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Abstract

Based on the principles of emerging *bio-smart materials*, in the framework of design-driven material innovation approach and cross-disciplinary research practices, the aim of this paper is to make clear how these materials are creating new opportunities to realize answers to the complex needs of contemporary society, while defining bio-smart materials main qualities, and questioning the implications on research design practices. We present a review of case studies of bio-smart materials applications in order to demonstrate that their diffusion is underway, especially in some application sector characterized by more

complexity and a higher propensity for the use of biotechnological innovations. The examples described, are framed in three specific areas: biomedical design, sports design, and design for the environment that are particularly interested of the development and application of novel materials for both their performances and sustainability.

Keywords (separated by '-')	Bio-smart materials - Design research practices - Biomedical design - Sport design - Design for environment

Bio-smart Materials for Product Design Innovation: Going Through Qualities and Applications

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Abstract. Based on the principles of emerging *bio-smart materials*, in the framework of design-driven material innovation approach and cross-disciplinary research practices, the aim of this paper is to make clear how these materials are creating new opportunities to realize answers to the complex needs of contemporary society, while defining bio-smart materials main qualities, and questioning the implications on research design practices. We present a review of case studies of bio-smart materials applications in order to demonstrate that their diffusion is underway, especially in some application sector characterized by more complexity and a higher propensity for the use of biotechnological innovations. The examples described, are framed in three specific areas: biomedical design, sports design, and design for the environment that are particularly interested of the development and application of novel materials for both their performances and sustainability.

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1 Introduction

Materials for design are changing and Design Culture is consequently changing. In the approaching bio-technological era, the most adequate artifacts to *survive* the emerging conditions of extreme complexity and mutability will be those able to express a kind of smartness as close as possible to the *intelligence in nature* [1]. The concept of bio-smartness associated with materials and material systems, therefore, assumes increasingly hybrid connotations between the synthetic world and the biological world that lead to the expansion of the traditional concept of smartness as a digital computational content. Up to date, this is one of the most desirable and promising research vision expanding from the sciences of life to the design, as it put right the old dichotomy between nature and artifice. Nature is an infinitely variable and dense model of stimuli for the project. In the bio-smart vision, through cybernetic, bionics and biomimetics, Nature is increasingly mixed with the new green technologies, breaking the patterns imposed by physical and sensorial limits to give rise to hybrid and intelligent objects

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able even to live their own almost-autonomous-life. As in an inverse process, the complexity of contemporary technologies - and in particular the interaction between biomimetics, robotics, and neuroscience - influences the design project, causing it to replicate, invade and disseminate nature, to reproduce the apparent simplicity through extremely sophisticated techniques [2].

Based on a previous study and definition of *bio-smart materials* [3], this paper opens a scenario of possible cross-disciplinary practices in the framework of design-driven material innovation approach. Four are the main principles of bio-smart intelligence: i. be sustainable: biodegradable and intelligent release; use multi-functional design; ii. be adaptable and responsive: use feedback; self-renewable materials; resilient through variation, redundancy, and decentralization; iii. evolve to survive: integrate the unexpected; iv. to develop: self-organize; alive and growing.

In this paper, we will question how bio-smart materials, responding to the aforementioned principles, are already changing our daily reality by introducing products innovation.

2 Method

In order to make clear the big potentiality of bio-smart materials, we present a review of worldwide case-studies of bio-smart materials applications at different levels of development - from the prototype dimension to market products - in order to demonstrate that their diffusion is underway, especially in some sector of applications characterized by complexity and a higher propensity for the use of biotechnological innovations.

Presenting the following selection of case studies, allows us to clarify the peculiarities of smart materials, clearly distinguishing them from biomaterials and biomimetic materials. While bio-smart materials can be biomaterials, not all these last can be identified with the bio-smart category. Many bio-smart materials are biomimetic, that is, they draw inspiration from principles and logics observed by biologists in living systems, linked to forms of smartness such as the ability to react to external inputs, adapt to disputes or integrate multiple functions into one detail to achieve synergistic performance. Not all biomimetic materials show characters of smartness from Nature, so not all are bio-smart. Similarly, bio-smart materials have a natural origin or integrate biological components such as microorganisms, but it is not correct to declare that a bio-smart material must necessarily be of natural origin since even synthetic materials can have a similar intelligence content. Then, we have chosen to showcase studies in which the materials have a biological-like intelligence, or they yield, the intelligence of nature integrating it with artificial intelligence systems.

The selection is framed in three specific areas: biomedical design, sports design, and design for the environment, particularly interested in the development and application of novel materials for both their sustainability and high performance. The analysis of the following examples will allow us first consideration of their distinctive qualities.

3 Bio-smart Materials and Biomedical Design

The evolution of healthcare intervention model is taking advantage of the progress in biotechnologies and materials, stimulating research in the design of products for home use, and wearable devices. The healthcare sector, therefore, requires a multidisciplinary approach linked to the design know-how. Bio-smart materials are particularly adequate to be applied in the biomedical field, in which they have a high potential for disruptive innovation impacting on people's quality of life. We will present below, some of the most exciting researches in this sector, to demonstrate the great opportunity offered by bio-materials to the improvement of people wellness.

The project *Anura* is a materials and processes system to produce an instant beneficial patch. The designer Giuliana Califano developed it in 2018, during the Master D.RE.A.M. Academy – Design, Research, Advanced Manufacturing, at Città della Scienza di Napoli, in collaboration with the CNR Institute IPCB, and Hybrid Design Lab. The instant soft patches are composed of a matrix of biological hydrogels including active ingredients. Realized through 3D printing techniques patches are biocompatible, biodegradable and bio-active at the interface between body and device, through flows and exchanges of the beneficial principles, thanks to the chemical structure and the transdermal microstructure. They are adaptable, responsive and could be deposed on a specific and delimitated area of the skin with a desired shape like a tattoo, in case of injury, inflammation or abrasion. Tattoo patches can be used for therapeutic applications related to joint trauma. In this case, the transdermal patch includes active pain-relieving and anti-inflammatory ingredients that reduce healing times. At the same time, the part covered by the tattoo, thanks to the thickness and the mechanical characteristics of the material, is also more mechanically protected, if compared to the use of a cream or a simple plaster as it absorbs shocks at the traumatized area.

The biosensor can wirelessly transmit data about the body's electrical activities to a smartphone, like a microsystem developed in 2017 by a joint research team that includes DGIST from the Northwestern University, and scientist from the USA, Korea, China and Singapore [5]. This soft electronics microsystem contains a variety of sensors, connected by a unique network of tiny wire coils, all placed in a soft silicone material to protect its components and to make an easily attached pad to the skin. The field of biosensors is very promising from a huge number of applications from monitoring to implantable sensing.

4 Bio-smart Materials and Sports Design

Sports design is a growing application field of design, engineering, and also biology, driven by the global sports market, benefit the multi-billion dollar sports industry. Sports design actually focus on improving the performance and safety of athletes. It includes the design of sports equipment but also the design of sport clothing that can increase athletic or practitioners performance.

A research group from the University of New South Wales, in Australia, coordinated by Melissa L. Knothe Tate [6] has developed an intelligent biomimetic fabric

useful for clothing, with a particular structure that ensure high elasticity and impact resistance, like bones. The research project inspired by the *periosteal*, a membrane that covers the external surface of most human and animal bones, characterized of a greater ability to withstand strong impacts. In addition to the functional characteristics of the fibers, the weaving methods observed under the microscope and modeled in 3D were also transferred. Starting from these models the researchers have made a further evolution by expanding the weaving patterns similar to those natural ones suitable for processing with an innovative digital jacquard frame. Prototype samples were then made which, subjected to mechanical tests, showed mechanical properties similar to the *periosteum* tissue. Among the potential applications of the fabric there are skiers sportswear and clothing for race car drivers able to protect some parts of the body from strong impacts.

Living materials as microbial cultures integrated with electronic circuits are about to dramatically change the very essence of product design, performing sport and daily life workout activity, monitor biochemical vitals during workout. The *MIT Lab* project for a highly innovative shoes concept in partnership with athletic sportswear company *Puma*, and developed in collaboration with Biorealize, applies the new available technology *Deep Learning Insoles* to the next pair of performing sport shoes to prevents fatigue and improves athletes' performance [7]. Deep Learning Insoles are silicone based disposable inlays containing microbial cultures, able to monitor biochemical vitals that normally change during running or workout. Since the very early stage of dissemination, also in terms of marketing, just as reported by the launching campaign, the role of bacteria was made quite clear and loud stating that "Microbial layer is composed of mini cavities that are filled with bacteria and media that are specialized in sensing different compounds present in sweat". Bacteria then respond to what they sense with specific chemicals causing a pH and a conductivity change in the sole itself, which gets recorded by a network of electrical circuits, connected to microcontrollers positioned in the third layer. Invisible living organisms are about then to dramatically change the workout and endurance routine and such a new step in bridging science and design is being broadly communicated also to potential mass consumers.

5 Bio-smart Materials and Design for the Environment

Design for the environment plays an essential role in innovation based on sustainability, establishing scenarios for the new bio-smart materials and giving value and meaning to these technological advances. In this area, microbiology and biotechnology are showing a great promise in solving a plethora of problems filling the gap of knowledge in the field of environmental sustainability and covering the different technologies available to sustain the environment. One of the actions in which bio-smart materials can prove particularly useful is detection pollutant and substances harmful to human health, such as particles or radiation, present in air and water.

In this direction, a team of researchers from the City College of New York is working. The team is led by the chemical engineer Teresa Bandosz, who has developed smart fabrics capable of adsorbing, degrading and detecting substances that fall within

the most dangerous and developed class of Chemical Warfare Agents (CWAs), the Organophosphate (OP) Nerve Agents. The fabric is made of a natural cotton filaments on which a coating of a heterogeneous porosity nanocomposite (MOFgCNox) is obtained by impregnation obtained from the combination of oxidized graphite carbon nitride (g-C3N4-ox) and Cu-BTC MOF. The fabric gradually changes color when it detects nerve gas and, following a photocatalytic effect, oxidizes it into non-toxic compounds [8]. The photocatalytic oxidation effect is very similar to chemical processes that occur in some plants through photosynthesis and which make plants natural scavengers. Based on this material research, the designer Nikolas Gregory Bentel applied this technology to a T-shirt, an object that can be used every day and is visible from any direction. In 2016, he released *Aerochromic*, a new line of shirts in three designs that change colors according to pollution levels in the air [9]. Chemical salts turn carbon monoxide into carbon dioxide, and that oxidation process transforms the color of the shirts (Fig. 1). AQ1

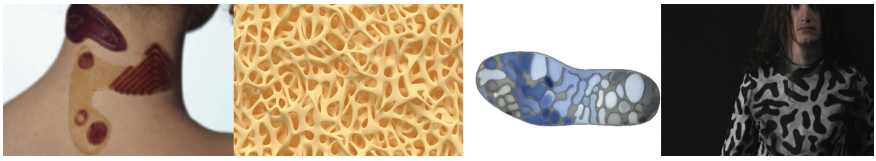

Fig. 1. From right to left: G. Califano, *Anura*, 2018; M.L. Knothe Tate, intelligent biomimetic fabric like bones, 2017; MIT lab and Puma with Biorealize, *Deep Learning Insoles*, 2018; N. G. Bentel, *Aerochromic*, 2016.

6 Conclusion

Which are the main qualities of bio-smart materials while envisioning next design products, and questioning the implications of product design practices, cultures based on material design, and finally the impact on the user perspective?

The principles listed in the introduction were decoded into the material peculiarity used as a criterion for selecting the case study described in the paper. These do not necessarily have to be all in a material to ensure the belonging to the bio-smart materials category. What is important is the presence of an intelligent "behavior" in a biological sense. Some of the peculiarity observed in bio-smart materials are: biological origin (vegetable or animal); biodegradability, reactivity; self-adaptability; ability to process inputs to output variable outputs according to internal or external conditions; renewability; functional redundancy able to respond to unexpected events; self-organization capability; ability to evolve, grow or develop; incorporation of living biological matter.

While the principles propose design logics useful to develop new bio-smart materials (tools for materials designers), the peculiarities could be used as a filter, a sort of checklist, and tools for a critical design study of the bio-smart materials and interpret this in new product qualities. This list emerges not only from the translation of principles but also from a critical case studies analysis that helped to identify qualities that

can be considered tangible, observable, recognizable and correlated to the new user experience.

The *Anura* case study demonstrates how materials with biodegradability and biocompatibility characteristics can be rendered bio-active, therefore implemented with intelligence that makes them capable of interacting with the human body. The case studies of smarts shoes developed by MIT and Puma and the bio-photovoltaic panels by Iaac present promising field of bio-smart materials based on incorporating smartness through embedding living matter such as bacteria, microorganisms, and cells. The DGIST case demonstrates how the material of petrochemical origin, like silicon, can acquire multiple sensitive capacities that place it in the bio-smart category. Material *periosteum* tissue inspired illustrate how the in-depth observation of nature details conducted with advanced instruments, like sophisticated microscopes, allows changing not only the structure but also the intelligent behavior of biological materials.

This contribution shows how the design proposes an important opportunity to associate the intelligence of these materials with applications in products that interpret this intelligence to meet the new needs of contemporary living, therefore through equally intelligent products, which can also refer to the principles on which the adaptability and fitting strategies of biological systems are based.

Novel bio-smart materials and cross-disciplinary research are creating a huge opportunity for design practices and user experiences. Due to their biological-like peculiarities and smartness, bio-smart materials are particularly promising to give right answers to the complex needs of contemporary society, stimulating disruptive innovations.

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