring in properties such as temporality, reversibility, computed causality, and connectability.

Aesthetic of Interaction

Other studies move from a tangible interaction standpoint (Hornecker, 2011) and focus on the aesthetic of interaction, e.g. the interrelation between shape, size, material and behaviour in the perception of users (Petrelli, et al., 2016). (Petrelli, et al., 2016) sheds some light on the aesthetics of interaction, providing a useful starting point to analyse the perception of ICS materials along physical (size, shape, material) and behavioural (emitting light, emitting sound, vibrating) characteristics. This study identifies seven aesthetics dimensions of tangible interaction, namely pleasant, interesting, comfortable, playful, relaxing, special, and surprising, that are linked to the *affective level* of Materials Experience, and could be useful to describe the emotions elicited by ICS materials.

Connective Experience

To fully grasp the experience with ICS materials, an additional level that captures the relationship between the materials and their surroundings is needed. Indeed, ICS Materials are able to establish connections with other non-human entities, i.e. the environment or other materials, artefacts and organisms, to transfer and receive data. However, these interactions beyond the human control, are observed and perceived by people, contributing to the materials experience. We name this level as the *connective level*, as an expansion to the current levels of materials experience (Figure 2). It describes the interactive behaviour of materials and addresses the following questions: *"How do materials interact with the environment and other things around them? How do their constituting components interact between them? In which manner and with which behaviour? How can materials mediate between the human and the environment? What are the results?"*. The qualities in this level map criteria such as the speed of action, the regularity or irregularity of actions; the reversibility or irreversibility of mutation; the predictability or unpredictability of actions, the repetition, the autonomy or automatism of action, the modality of transformation and expression, e.g. stratification, reduction, movement, sound, light, etc. Although all these observations are prominent in interactive materials, they may also be applied to materials with a low degree of interactivity, such as ageing materials. The notion of Becoming Materials (Bergstrom, et al., 2010) highlights this dynamic and open feature.

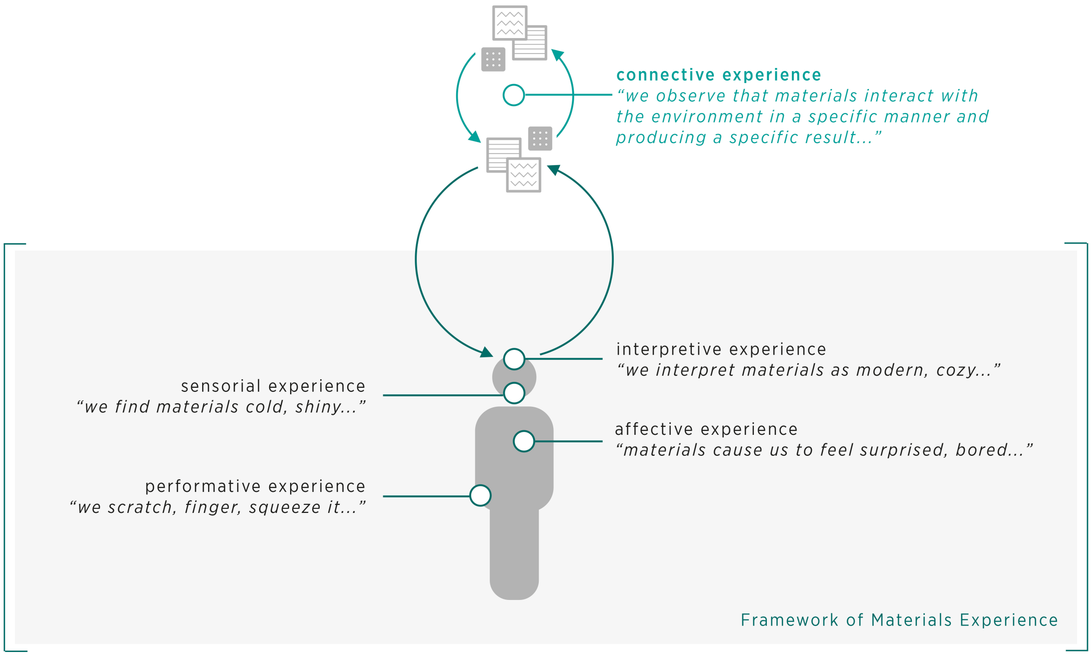

Figure 2. The Materials Experience framework (Karana, et al., 2015; Giaccardi and Karana,2015) enriched with an additional level related to non-human relations, namely the connective level of materials experience.

Unfolding qualities of ICS materials

As the proposal of the connective level of materials experience may suggest, with the emergence of ICS Materials, new qualities related to interaction, dynamism, and connectivity are arising and old models to observe and interpret materials become obsolete. Furthermore, the aforementioned diverse models to interpret materials are not mutually exclusive but may overlap. For example, the affective and interpretative levels of materials experience correspond to aesthetic qualities of materials, whilst the sensorial level of materials experience corresponds to expressive-sensorial qualities of materials.

We illustrate the extended framework with four cases of ICS materials going through the levels of materials experience, namely the sensorial level, by referring mainly to the expressive-sensorial characteristics, the affective level, by referring mainly to the aesthetic qualities of interaction, the interpretative level, the performative level, and the connective level here proposed, to address the integration of interactive and smart capabilities of such materials. It is presented as a short description that summarizes the analysis conducted over the selected materials, in form of case study. These four cases of proactive materials have been selected from a collection of 98 examples of interactive materials, gathered in the scope of the research project and analysed to ground the framework. The four selected cases exemplify different ways of materials to be interactive, connected and smart through diverse means, namely electronic, chemical, biological, and mechanical.

Being the Materials Experience mainly based on a subjective interpretation, the analysis reported is based on the personal understanding of the authors that can be considered as an example of self-reflection applied to design. The aim of this analysis is twofold: first, to verify the validity of the framework for this new class of materials; and second, to identify similarities and differences with respect to other classes of materials at diverse levels of the Materials Experience.

Figure 3. DuoSkin by MIT Media Lab and Microsoft Research, 2016. Image used with permission, retrieved by http://duoskin.media.mit.edu.

DuoSkin

DuoSkin by MIT Media Lab and Microsoft Research is an on-skin interface made of gold metal leaf (Figure 3). It senses touch inputs, displays outputs with the use of thermo-chromic ink, and allows wireless communication (Kao, et al., 2016).

Sensorial level

Made of gold metal leaf, this artefact has a relatively smooth surface with an irregular texture. Because of its nature of thin mono-material surface, it is very lightweight. Its chromatic appearance is based on the natural colours, reflectiveness and glossiness of metals.

Affective level

Being in contact with the wearer's skin in the form of a tattoo, it evokes an intimate and personal feeling. For the same reason, sometimes it might be perceived as intrusive. When it is used as an interface or display, it may be felt as playful and surprising. Being customizable, it elicits a sense of ownership.

Interpretative level

Being similar to a jewellery as an instance of body-decoration, it can evoke a sense of preciousness and luxury, and it is decorative. Due to its digital components, it can be perceived as high-tech. Being customizable by the user, it elicits uniqueness.

Performative level

The user is invited to customize the product by cutting it. As an interface, its sensorial-expressive qualities invite touching, fingering, and interacting.

Connective level

It interacts electronically with a digital device, by providing an immediate input or reproducing a physical output, activating colour changes through the use of a thermo-chromic ink applied to the tattoo surface. In this last case, the interaction is quite fast, but gradual and reversible. It may be also possible to obtain visual patterns for colour changing response, by using different inks and designing circuits.

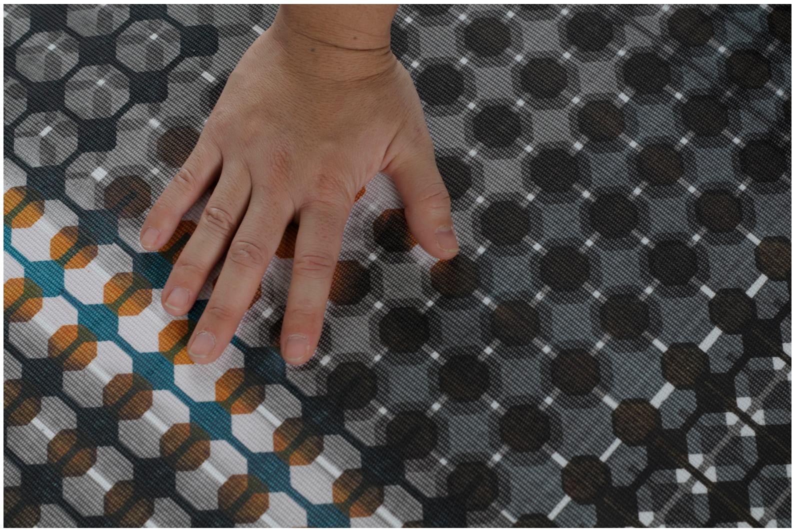

Figure 4. Recurring Patterns Project by Smart Textiles Design Lab at the Swedish School of Textiles, 2011. Image used with permission*, courtesy of Linda Worbin and the Smart Textiles Design Lab at the Swedish School of Textiles.*

Recurring Patterns project

This project (Figure 4) is a collaboration between the furniture company IRE, Smart Textile Design Lab at the Swedish School of Textile, University of Borås and Smart Textiles prototype factory (Nilsson, et al, 2011). The researchers involved in this project are Linnéa Nilsson, Mika Satomi, Anna Vallgårda, and Linda Worbin. The project explores how to use programmable textile qualities changing in context over time in furniture design. To answer, the prototype of a pouf, a cushioned footstool, was covered with a smart textile that changes expressions in a dynamic interplay with its use. A bright pattern gradually reveals when someone sits on it, and disappears when the user stands up. This is possible thanks to four components of the material: woven cotton with embedded conductive threads; a layered pattern printed with a combination of pigment colour and thermo-chromic ink (with a state of change at 27°C); pressure sensors to detect when someone sits; a computer programmed to control which conductive thread should be activated thus triggering the colouring of the thermo-chromic fabric.

Sensorial level

Made of woven cotton, the surface is warm, soft, and regularly textured. The patter is regular and geometric, and with desaturated and neutral grey colours in its static state. When activated, the conductive threads heat up the surface and let a bright yellow and blue pattern emerges.

Affective level

Thanks to cotton fabric, the material may be felt as relaxing, pleasant and comfortable. Furthermore, woven cotton is a conventional and daily used material, therefore the sofa may elicit a sense of trusting and familiarity. When in action, it may be perceived as surprising, interesting, and even playful.

Interpretative level

Due to the nature of the material, it elicits a sense of ordinary and traditional. Its sensorial qualities may provide a sense of cosiness. At its static state, its neutral colours may evoke sobriety. When the colour changes, it may be interpreted as modern and strange.

Performative level

The shape of the artefact and the sensorial qualities of the material invite to comfortably sit down and caress the surface. When the change of colours occurs, the user may be more focused on observation and visual interaction.

Connective level

In this case, the material interactions and expressions are strictly connected to the user but mediated by a computer. When someone sits down on the pouf, the sensors detect it. A computer then activates the conductive thread that heats up and gradually reveals a bright pattern, thanks to the chemical reactions to heat of the thermo-chromic ink. The pattern gradually disappears when the user stands up. This material can be programmed to obtain other results and qualities of interaction and expression.

Figure 5. BioLogic by MIT Media Lab, 2015. Image owned by MIT Media Lab, retrieved from http://tangible.media.mit.edu/project/biologic/.

BioLogic fabric

Another example by MIT Media Lab, Tangible Media Group, is BioLogic Fabric (Figure 5), a shape-changing fabric using embedded Bacillus Subtilis Natto bacteria as bio-actuators reacting to moisture. In partnership with New Balance, this material was applied to sportswear, reacting to body sweat, causing heat zones to open, and enabling sweat to evaporate (Yao, et al., 2015).

Sensorial level

Made of synthetic fabric, it is lightweight, flexible and tight. Its surface is textured in a regular way. Its surface is dark, desaturated, and matte. Thermally, its functioning allows to ventilate the skin and to provide a cool sensation.

Affective level

Being in contact with the user's skin in the form of a garment, it evokes an intimate and protective feeling. For the same reason and for the use of bacteria, it might be perceived as intrusive, dangerous and unreliable. When it is shape-changing it may be perceived as surprising or interesting. When it is cooling down the body, the feeling may be pleasant, relaxing, and comfortable.

Interpretative level

Because of its aesthetic and functioning it could be perceived as technical, high-tech, futuristic, and sophisticated.

Performative level

The user wears the material, but it does not have a direct and intentional engagement with its functioning. The performance regards the body heat and the sweat produced by the user in his or her practices, actions and movement.

Connective level

Thanks to the bacteria that are embedded in the fabric, it reacts to humidity causing a shape-changing reaction and allowing a laser-cut texture to open. This action is gradual and proportional to the degree of humidity and heat. It is reversible.

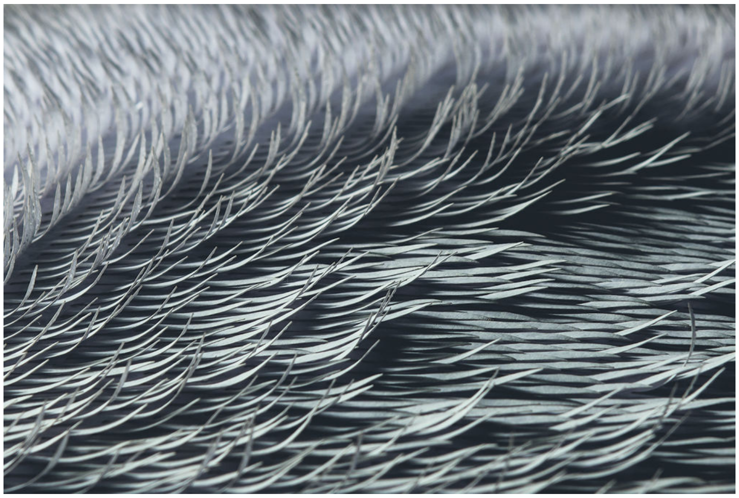

Figure 6. Transformative Paper by Florian Hundt, a result of the cooperation "Intuitive brain" between Prof. Dr.-Ing. Markus Holzbach, Institute for Materialdesign IMD, HfG Offenbach and BMW AG, 2015. Image used with permission, retrieved from http://www.hfg-offenbach.de/en/pages/institute-for-materialdesign-imd#projects.

Transformative paper

Transformative paper (Figure 6) is a layered structure, which reacts to short-term environmental conditions, morphing into various states. Due to the anisotropic property of moisture expansion of paper, the small segments in which this surface has been designed reacts to humidity by stiffening. Designed by Florian Hundt, this project is a result of the cooperation "Intuitive brain" between Prof. Dr.-Ing. Markus Holzbach, Institute for Materialdesign IMD, HfG Offenbach and BMW AG.

Sensorial level

Made of paper, it is lightweight and porous. The texture in which the surface is segmented could be regular or irregular, providing different shape-changing reactions. The colour is the natural and neutral colour of paper.

Affective level

Being made of a well-known and daily used material, this surface may elicit a sense of trust and familiarity. When in action, it may be perceived as surprising or interesting. Its textured surface may be felt as relaxing, pleasant, and seductive to the eye and touch.

Interpretative level

Due to the nature of the material, it elicits a sense of ordinary, sober, and traditional and nostalgic. When its shape changes, it suggests sophistication and modernity. The qualities of the interaction may evoke a feeling of cosiness.

Performative level

When dry, the surface is very tactile and invites the user to caress and to raise the separate fragments. When the material performs movements the user's curiosity to observe and touch is stimulated.

Connective level

Exposed to minimal change of moisture, it creates a subtle and almost invisible movement. When it gets wet, it produces a very evident transformation by performing movements. This action is reversible.

Discussion and Conclusions

The case studies bring about some preliminary considerations on qualitative patterns that characterize ICS materials. We now outline the peculiarities of this class of materials against traditional ones, according to the five levels of the Materials Experience.

A first reflection regards the three levels of the Materials Experience defined as Sensorial, Affective and Interpretive. What emerges is a substantial similarity between ICS and traditional materials since the novel technological materials analysed are initially perceived as traditional ones (e.g. gold leaf, paper, technical sport-swear…). At a sensorial level the impression is indeed given by the material used as external skin and not modified by its technological augmentation. Similarly, the affective level strongly depends on the previous experience of users with the material constituting the skin of a product, despite the un/expected behaviour could add a sense of surprise. Similar considerations can be drawn for the interpretive level: in static conditions the materials do not differ from traditional ones, but they may trigger different interpretations while acting the programmed behaviour.

It is evident in all the case studies that, compared with traditional materials, the qualities of ICS materials are dynamic, usually reversible, and ever-changing in reaction to different stimuli. In other words, ICS materials are never the same, modifying their qualities over time: they are qualities *to become* (Bergstrom, et al. 2010). The evident difficulty to describe ICS materials qualities in their continuous modification shows the limits of the three aforementioned categories of the Materials Experience. Tools and models to analyse, describe, and characterize these materials, as the Sensorial-Expressive Atlas (Rognoli, 2010), the framework of Materials Experience (Giaccardi and Karana, 2015), and the Meanings of Materials tool (Karana and Hekkert, 2010) seem indeed in need to be reframed and redesigned to fit these dynamic and ever-changing experiences, considering materials and their sensorial, affective, interpretative, performative, and connective relations also by a temporal perspective. Moreover, interactions and responses, that might be programmed in advance by the designer, should be considered in the expressive-sensorial and experiential characterization, as features of the material. Looking at ICS materials through the lens of the performative level, their dynamic behaviour emerges to an even greater degree, since the interaction they trigger in the user is strongly dependent on their actual state. In this sense the connective level, namely what happens out of user's control, acquires a predominant role, influencing the other four levels.

Furthermore, it must be noted that in the analysed cases arises a tension between the sensorial and emotional comfort and solace, and the possible feeling of intrusion and not confidence provoked by the means of interaction, either digital and biological. Sometimes this tension is even stressed by the contrast between a high-tech and futuristic behaviour of materials, and a familiar and traditional feeling due to the use of conventional materials in their natural and more iconic appearance, such as paper and gold leaf. This behaviour usually is unexpected and is a reason of surprise and interest for the user. Because of this behaviour, intentional tactile interaction between the user and the material become limited to make room for the observation of materials activity through non-human relation with the environment and other entities, and with the users' body.

These results show that ICS materials are extremely flexible in providing countless qualities pertaining the Materials Experience at its five levels. In doing so, they could potentially allow designers to modify the properties of the materials according to the functional, aesthetic and sensorial aims they intend to embed in the final product. In other words, designers can become the programmers (Vallgårda, et al., 2016) of the qualities of materials, both in terms of functionality and aesthetic at large, overturning the role of designers in respect to materials. The materials are not chosen anymore for their properties but are programmed, modified, crafted to respond to specific needs or situations. The design contribution acquires therefore a relevant role as it happens for the so-called metamaterials, whose technical characteristics are given by the shape, rather than the material itself. Similar reflections about programmability could be done regarding the final users of products that integrate ICS materials: as a matter of fact, their programmability could be also delegated to the user.

Beyond the foreseen programming capabilities of ICS materials, their characteristics of being Interactive, Connected and Smart offer relevant opportunities in terms of tangible interaction. The materials themselves can become the product interface or components of interface to interact with a computing or information processing systems (Kretzer, Minuto, and Nijholt, 2013; Minuto, et al., 2011) in a vision that opens great opportunities and new paradigms for product and interaction designers, that could act on different levels of the design project at the same time. The product interface, while fulfilling a technical role (e.g. the shell of a household appliance), could also be programmed to have defined aesthetic qualities, acting as switch or feedback system. To these, we could also add a certain level of programmability on the users' side, providing a dynamic and customizable experience.

This extreme flexibility and programmability makes even clearer the complexity connected to the design of/with ICS Materials and the inadequacy of analytical tools such as the Materials Experience framework in supporting designers in the definition of expressive-sensorial, aesthetic and experiential qualities of the materials. Consequently, the primary results seem to suggest the need of a new analytical tool able to frame the complexity of ICS Materials. Nevertheless, to validate these initial results, a more in-depth analysis on other examples of ICS materials gathered in the research is needed.

Which tools and methods can help to analyse, describe, and characterize the qualities of these materials? How can designers program ICS materials and thus to control the final qualities of a product? How can users modify the qualities of a product acting directly on its constituting materials? What opportunities do ICS materials open in terms of design innovation? These are focal questions to be addressed in the prosecution of the research.

Acknowledgements: the research project "ICS_Materials" is funded by FARB Basic Research Funding of Politecnico di Milano, Department of Design, and partially supported by the Scholarship for PhD candidates by Fondazione Fratelli Confalonieri. We are thankful to our colleagues of the Department of Design of Politecnico di Milano involved in the project "ICS_Materials", Venanzio Arquilla, Camilo Ayala Garcia, Arianna Bionda, Mauro Attilio Ceconello, Marinella Ferrara, Venere Ferraro, and Andrea Ratti, who provided insight and expertise that greatly assisted the research. We are thankful to our colleagues of the Materials Experience Lab for their support.

REFERENCES

Antonelli, P. (2008). *Design and the Elastic Mind*. Museum of Modern Art.

Ashby, M., & Johnson, K. (2002*). Materials and Design, Third Edition: The Art and Science of Material Selection in Product Design*. Butterworth-Heinemann, Oxford.

Ayala Garcia, C., & Rognoli, V. (2017). The New Aesthetic of DIY-Materials, *The Design Journal, 20:sup1, S375-S389*

Bergström, J., Clark, B., Frigo, A., Mazé, R., Redström, J., & Vallgårda, A. (2010). Becoming materials: material forms and forms of practice. Digital Creativity Vol. 21(3). https://www.researchgate.net/publication/233719521_Becoming_materials_Material_forms_and_forms_of_practice

Coelho, M., Hall, L., Berzowska, J., & Maes, P. (2009). Pulp-based Computing: a framework for building computers out of paper*. CHI '09 Extended Abstracts on Human Factors in Computing Systems. Pages 3527-3528.* http://xslabs.net/papers/coelho-pulp-ubicomp07.pdf

Cornish. E. H. 1987. *Materials and the Designer*. Cambridge University Press, Cambridge.

Desmet P., & Hekkert, P. (2017). Framework of Product Experience. *International Journal of Design*. Retrieved May 20, 2017 from http://www.ijdesign.org/ojs/index.php/IJDesign/article/view/66/15

Fernaeus, Y., Tholander, T., & Jonsson, M. (2008). Beyond representations: towards an action-centric perspective on tangible interaction. *International Journal of Arts and Technology 1, 3-4: 249–267.* https://doi.org/10.1504/IJART.2008.022362

Fernaeus, Y., & Sundström, P. (2012). The Material Move How Materials Matter in Interaction Design Research. *In Proceedings of the Designing Interactive Systems Conference (DIS '12), 486–495.* https://doi.org/10.1145/2317956.2318029

Fernaeus, Y., Murer, M., Tsaknaki, V., & Solsona Belenguer, J. (2013). Handcrafting Electronic Accessories Using "Raw" Materials. *In Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction (TEI '14), 369–372.* https://doi.org/10.1145/2540930.2567906

Ferrara M., Rognoli V., Arquilla V., Parisi S. (2018). ICS Materiality. In: Karwowski, Waldemar, Ahram, Tareq (Eds.). Intelligent Human Systems Integration, *Proceedings of the 1st International Conference on Intelligent Human Systems Integration* (IHSI 2018): Integrating People and Intelligent Systems, January 7-9, 2018, Dubai, United Arab Emirates, Volume 722 of the Advances in Intelligent Systems and Computing series, ISBN 978-3-319-73888-8. pp.1-7

Ferrara, M., Bengisu, M. (2013). *Materials that Change Color: Smart Materials, Intelligent Design*. Springer.

Giaccardi, E., & Karana, E. (2015). Foundations of Materials Experience: An Approach for HCI. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15), 2447–2456. https://doi.org/10.1145/2702123.2702337

Hornecker, E. (2011). The Role of Physicality in Tangible and Embodied Interactions. *ACM Interactions 18, 2: 19–23.* https://doi.org/10.1145/1925820.1925826

Kao, Cindy Hsin-Liu, Christian Holz, Asta Roseway, Andres Calvo, Chris Schmandt (2016). DuoSkin: Rapidly Prototyping On-Skin User Interfaces Using Skin-Friendly Materials. In *Proceedings of ISWC'16*. Heidelberg, Germany (September 12-16, 2016). ACM, New York, NY, USA, 8 pages.

Karana, E., Pedgley, O, & Rognoli, V. (2015). On Materials Experience. *Design Issues 31, 3: 16–27.* https://doi.org/10.1162/DESI_a_00335

Karana, E., Pedgley, O., & Rognoli, V. (eds.) (2014). *Materials Experience: Fundamentals of Materials and Design*. Butterworth-Heinemann, Amsterdam.

Karana, E., Hekkert, P., & Kandachar, P. (2010). A Tool for Meaning Driven Materials Selection. *Materials and Design, 31, 2932-2941.*

Karana, E., Hekkert, O., & Kandachar, P. (2008). Materials Experience. Descriptive categories in material appraisal. In *Proceedings of the International Conference on Tools and Methods in Competitive Engineering* (TMCE), Izmir, Turkey.

Karana, E., Hekkert, P., & Kandachar, P. (2007). Material Considerations in Product Design: A survey on crucial material aspects used by product designers. *Materials and Design, 29, 1081-1089.*

Karana, E., & Hekkert, P. (2008). Attributing meanings to materials. *Proceedings of 6th International Design & Emotion Conference*, Hong Kong.

Karana, E., & Hekkert, P. (2010). Material-Product-User Interrelationships in Attributing Meanings*. International Journal of Design, Vol. 4,(3).*

Karana, E., Giaccardi, E., Stamhuis, N., & Goossensen, J. (2016). The Tuning of Materials: A Designer's Journey*. In Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS '16), 619–631.* https://doi.org/10.1145/2901790.2901909

Kretzer, M., Minuto, A., & Nijholt. A. (2013). Smart material interfaces: "another step to a material future." *In Proceedings of the 15th ACM on International conference on multimodal interaction (ICMI'13), 611–612.* https://doi.org/10.1145/2522848.2535893

Manzini, E. (1986). *La materia dell'invenzione*. Arcadia Edizioni.

Myers, W. (2012). *Bio Design*. Thames & Hudson.

Minuto, A., Vyas, D., Poelman, W., & Nijholt, A. (2011). Smart Material Interfaces: A Vision. In *Intelligent Technologies for Interactive Entertainment*, Antonio Camurri and Cristina Costa (eds.). Springer Berlin Heidelberg, 57–62. Retrieved October 14, 2016 from http://link.springer.com/chapter/10.1007/978-3-642-30214-5_7

Nilsson, Linnéa, Mika Satomi, Anna Vallgårda, & Linda Worbin (2011). Understanding the Complexity of Designing Dynamic Textile Patterns. *Ambience 2011*, November, 28-30, 2011 in Borås, Sweden

Parisi S., Spallazzo D., Ferraro V., Ferrara M., Ceconello M., Ayala Garcia C., Rognoli V. (2018). Mapping ICS Materials: Interactive, Connected, and Smart Materials. In: Karwowski, Waldemar, Ahram, Tareq (Eds.). Intelligent Human Systems Integration, *Proceedings of the 1st International Conference on Intelligent Human Systems Integration* (IHSI 2018): Integrating People and Intelligent Systems, January 7-9, 2018, Dubai, United Arab Emirates, Volume 722 of the Advances in Intelligent Systems and Computing series, ISBN 978-3-319-73888-8. pp.1-7

Petrelli, D., Soranzo, A., Ciolfi, L., & Reidy, J. (2016). Exploring the Aesthetics of Tangible Interaction: Experiments on the Perception of Hybrid Objects. *In Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '16), 100–108*. https://doi.org/10.1145/2839462.2839478

Razzaque, M. A., Dobson, S., & Delaney, K. 2013. Augmented Materials: Spatially Embodied Sensor Networks. *Int. J. Commun. Netw. Distrib. Syst. 11, 4: 453–477.* https://doi.org/10.1504/IJCNDS.2013.057721

Robles, E., & Wiberg, M. (2010). Texturing the "Material Turn" in Interaction Design. *In Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '10), 137–144.* https://doi.org/10.1145/1709886.1709911

Rognoli V., Arquilla V., Ferrara M. (2017). ICS_Materials: materiali interattivi, connessi e smart. In: *Material Design Journal, vol 2,* Università di Ferrara.

Rognoli V., (2010). A broad survey on expressive-sensorial characterization of materials for design education. *Metu, Journal of the Faculty of Architecture, vol. 27; p. 287-300.* DOI 10.4305/METU.JFA.2010.2.16

Rognoli, V., Bianchini, M., Maffei, S., & Karana, E. (2015). DIY Materials. *Special Issue on Emerging Materials Experience. Materials and Design, vol. 86, pp. 692–702*; DOI 10.1016/j.matdes.2015.07.020.

Rosner, D. K., Ikemiya, M., Kim, D., & Koch, K. (2013=. Designing with Traces. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13), 1649–1658.* https://doi.org/10.1145/2470654.2466218

Rosner D. K., & Taylor, A. S. (2012). Binding and aging. *Journal of Material Culture 17, 4: 405–424.* https://doi.org/10.1177/1359183512459630

Tsaknaki V., & Fernaeus, Y. (2016). Expanding on Wabi-Sabi as a Design Resource in HCI. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, 5970-5983.*

Tsaknaki, V., Fernaeus, Y., & Schaub, M. (2014). Leather as a Material for Crafting Interactive and Physical Artifacts. *Proceedings of DIS '14, 5-14.* http://www.mobile-life.org/sites/default/files/p5-tsaknaki.pdf

Vallgårda, A., Boer, L., Tsaknaki, V., & Svanaes, D. (2016). Material Programming: A New Interaction Design Practice. In *Proceedings of the 2016 ACM Conference Companion Publication on Designing Interactive Systems (DIS '16 Companion), 149–152.* https://doi.org/10.1145/2908805.2909411

Vallgårda, A., & Sokoler, T. (2010). A material strategy: Exploring material properties of computers. *International Journal of Design, 4(3), 1-14*. Retrieved May 20 2017 http://ijdesign.org/index.php/IJDesign/article/view/628/309

Warneke, B., Last, M., Liebowitz, B., & Pister K. S. J. (2001). Smart Dust: communicating with a cubic-millimeter computer. In *Computer*, *vol. 34, no. 1, pp. 44-51,* Jan 2001. doi: 10.1109/2.895117

Wiberg, W. (2014). Methodology for Materiality: Interaction Design Research Through a Material Lens. *Personal Ubiquitous Comput. 18, 3: 625–636*. https://doi.org/10.1007/s00779-013-0686-7.

Yao, Lining, Jifei Ou, Chin-Yi Cheng, Helene Steiner, Wen Wang, Guanyun Wang, and Hiroshi Ishii (2015). bioLogic: Natto Cells as Nanoactuators for Shape Changing Interfaces. *In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15).* ACM, New York, NY, USA, 1-10.

About the Authors:

Stefano Parisi is a Ph.D. candidate at the Department of Design of Politecnico di Milano, researching at the intersection of emerging advanced materials, meaningful materials experiences, and future scenarios. He is a member of the Materials Experience Lab and Madec research center.

Valentina Rognoli is Assistant Professor at the Department of Design of Politecnico di Milano. She is one of the coordinators of Madec, Materials Design Culture research center at the Design Department of Politecnico di Milano, and one of the founders of the Materials Experience Lab.

Davide Spallazzo is Assistant Professor at the Department of Design of Politecnico di Milano. He makes research in the field of Interaction Design, investigating the role of digital technologies in modifying and enhancing the user experience.

Daniela Petrelli is Professor of Interaction Design at the Art & Design Research Centre, Sheffield Hallam University. She started working on new technologies for cultural heritage in 1996. She led the European project meSch. She is director of the Digital Materiality Lab at the Art & Design Research Centre.