Intelligent design with chromogenic materials

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This paper introduces the new qualitative dimensions that smart materials bring in industrial and product design with the aim of stimulating designers to take a more proactive attitude in the choice and application of these materials. Chromogenic materials enable designers to make visible, by emitting colour signals, what is happening under certain environmental conditions, normally invisible to our eyes. This allows the increase of comfort and safety of the designed environment. The possibility to create kinetic elements and dynamic products that change their expression over time allows design to contribute to a pleasant user-product interaction.

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Introduction

Various reports on key technologies for the near future address the critical role that will be played by smart materials. Smart materials and systems are expected to play a key role in the improvement of quality of life, productivity, economic welfare, and sustainability. The implementation of smart materials is usually intertwined with other critical technologies such as nanotechnology, new manufacturing processes, microelectronics, robotics, and biotechnology [1-3]. Many smart material solutions have already been commercialised successfully. Self-cleaning textiles, self-healing components for construction, smart drug delivery, and smart windows are some examples [2,4].

At the current moment of promising smart material applications, it is necessary to prevent the trivialisation of this radical innovation. Instead, it is necessary to make these materials available for design research such that they are used for symbolic and expressive innovation. To this end, it is necessary to stimulate research on the tools and techniques of design. Therefore, the aim of this paper is to stimulate designers to take a more proactive attitude in the choice, exploration and application of these materials, in an efficient manner and to realise innovations that can contribute to the benefit of the users and not just for commercial exploitation. Within the context of rising sustainable and human-centred design agendas, this paper will demonstrate the role and influence of these new materials and technologies on design, and discuss how they can implement and redefine our objects and spaces to encourage more resilient environments.

This research, conducted jointly by the two authors, is part of a wider research about 'materials that change colour', recently published in its entirety by Springer. It introduces the new qualitative dimensions that smart materials bring in industrial and product design.

Materials that change colour: how they work, how they are applied and their multi-faceted nature

Materials that change colour are scientifically termed *chromogenics* and they are described as "chameleonic" because they change their colour reversibly as a response to changes in environmental condition (such as change of temperature, brightness, etc.) or by induced stimuli. The technical principle, by which these materials change colour, can be explained by an alteration in the equilibrium of electrons caused by the stimulus, like cleavage of the chemical bonds or changes occurring inside the molecule, among electrons, with a consequent modification of optical properties, such as reflectance, absorption, emission, or transmission . When the stimulus ceases, the material returns to its original electronic state, regaining the original optical properties, thus the initial colour or transparency. This process, named *chromism*, implies 'pi' and 'd' electron positions so that the phenomenon is induced by various external stimuli bearing the ability of altering electronic density of the compound or a substance [5,6].

Many natural compounds exhibit chromism and now a number of artificial compounds of specific chromic properties have been synthesised. Chromic materials have this interesting capability of reacting to external stimuli and exhibit modification in colour. These materials are grouped in categories that take their names from the energy source that provokes the modification of optical properties. A general frame of reference of the most important categories and their most common applications is given below.

- *Photochromic* materials change colour when the intensity of incoming light changes. These materials, whose working principle is based on the absorption of light, are usually employed in the context where the limitation of ultraviolet (UV) and infrared (IR) radiation is the principal objective, such as in the case of optical lenses for solar protection or smart windows for adaptive solar control, which represent two of the primary applications. The lenses of photochromic sunglasses get darker with increasing UV intensity and optimise the light that passes through them. When the UV intensity is lower, for example in the interior of a building, smart windows become more transparent and make it easier for the user to see through while allowing more solar radiation to enter the building for balanced internal temperature. Photochromic materials in the form of pigments can be mixed with conventional materials or other common pigments in order to obtain paints and inks with effects that vary from one colour to another. Very fine layers of the ink, deposited on a substrate, for example fabric or paper, or inserted between two polymeric films, change rapidly from an invisible state to an intense colour of black, blue, or purple, and maintain the acquired tonality for approximately thirty seconds.

- *Thermochromic materials* respond to a variation in environmental temperature by changing their colour. Their capacity of acquiring different states of colours at different temperatures and through temperature variations countless times makes them particularly interesting. Thermochromism is a phenomenon common in many chemical systems, both organic and inorganic, including metal oxides that transform into conductors at a specific temperature. A well-known product that makes use of this phenomenon is a ceramic mug, which changes colour when a hot drink is poured inside. The transformation is reversible; thus the colour of the mug goes back to its original one when it cools down to room temperature.
- *Electrochromic materials* are characterised by an optical change upon the application of an electric field. A big market for electrochromic materials today is dynamic antiglare mirrors that detect glare and automatically compensate for it, especially for night time driving safety. Electrochromism is probably the most versatile of all chromogenic technologies because it is the easiest to control and because it can easily be used in combination with different stimuli such as stress or temperature.
- *Mechanochromic/Piezochromic* materials show a change in colour when a mechanical stimulus, i.e. stress, is applied. These materials are currently studied intensely because of their potential use in stress detection, particularly for in situ failure monitoring due to fracture, corrosion, fatigue, or creep.
- *Chemochromic materials* respond to chemical changes in the environment by changing colour. This phenomenon is used, for instance, to develop double pane windows with the ability to change colour upon contact with hydrogen gas in the gap between the two panes. The WO3 coating with the help of a catalyst layer switches from colourless to dark blue and reduces the transmittivity of light. *Halochromic materials* can be considered a subgroup of chemochromic materials that change colour as a response to pH changes in the environment. *Ionochromic* is a term similar to chemochromic, indicating a reaction to the presence of ions in a medium by a colour variation.
- *Solvatochromic materials* display the phenomenon called solvatochromism, typical of some chemical substances that are sensitive to a given solvent (liquid or gas). *Hydrochromic materials* change colour in response to contact with water or in the presence of humidity. The substance that contains chromophore groups is sensitive to the polarity of the solvent, which functions as a constant electrical field and determines the effects on the spectroscopic properties of the substance, hence a change in colour. In the field of chemical research, solvatochromism is used in environmental sensors, in probes with the capacity of determining the presence and the percentage of a solvent, and in molecular electronics for the construction of molecular switches.
- *Biochromic materials* were developed to detect and report the presence of pathogens with a colour shift. Potential applications of biochromic materials include colorimetric detection of pathogens against food poisoning or bioterrorism.

The current interest in smart materials stems from the potential added value they bring to products. New smart materials are continuously being discovered, updated or replaced. If the behaviour of smart materials is clearly understood in relation to the properties and energy fields, such knowledge may be applied to new products and projects.

Materials that change colour are potentially promising for design-driven innovation, thanks to their novel properties. Integrating intelligence, autonomy and multi-functionality, these materials potentially permit the realisation of products with similar functional abilities while saving energy with respect to traditional systems. For example, labels using chromogenic technologies (already available commercially) are much more cost- and energy-efficient compared to other methods that depend on logistics, electronics, and communication technologies for the monitoring of temperature breaches in the cold chain of fresh, chilled, or frozen food, since they don't require sophisticated instrumentation or costly statistical quality control procedures.

Chromogenic materials also are useful instruments for elevating the expressive value of objects and environments. In fact, since colour and transparency are the most immediate among visible aspects of an object or ambient, these materials offer new opportunities for aesthetic demands and new possibilities for the emotional experience of users.

Designing with materials that change colour – case histories

When materials and technologies change, so does the design process. In the field of design, smart materials have already put the rationalist theory in crisis, which claimed that the only decoration of materials should be their natural colour and texture [7], replacing it with the slogan "sincerity and ambiguity" [8]. In fact, smart materials, unlike common ones, have multiple colours and appearances, characterised by autonomy, reversibility, and possible repetition through their sensibility to applied energy fields. These characteristics challenge the adequacy of the tools used till today for design of objects [9] because they add new variables that increase the complexity of the design process. Thus, objects and their material environments change with smart materials, while the mode, in which they are conceptualised, experimented with, designed, and manufactured, also change.

Another critical element for design with smart materials is related to their size in the case of nano-smart materials. Many recently developed smart materials fall in the category of nanoscale materials or nanomaterials. The extremely small size scale poses serious problems in viewing and handling such materials during production and there are some potential health risks that are still under investigation. Nevertheless, there are already several strategies to deal with these problems such as using nanomaterials as a coating on conventional materials, or using them as a second phase in a conventional matrix such as a polymer.

Experimentation with smart materials by designers is a very interesting process in progress. The following section discusses a number of case histories: products, projects, concepts and experiments using smart materials. These case histories have been chosen to explore new design territories, roles and opportunities in different fields of design, including product, interior, fashion and communication design. The case histories, by showing design methods and their results, are useful to understand both the functional and expressive nature of materials that change colour. They also help understand certain ways of experimentation in different fields of design.

Photochromic Sculpture by Tomoko Hashida, Yasuaki Kakehi and Takeshi Naemura, University of Tokyo, 2011

The system that creates a "photochromic sculpture" consists of mainly two parts. The control part, which is basically a projector, provides the ultraviolet (UV) light source when desired. The control part is a hidden system that contains a UV light source at 365 nm and a digital micromirror, which is able to control two-dimensional invisible patterns dynamically. The second part is a three-dimensional display that becomes visible under UV light [10]. A photochromic sculpture is created by several layers of transparent plates coated with photochromic spiropyran granules. Spiropyrans are a group of organic photochromic molecules that have reversible switching capabilities. Their coloration-bleaching cycle can be repeated up to 1000 times [11-12]. When UV radiation hits the stacked layers, coloured pixels appear within seconds (Figure 1). Similarly, when the UV radiation is blocked, the colours gradually fade away until the layers become transparent. One requirement in this system is that granules in upper layers should not block those underneath so that the UV light can effectively hit the desired pixels in the lower layers. The sculpture made of colourful pixels can be dynamically modified by changing the pattern of UV light projected by the control part.

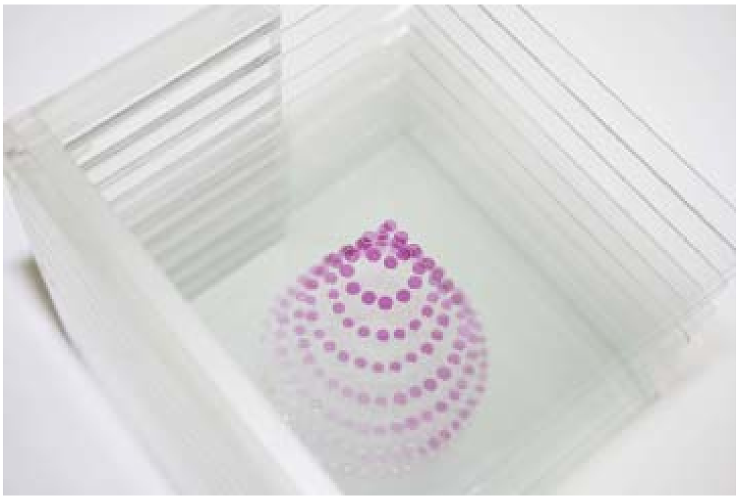

Figure 1: Photochromic sculpture made visible by UV radiation (Courtesy: Tomoko Hashida).

This project highlights the potential of using 2-D photochromic surfaces to represent 3-D objects in a novel way. The underlying idea can be used for art displays and interactive design projects. Furthermore, it could be developed further as cost-efficient and sustainable display technologies for advertisement.

In Heat by Jürgen Mayer, Installation with Thermosensitive Surfaces, HUA Gallery New York, 2005

German architect Jürgen Mayer is involved in a wide range of fields from architecture to art, from design to philosophy. Two of his fields of interest are data security patterns and thermosensitive surfaces [13]. These two themes appear in many of his installations and objects. Mayer describes data security patterns as "multi-leaf forms that courier services use" for data monitoring. In an interview, he explained that he used these patterns together with heat-sensitive print in a guestbook, in one of his exhibitions. Thus, the patterns became visible when heated, for example by the heat of the visitor's hand that wrote a comment, and disappeared once the visitor's hand moved away from the guestbook. To him, these patterns, which he collects, represent "strategic ornamentation" symbolising volatility or evanescence of things [14]. Thermosensitive surfaces appear in most of his installations as metaphors, just like data security patterns.

One example is "In Heat". This is an installation, exhibited at the Henry Urbach Architecture (HUA) Gallery, New York, in 2005. Certain parts of the walls and seats in this installation incorporated thermochromic paint, which reacts to touch or body heat by losing colour (Figure 2). The thermosensitive surfaces represent a three-dimensional painting where "the viewer, creating a temperature shadow by touching, melts into the overall exhibition design" (Fig.3). "In Heat" was inspired by Friedrich Kiesler's exhibition in 1947 presented at the Hugo Gallery in New York. Kiesler, who was also an architect, aimed to remove the boundaries of the wall, the floor, the ceiling, and merge them into a seamless, endless surface and space. He even included the viewer and made her part of the installation. Mayer's work took Kiesler's ideas one step further. With the help of new materials and techniques, he was able to create seamless internal and external surfaces. Furthermore, with the help of thermosensitive surfaces, a fourth dimension can be experienced: time. The visitor, just like it was in Kiesler's Blood Flames exhibition, becomes part of the installation by leaving an imprint, a "temperature shadow" on thermosensitive surfaces. Thus, the viewer "melts into the overall exhibition design" [15-16].


Figure 2 (left): In Heat: general view of the installation. HUA Gallery, New York, 2005. (Photographer: Mauro Restiffe; Courtesy: J. Mayer H. archive, Berlin).

Figure 3 (right): In Heat: detail from walls with thermosensitive paint. (Photographer: Mauro Restiffe; Courtesy J. Mayer H. archive, Berlin).

Fabrication Bag by Hanna Landin & Linda Worbin, 2005

Linda Worbin, researcher in Textiles and Interaction Design at the Swedish School of Textiles has been exploring smart materials for some time to create interactive textile. The Fabrication Bag may be defined as an investigation on a pattern of static forms that change colour, or an investigation on a dynamic textile pattern of static form, by digital information (mobile phone data). This project applies thermochromic ink (heat sensitive pigment - variotherm 27°C) in grey colour, general textile pigment (five different colours: pink, light blue, light green, yellow, orange) on textiles in cotton combined with conductive yarn on the backside to control the colour change of the thermochromic print. The smart system is completed by a 14 V battery for power supply, a program basic X and a microcontroller BX24. The Fabrication Bag has been conceptualised as an accessory for mobile phones that replaces the sound and vibration signals with changing colours in textile patterns on the outside and inside of a bag. Initially the fabric of the bag is white with grey dots in different nuances, and when the phone receives calls or text messages the coloured dots slowly change from dull to colourful (Figure 4).

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Figure 4: Fabrication Bag by Hanna Landin & Linda Worbin, 2005.

The fabric of the bag contains multiple layers of thermochromic ink printed in dots that are activated by heat patches positioned underneath. Nine heat elements are mounted inside the bag and when a heat element is turned on (individually or combined in group), the surface print changes colour. When an incoming call is detected, different areas of the heat patches are activated in order to cause localised heating of the thermochromic print. The idea behind the programming was to connect different kinds of data, calls etc. with different visual design expressions. Depending on the level of code abstraction the bag will be more or less easy to 'read' [17].

The relation between data and visual expression is able to introduce new design possibilities and variables. The data contributes to the visual expression of dynamic patterns, varying from time to time. It can be done in real time, or recorded in advance or with a delay. The project also suggests and exemplifies new behaviors of textile patterns, as well as interaction with mobile phones.

Pollution monitoring fashion by Sue Ngo and Nien Lan, New York, 2011

Sue Ngo e Nien Lan, New York City based interaction designer and programmer, respectively, designed and prototyped a series of pollution monitoring sweatshirts during their Master's Degree in Interactive Telecommunications Program at New York University. Drawing inspiration from the hypercolour T-shirts of the 80s and 90s, the "Warning Signs" line was born. These garments are capable of emitting visible signals of air pollution, usually in the form of invisible organic volatiles.

Among the prototypes created by the two young designers, there are white sweatshirts with a pink heart or a set of lungs made of thermochromic fabric. The shirts emit a warning sign when in contact with high levels of carbon monoxide (CO): the veins on the lungs or heart, initially invisible, subtly change colour from a healthy pink to a slightly worrying blue-grey, as if to indicate that the CO is penetrating the human body and reaching the organs (Figure 5) [18].

The transformation of the sweatshirt is made possible by a smart system hidden between the two layers of textile in the front of the T-shirt. This smart system is composed of a MQ-7 gas sensor, thermochromic textile, a resistive wire for heating, connector wires, and a powerful micro-controller. The MQ-7 sensor reveals the concentration of CO in the air nearby, thanks to a semiconductor layer of gas sensor made of tin dioxide (SnO_2). This sensor detects the presence of gas in the range of 20 to 2000 ppm (parts per million), with very rapid response times, and provides an output as resistivity directly proportional to the gas concentration.

Figure 5: Pollution monitoring fashion by Sue Ngo and Nien Lan, New York, 2011.

Piezochromic Materials

Piezochromic materials display a change in colour or opacity upon application (or variation) of stress. There are various types of stress, pressure (compression) and tension being the two simplest ones. Piezochromic materials can respond to compressive, tensile, or more complex forms of stress. Another term used instead of piezochromic is *mechanochromic*.

Although they offer many interesting application possibilities, piezochromic materials have not received much attention so far, partly because the related technology is not mature yet. Even patents related to piezochromic materials are relatively small in number. To prove this point, we can compare the number of patent abstracts citing the word “piezochromic” or “mechanochromic”. The number of such patents found in the US patent database [19] is only 8. On the other hand, there are 418 patents citing the term “thermochromic” and 974 patents citing the term “photochromic”.

Certain polymers and inorganic materials have been shown to exhibit piezochromism. Cyano oligo (p-phenylene vinylenes) – thermoplastic polyurethane blends exhibited piezochromism and mechanochromic luminescence [20]. Photoisomerisation of azobenzene polymers is a long-known phenomenon. The trans isomer can be converted to the cis isomer under ultraviolet light and back to the trans form under blue light. Since the trans isomer is thermodynamically favored, cis to trans transformation can also occur thermally [21]. The unstable cis form can be chemically trapped to cause the cis to trans transformation later, under a mechanical force. Some progress has been achieved with this idea, but the practical use is currently limited due to the short lifetime of cis-azobenzene (~6h) [20]. Recently Seeboth *et al.* [22] developed a polymeric mixture that involves cholesteryl derivatives. This material is able to respond to very low levels of pressure (several bars) and switch reversibly from red to green colour. The ability to obtain a piezochromic effect at several bars is an important achievement for practical and economically feasible applications.

Chen *et al.* [23] used computational analysis to develop new piezochromic compounds using anthraquinone imide (AQI) derivatives with electron donating substituents. This effort resulted in three piezochromic polymers with different colour transformations, i.e. orange to deep red, dark purple to black, and green-yellow to red. A pressure of 0.9 GPa (9 kbar) was applied to obtain the piezochromic transformation. The colour change was irreversible in these polymers. Piezochromic luminescence was also observed in the piezochromic compounds that were developed.

Some inorganic materials are also known to exhibit piezochromism, including LiF and NaCl single crystals, $CuMoO_4$, and palladium complexes. The α to γ phase transformation of $CuMoO_4$ requires a pressure of 2.5 kbar, reversibly modifying its colour from green to brownish red [24]. Ni (II), Pd (II), and Pt (II) dimethylglyoxime complexes change colour under pressures of 63-150 kbar [25]. Another inorganic material that exhibits piezochromism is samarium monosulfide (SmS). SmS undergoes a semiconductor to metal phase transformation under a pressure of 0.65 MPa (6.5 bar), along with a piezochromic response [26].

Applications of piezochromic materials discussed in patents

A field of application that has great potential in different industries is stress sensing and failure detection. One of the major driving forces for research in this field is the aerospace industry that spends great sums of money for maintenance and inspection of air and space vehicles. Different solutions have been proposed in patents where piezochromic materials signal an abnormal level of stress, indicating that there is corrosion, overloading, or fracture initiation that has already developed under the surface where the piezochromic material was applied. One approach involves microcapsules or hollow fibers that contain a coloured substance. Under high loads, the hollow fibers or microcapsules rupture and the coloured substance is exposed, signaling a critical stress level. A homogeneous distribution of these fibers or microcapsules is essential. Two part systems are also envisioned where a dye and an activator mix and react to form a coloured substance when overload or damage occurs. Smart coatings involving piezochromic polymers such as diacetylene segmented copolymer or spiropyran have also been studied for the same application [27].

Two patents were granted to Unilever regarding a smart toothbrush. The toothbrush body incorporates a piezochromic liquid crystal cholesterol ester whereby the user is informed whether correct or excessive force is being applied during brushing. The main intention of this product is to prevent damage caused to teeth and gums due to brushing too hard [28-29]. Another patent employs piezochromic materials on industrial roll covers [30]. Such rolls are used, for example, in papermaking, printing, and coating industries. Uneven or extreme pressures can damage the rolls and the use of a piezochromic material is proposed as an alternative to electronic sensors. Electronic sensors typically require a power source, some communication equipment, data processing, and maintenance. On the other hand, piezochromic coatings would not require any of these. One disadvantage of this application might be the requirement of visibility: the whole roll surfaces must be visible during operation, which may not be possible for all such systems.

New Concepts with Piezochromic Materials

There are a vast number of opportunities and applications to be explored with smart materials in general, and piezochromic materials in particular. We approached the subject from the industrial design perspective to scratch the surface of opportunities and explore new ideas for applications. A simple mind map [31] was the only tool used to generate these ideas.

Piezochromic paint for tennis, volleyball, basketball, and similar courts

If you ever acted as a referee for a tennis match, you would probably remember how difficult it is to rule whether a ball served at 180 km/h that hits close to the service line, or side-line, is in or out. This problem was initially solved by electronic sensors. An electronic line judge was first used in a tennis tournament in 1977 [32]. Because of the high cost and occasional breakdowns, other options have been also tried. In 2006, United States Tennis Association (USTA) started to use instant replay technology along with a player challenge system, which became popular in grand slam tournaments [33]. Players can challenge a line call and an official replay is used to see where the ball dropped exactly. Although this technology is more dependable than electronic line judges, it is costly and it may lead to interruptions during the game. Our solution to this problem is relatively simple. The court is painted with a paint, which contains piezochromic pigments with the ability to sense the force applied by the ball and reversibly change colour from its normal colour (green or blue) to a contrasting colour such as red or orange (Figure 6). The mark left by the ball should fade away slow enough for the referee and players to decide whether it was in or out, for example 60 seconds. It is sufficient to use the piezochromic paint for the lines and near them, since the indecision only occurs in these regions and also because footprints due to the piezochromic effect all over the court would cause confusion. The same type of paint could be used for other courts such as squash courts, volleyball courts, and basketball courts.

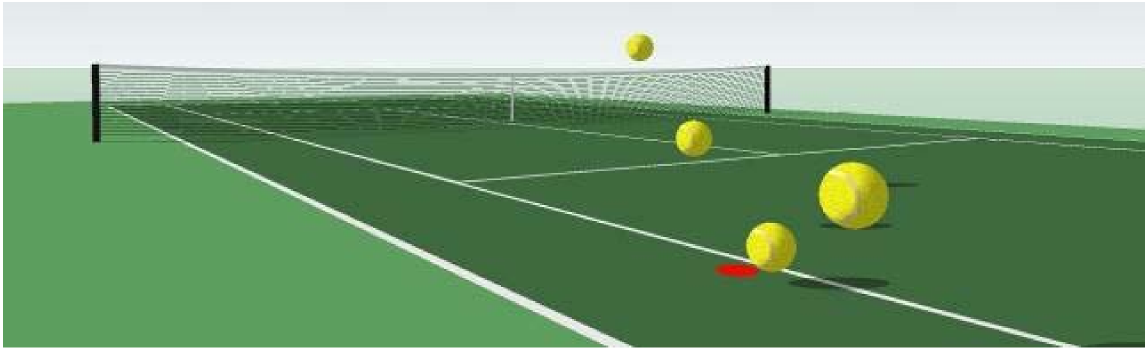

Figure 6: Schematic depiction of temporary mark left by a tennis ball after hitting just next to the line.

Piezochromic bathroom and kitchen scales

There are many types of scales in the market today, used for different weighing purposes. Two types of scales used at homes are bathroom and kitchen scales. A common and elegant design used for bathroom scales involves a glass platform and a digital display. Unlike this electronic scale, our piezochromic scale concept does not need any batteries, mechanical or electronic parts. The product consists of a glass plate, under which there is a graphic design printed with piezochromic ink. This image will show the corresponding weight of the person with the help of colours, shapes, or numbers. The piezochromic image can be printed on a polymeric backing plate or it can be applied as a separate film. A similar approach can be used for a kitchen scale. However, in this case, a container is needed to contain the sugar, flour, or milk. Thus, a special container with a small base may be designed to provide more visibility for the piezochromic illustrations that must be seen by the user.

Piezochromic bathroom and kitchen scales

The use of a piezochromic labels or surfaces indicating overload conditions could be a useful application under different circumstances. Overloading of packaged items could be a problem especially with liquid, gas, or fragile solid contents. Common situations where overload might occur include stacking of many boxes in warehouses or supermarkets, which might cause damage to the lowermost box, and overloading of an individual box which, when lifted, may cause breakage or tearing of a box, resulting in injury to the person who lifts it. Piezochromic labels or surfaces can be used to indicate an overload condition in the box or package.

A related application would be tamper-evident closures. A piezochromic film can be used in the closure area of a food or medicine container. Tampering or accidental damage to the closure area would be made visible through the colour change of the film. A similar idea was mentioned specifically for pharmaceutical bottles and jars [34].

Certain conditions in canned foods result in slight or obvious swelling or bulging of the container. For example, enzymatic action, non-enzymatic browning, and microbial growth cause carbon dioxide evolution and spoilage of the ingredients [35]. A piezochromic coating on the can could be designed and developed to warn the consumer about the possible spoilage of the canned ingredients.

Piezochromic materials can also indicate a decrease of pressure if the packaging and the piezochromic substance is designed accordingly. This effect could be used in pressurised tennis ball cans or other pressurised packaging, such as plastic soft drink bottles. High quality tennis balls are kept under ~2 atm pressure so that the balls maintain their pressure while they are stored. A visible label on the packaging of transparent plastic containers or bottles could be used to detect a fall in pressure that might be due to defective package or because it has been opened, and thus to warn the customer about the condition of the product.

Piezochromic game

This is a mystery game intended for children, age 8 to 13. The game involves several cube blocks made of an elastomeric material such as synthetic rubber (polyisoprene or silicone rubber). Alternatively, wooden or plastic cubes can be covered with an elastomeric material. Each face of each block is printed with a piezochromic image. When players rub the two blocks against each other, a symbol appears temporarily on the faces that are being rubbed together, because of the pressure. One set of the blocks is the key to the symbols. The players try to find out what types of symbols are written on the blocks and what they mean. When they put together all the symbols on all sides of one or more blocks, and when they find out to which letters or numbers they correspond to, they solve the mystery. This game could be played by one or two players, or by two or more teams.

Conclusions

Like all technological innovations, chromogenic materials are creative stimulants; they implicate investigation with regard to characteristics, technical behavior, techniques of application and aesthetic possibilities. The design process is fuelled by a sense of curiosity and a desire to understand how far certain materials can be pushed. This can lead to small or large inventions, product innovations, new poetics of design, original insight, and interesting interpretations of everyday life.

Unlike industrial patents, design case histories on chromogenic materials, by showing design methods and their results, are useful to understand the true functional-expressive nature of these materials. Therefore they show the role that these new materials and technologies can play, and their contribution to different areas of product design.

Chromogenic materials have opened new technological trajectories for the improvement of microclimatics and interior comfort of buildings, which reconcile energy savings with increased thermal and luminous performance. At the same time, they have contributed to the evolution of the architectonic languages in solutions equipped with dynamic qualities, characterised by reactivity and variability, opening up new opportunities of interaction with users.

In product design, they improve the interaction between product and user, making the communicative interchange intelligent. Through the modification of colour, it is possible to send messages and information to the users, communicating what is happening inside the product or how to use it. Chromogenic materials open new modalities to augment the reality of interactions, making it more continuous, persistent, and coherent to the feedback [36].

The case histories shown in this paper attempt to develop a methodological approach for the use of these materials and technologies, and a vision of feasible and sustainable design in the frame of current problems. Sculptures sensitive to light, thermochromic surfaces and environments, objects which display dynamic patterns, e.g. to tell us that tea is ready, garments which signal the danger of air pollution, textiles which visualise a phone call; these design projects shed light on research between design poetics and new use of technologies.

The applications of smart materials are able to safeguard energy and material resources, to enrich product function, aesthetics, safety, and their communicative potential, and to contribute to a pleasurable user-product interaction. It would be possible to talk about "intelligent design" only when these potentials are put into action by design. Smart materials provide new sources and perspectives for intelligent design. They are expected to be one of the key contributors to revolutionary products and systems of the near future.

Credits

The paper was written by the two authors on the basis of a research conducted jointly, by mutual agreement on the issues and a broad comparison. Sections 1, 2 and 5 were written by the two authors jointly. Section 3 was written by Marinella Ferrara and section 4 was written by Murat Bengisu.

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