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SOCIETY 5.0: CONSTRUCTING WITH SMART MATERIALS

Emre ALP[1,a,*]

[1]Metallurgy and Materials Engineering, Faculty of Engineering, Architecture and Design, Bartin University, Bartin, Türkiye
[a]emrealp@bartin.edu.tr, ORCID: 0000-0002-3857-0880

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ABSTRACT

Human-centred, resilient, and sustainable creations will be at the heart of the next society. Some perspectives such as “Extension of healthy lifespan”, “FinTech”, “Creation of next-generation supply chains”, “Building of pleasant infrastructure”, and “Realization of the mobility revolution” are proposed for the future society. The smart society concept requires the acquisition of enormous real-time information gathering from large networks of smart devices. So, the proposed future society needs some technological infrastructure such as Cyber-Physical Systems (CPS), Artificial Intelligence (AI), Big Data and Cloud, and the Internet of Things (IoT). Creating “smart materials”, that detect, process, and respond to external stimulations with decentralized resources is mandatory to reach the vision of future society. In this review, a group of smart materials that can be used to create the society planned have been briefly mentioned.

Keywords: Society 5.0, Super Smart Society, Smart Industry, Smart Materials, Smart Cities, Smart Devices

TOPLUM 5.0: AKILLI MALZEMELER İLE İNŞA ETMEK

ÖZET

İnsan merkezli, dayanıklı ve sürdürülebilir olgular gelecekteki toplum yapısının kalbinde yer alacaktır. Geleceğin toplumu için “Sağlıklı yaşam süresinin uzatılması”, “Keyifli altyapının inşası”, “Mobilite devriminin gerçekleştirilmesi”, “FinTech” ve “Yeni nesil tedarik zincirlerinin oluşturulması” gibi bazı perspektifler önerilmektedir. Akıllı toplum konsepti, büyük akıllı cihaz ağlarından gerçek zamanlı olarak toplanan muazzam miktarda verinin toplanmasını gerektirir. Bu nedenle, önerilen gelecek toplumunun Yapay Zeka (AI), Nesnelerin İnterneti (IoT), Büyük Veri ve Bulut ve Siber-Fiziksel Sistemler (CPS) gibi bazı teknolojik altyapılara ihtiyacı vardır. Bu vizyonu ulaşmak için, merkezi olmayan kaynaklarla çevresel uyaranları algılayabilen, işleyebilen ve bunlara yanıt verebilen "akıllı malzemeler"

*** Corresponding Author (Sorumlu Yazar)**
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geliştirmeye ihtiyaç vardır. Bu derlemede, planlanan toplumu oluşturmak için kullanılabilecek bir grup akıllı malzemeden kısaca bahsedilmiştir.

Anahtar Kelimeler: Toplum 5.0, Süper Akıllı Toplum, Akıllı Endüstri, Akıllı Cihazlar, Akıllı Şehirler, Akıllı Malzemeler

1. INTRODUCTION

Because of the effects of the Industrial Revolution (also known as the First Industrial Revolution), technological improvements in the industry field caused significant societal changes. The first Industrial Revolution (Industry 1.0) (i.e., the 1780s) started with generating mechanical power through steam and fossil fuels. , electrical energy-based mass production could be executed during the second revolution (Industry 2.0) in the 1870s. In the 1970s, incorporating automation into mass production was launched using electronics and Information Technologies (IT) throughout the third Industrial Revolution (Industry 3.0). [1]. Artificial Intelligence (AI), Cloud Computing, Big Data, Cyber-Physical Systems (CPS), and the Internet of Things (IoT) work as interface operators between the physical worlds and the virtual worlds during the fourth Industrial Revolution (Industry 4.0) [2].

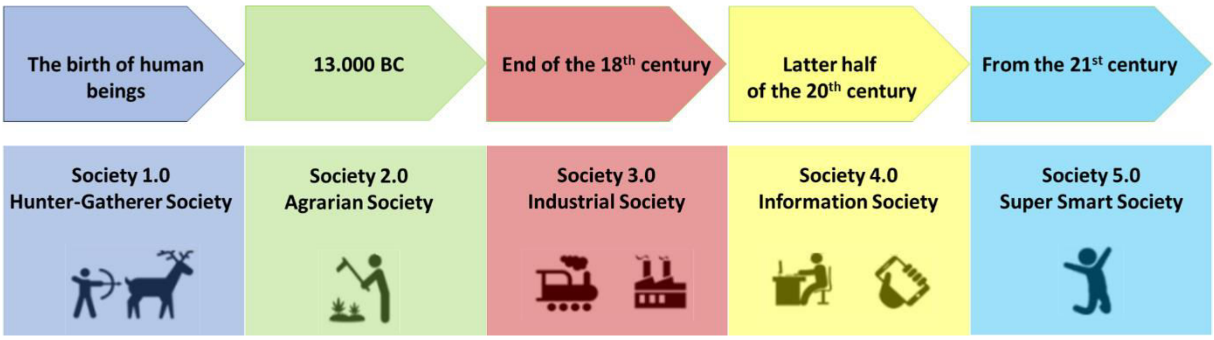

Figure 1: A chronological view of the differentiation concept of society evolutions.

When we look at human history, it is observed that there have been different periods with distinct differences. We can describe them as different periods of society. Society 1.0 is described as groups of hunter-gatherers. Society 2.0 formed agriculture and settled communities based on increasing organization, state-building, and agricultural cultivation. Society 3.0 is a society that supports industrialization accompanied simultaneously by the Industrial Revolution, making it possible to produce mass production. The term Society 4.0 describes an information society that executes significant worth by linking intangible assets as information networks. At the end of these transformations, nowadays, Society 5.0 describes an information society that aims for a human-centred community (schematically illustrated in Figure 1) [3].

Europeans have actually implemented the Industry 4.0 strategy since long ago, but the applications' notions only focus on manufacturing. In addition to that, the so-called Society 5.0, also covers social arrangement/formation and the surrounding environment [4].

Prioritizing being in harmony with the ecosystem and natural life, Society 5.0 aims to execute this by using digital transformation to overcome difficulties of social actualities in circular economic growth. The UN Sustainable Development Goals (SDGs) [5] s able to be accomplished with the help of the conception of Social 5.0 for future societies. The dedicated concept of "Society 5.0 for SDGs" is briefly introduced in Figure 2. As seen in the illustrated figure, Society 5.0 embraces the entire concepts of the SDGs.

Figure 2: Schematic illustration of relationships between Society 5.0 and Sustainable Development Goals.

The concept of Society 5.0 is defined as "a human-centred society that balances economic advancement with the resolution of social problems through a system that highly integrates cyberspace and physical space" [6]. Society 5.0 also handles social events, such as a healthy and good life, smart and sustainable agriculture approaches, prosperity, access to clean water and food, and gender equality. Because of the concept of sustainable energy policy, safe and smart waste management, economic growth, efficient production, and sustainable infrastructure systems, there is a strict connection between Industry 4.0 and SDGs [7]. The sustainable infrastructures connect with SDGs regarding smart agriculture and food, e-learning systems, empowering women and remote sensing and oceanographic data [8]. It is thought that the efficient location identification system according to real-time position for the drivers will reduce greenhouse gas emissions by constructing efficient infrastructures (such as; roads, bridges, and tunnels) and so, building smart cities [9]. Japan tries to lessen the influence of natural disasters through the establishment of effective control systems. It is aimed to execute smart food and agriculture applications for a sustainable society through Society 5.0 [10, 11]. Smart energy-saving lighting practices are used along with solar energy strategies at residences. [12].

2. LITERATURE REVIEW

The emergence of new materials and corresponding devices will be critical in a coming society called Society 5.0. Smart materials are reactive materials that have the ability to alter their own features in response to some changes in external environmental conditions. Encyclopedia of Chemical Technology Materials ‘smart materials and structures are those objects that sense environmental events, process from sensory information, and then act on the environment’ [13]. They have become the basis for many new technological enhancements due to their stimuli-responsiveness behaviour and autonomous characteristics. Smart materials have remarkable features that can be altered by outer environmental conditions, such as magnetic and electric fields, temperature, pH, moisture and stress [14]. Smart materials are described as advanced and/or intelligent materials that react smartly to external conditions. Although the term “smart material” was first used in the 1980s; it is known that many materials realizing smart behaviour have been available more than 30 years ago. [15]. Smart materials and smart systems, in a manner of a larger view, comprise systems with sensors and actuators that are either implanted in or connected to the system to create a complementary component. The system and cooperated elements of the system constitute a structure that will perform in an anticipated mode and eventually serve in a way that mimics a biological system, typically like a living organism [16, 17]. In that manner, the future engineering systems' capability is based on the ability to combine and perform smart materials in terms of sensors, actuators, and control systems. If speaking with a view of Society 5.0, new materials should ensure reliability and good quality and be as green and smart. The ability of smart materials to adjust themselves to the external environment and the various system conditions is essential for these kinds of systems. Besides, the possibility of using control signals to alter the materials' properties leads to the possibility of designing innovative systems in diverse applications [18].

Smart materials are generally categorized as active and passive according to behaviour responding to external stimuli. Defined as passive, Smart materials can transfer energy. For instance, optical fibres are capable of transferring electromagnetic waves. Defined as active smart materials, they are also divided into two subcategories: when exposed to external stimuli, it is a type that cannot alter its features and another whose ability to convert one form of energy to another. Respectively, one belonging to kind is photochromic glasses, which are due to change only their colour when placed under light, an example of another is given as piezoelectric materials that can generate an electric charge under applied strain [19].

The word "smart" in defining these material groups is underlying because they act as actuator and sensor. This material group has some impressive properties differentiating it from conventional materials. Such properties are given in the following [19, 20, 21]:

transiency: having the ability to respond to diversified types of stimulation.

immediacy: having the ability to respond to external stimuli immediately.

self-actuation: aving the ability derived from internal to change their properties, such as form and appearance.

selectivity: the reaction is expected and distinguished

directness: both reaction and action occur in the exact location.

self-diagnostic: having the ability to detect any changes in itself.

self-healing: having the ability to heal itself.

Depending on their act response to environmental stimulations, they are classified into various types, such as piezoelectric materials responding to electricity and pressure, electrorheological fluids reacting with an electric field, shape memory alloys responding to thermal and pressure, magnetostrictive materials responding to a magnetic field, chromic materials reacting with varied types of stimulants (such as; temperature, light, field, loading, etc.), magnetorheological fluids reacting with a magnetic field, pH-sensitive materials responding to a pH variation [22]. They have been shortly explained sections below.

2.1. Types of Smart Materials

2.1.1. Piezoelectric Materials

The piezoelectric effect was first discovered by Pierre and Jacques Curie in 1880 [23]. Piezoelectric materials used as actuators are generally designated piezoelectric ceramics, unconventional materials with noncentrosymmetric structure. They have two unusual properties that make them unique, named the converse piezoelectric effect and the direct piezoelectric effect. [24]. While piezoelectric materials with the direct piezoelectric effect can produce an electric charge during mechanical deformation, piezoelectric materials with the inverse piezoelectric effect can create changes in the strain under the applied electric field. The piezoelectric materials with the direct piezoelectric effect are principally utilised in sensors, while piezoelectric materials with the inverse piezoelectric effect are typically employed in actuators [25]. They have been used in various applications. The micro-positioning accuracy, tyre pressure sensors, seat belt buzzers, airbag sensor, power generation in autos, knock sensors, high-precision autofocusing for cameras and piezo fuel injectors are one of the major employers of piezoelectric material applications [26, 27, 28, 29,30 , 31].

2.1.2. Shape Memory Alloys (SMA)

Shape memory alloy (SMA) or “smart alloy” was first discovered by Arne Ölander in 1932 [32]. After that, the term “shape memory” was first used for polymeric dental materials by Vernon in 1941 [33]. These material groups have the ability to change in form with temperature variations. The characteristic that makes them distinct from others is that they can remember their starting form when exposed to related stimulants. This phenomenon is called the shape memory effect. These shape changes occur during the transformation of martensite and austenite each other, phases that are stable at different temperatures [34]. The implementation of these group materials is relatively easy. The material is deformed with an applied force. Then, it will return to its initial form when heated above a specific temperature, either by heating internally or externally, or a magnetic field for called-magnetic shape memory alloys [35]. The significance of these material groups was realised in 1962 after

William Buehler and Frederick Wang demonstrated the shape-memory effect of nickel-titanium alloy [36, 37]. Since then, both interest and demand for related materials for engineering applications have been growing in countless commercial areas, such as and micro-electromechanical systems (MEMS), biomedical, aerospace, composite, mini actuators, automotive, damping and robotics [38, 39, 40, 41, 42, 43].

2.1.3. Magnetostrictive Materials

Magnetostriction is a phenomenon in which material is reversibly deformed through a magnetic field [44]. Magnetostriction was first discovered in 1842 by Joule, so it was also named the "Joule effect" [45]. He observed that a material sample altered the length under a magnetic field. When it came to 1864, Villari uncovered the reverse effect of magnetostriction, called the "Villari effect". It was observed that the change in the length/volume of a magnetic material can induce the change of magnetization [46]. Magnetostrictive materials have the ability to change their sizes under a magnetic field and return their actual sizes after removing the magnetic field [47]. Magnetostriction is a reversible material characteristic. When removing the magnetic field, the magnetostrictive material form starts back to its initial dimension at the beginning. Magnetostrictive materials can be classified into positive and negative magnetostrictive. These are the expansion, called positive magnetostriction, or contraction, called negative magnetostriction, in relation to a longitudinal magnetic field. They might be contracted or relaxed by altering the magnetic field [48]. Magnetostrictive materials are used and continuously investigated in numerous fields, such as reaction mass actuators, electro-hydraulic actuator, remote microactuator, magnetic field sensors, biodegradable mechanically active implants, sonar transducers, wireless linear micro-motor, torque sensors, wireless rotational motor, energy harvesters and drug delivery [49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59].

2.1.4. Electrostrictive Materials

Many recent innovations in electroceramics have employed the nonlinearities of material characteristics with factors such as electric field, temperature, and frequency. The nonlinear dielectric behaviours have opened new areas in communication and electronics [60]. The electrostrictive material group is capable of changing its size when exposed to electric fields. In the materials with electrostrictive characteristics under the electric field, the ions are removed from their actual positions, and correspondingly, the dimensions in the material are changed. The electrostrictive effect exists in every material and is not limited by symmetry. Therefore, the electrostrictive effect expresses the nonlinear characteristic of the strain under the applied electric field [61]. Piezoelectric materials also exhibit this kind of characteristic; however, there are some significant differences between them and some limitations. Although piezoelectric materials are the dominant transduction material in ultrasonic and sonar implementations, they have some limitations, such as distortion resulting from ferroelectric nonlinearities, mechanical limits based on fractures, and thermal limits because of the consequence of energy dissipation. For these reasons, there is a need for the development of electrostrictive materials as a new material group in transducers [62]. Typical applications belonging to electrostrictive materials are in deformable mirrors for large ground-based and space telescopes, drivers for relays and switches, micropositioners for robots, , a steerable guide wire (catheter), laser communication systems and automatic focusing for movie cameras [63, 64].

2.1.5. Magnetorheological Fluids

Magnetorheological (MR) fluids are smart materials which exhibit a reversible and rapid transition from a liquid to a nearly solid state under magnetic fields [65]. Magnetorheological (MR) fluids are an example of field-controllable materials. Their rheological behaviours are altered through a magnetic field applied [66]. The magnetorheological (MR) phenomenon is generally attributed to the field-induced magnetization of the suspended particles. The suspension has a low viscosity in the absence of magnetic fields. In the presence of a magnetic field applied, the particles magnetize and therefore, attract one another along the field lines, creating anisometric assemblage to the full extent of the system. The field-dependent mechanical strength of magnetorheological fluids depends on various qualities such as volume fraction, composition, and particle size [67]. The viscous features of these kinds of materials can be modified by changing the magnetic field. The mechanical strength alters for field-dependent MR fluids depending on particle size, volume fraction and composition. Also, the viscous characteristic of magnetorheological fluids can be adjusted by changing the applied magnetic field [68]. The essential parameters affecting the behaviour of magnetorheological fluids are intensity and type of magnetic field, volume ratio of dispersed particles, viscosity of fluid, morphological characteristic of dispersed particles, geometry of stream, density of continuous fluid and operational condition [69]. The exceptional characteristic of magnetorheological fluids makes them outstanding candidates for applications such as active control of vibrations or torque transmission in mechanical systems. Typical applications belonging to magnetorheological materials are control valves, shock absorbers, seismic vibration dampers, brakes and artificial joints [70, 71, 72, 73]. It is used to control thermal energy transfer and for sound propagation, biomedical applications and chemical sensing applications. [74, 75, 76, 77].

2.1.6. Electrorheological Fluids

The electrorheological effect was discovered by Winslow seventy-five years ago [78]. The electrorheological effect continued to remain a curiosity until the 1980s, when advances in experimental and theoretical were eventualized [79]. Electrorheological fluids (ERFs) are colloids that are capable of altering their viscosity or solidification behaviour against an electric field applied. That rheological behaviour is reversible. The response time to changing electric fields can be as short as a few milliseconds [80]. Each solid particle would be polarized with a sufficient dipole moment under an electrostatic field because of the dielectric constant dissimilarities between the solid particles and the liquid. The induced dipole-dipole interaction indicates that the particles tend to create columns along the field. The generation of columns is why electrorheological fluid in the high-field state exhibits solid-like behaviour in the direction perpendicular to the external electric field [81, 82]. There are diverse industrial applications of electrorheological fluids in actively tuned hydraulic valves, vibration absorbers, vibration dampers, vibration isolators, shock absorbers, clutches, shock absorbers, and clutches. It is benefited from these material groups for structure base isolation and electroactive actuators because they can overwhelm defects caused by particle aggregation and sedimentation [83, 84, 85].

2.1.7. Chromic Materials

These smart material groups can be classified into subgroups according to which environmental conditions it responds to. The stimuli-responsive chromic material group has attracted significant attention in implementing switches, sensors, and displays. Generally, they are named photochromics, solvatochromics, mechanochromics, magnetochromics, electrochromics, hydrochromics, biochromics and thermochromics.

a) Mechanochromism, is related to alterations in absorption and/or fluorescent colours that happen in reply to changes in mechanical forces such as extension and compression. The photophysical properties concerning materials that undergo mechanochromism are based on the molecular structures of materials and the modes of assembly [86]. Molecules or material systems that change their optical properties by applying a mechanical stimulus are called mechanochromic materials. These changes are often observed as a changes in emission wavelengths or transmitted wavelengths. The changes can also be observed in lifetime and emission intensity. The phenomena of mechanochromism originated from one or more interactions in which light interacts with the molecular systems from a single molecule to supramolecular length scales [87].

b) Thermochromism is associated with a material having the ability to change its colour due to shifts in the ground-state structure at diverse temperatures [88]. The temperature as a stimulus can change the crystal structures of thermochromic material, alter the three-dimensional position of atoms, or rearrange atoms in molecules without altering chemical compounds in themselves [21]. Thermochromic materials are described as changes in colour when temperature changes take place at defined temperatures [89]. For instance, thermochromic devices can be used as a valuable solution to lessen the solar radiation entering buildings. In addition, the buildings generate internal heat derived from occupants and internal loads such as lighting and other devices used. Thermochromic materials can be a helpful solution to adjust heat from solar irradiation [90].

c) Photochromism, is the reversible photo-induced transformation between two distinct forms of a chemical species -isomers- (whose absorption spectrum is distinguishably different) under the impact of photons [91]. The physical properties, such as electron conductivity, absorption and emission characteristics, electrochemical properties, magnetic properties, and refractive index, may be adjusted by light in reversible photoisomerization [92]. By controlling the light intensity, it is possible to control the photokinetics of the colour-switching reaction. Thus, the photokinetics of the colour-switching serves information technologies such as recording, erasing, and rewriting [93]. Photochromism has attracted significant attention after the improvements of photochromic glasses. Sunglasses that protect human eyes from UV light or intense sunshine can be an excellent example of applying photochromic material [94].

d) Electrochromism, is a phenomenon associated with materials that can be reversibly varied between the transparent and distinct colours through an electrochemical redox (oxidation/reduction) reaction [95]. The reversible bond-coupled electron transfer (BCET) is an essential element for electrochromism [96]. The electrochromism phenomenon first appeared in the literature in the early 1960s [97]. Since then, electrochromism has been revealed in various organic and inorganic materials and has been employed to devise contrast-based displays and various other technologies.

The electrochromic material is essentially categorised into three groups [98, 99, 100]. In so-called Type I, the colouring species stay in solution at all times during electrochromic usage; in so-called Type II, the reactants are in solution, but the coloured products form a solid on the surface of the electrode; all materials are solid form in Type III. Type-I is used for anti-dazzle or rear-view mirrors in cars; Type-II is used for more oversized mirrors in commercial vehicles; and Type-III is used for smart windows [101]. Electrochromic materials are being developed for using smart windows, emerging energy-saving advances in buildings. Electrochromic coatings for controlling light transmission are significant in applications such as switchable mirrors for buildings and automobiles [102].

e) Magnetochromicsm is a phenomenon associated with changing colour when applying a magnetic field. The magneto-optical property in the presence of complex mixed metal compounds is designated magnetochromic when it appears in the visible region of the spectrum. [101].

Developing a magnetically responsive photonic crystal opens a new field for display technologies. Even novel solid magneto chromic photonic crystals that enable colourimetric reactions to an alternating magnetic field (AMF) have still been studied. [103, 104]. Magnetically tunable chromatic microactuators have a crucial role in colour modulation, such as the benefits of contactless control and easy implementation into devices. A magnetically tunable chromatic microactuator can be designed to utilize the optical and magnetic behaviours of self-assembled super-paramagnetic nanoparticles embedded in a polymeric structure. The original colour can be arranged during a simple photolithography process, and the colour can be adjusted by applying and changing an external magnetic field These kinds of microactuators are skilled in acting as pixels in colour-changing patterns [105].

Magnetically tunable photonic systems continue to develop, which provides a new platform for chromatic applications [106, 107].

f) Chronochromism is a phenomenon associated with processes where a change of colour occurs concerning a defined period. They are typical examples of chronochromic cases since the colour changes occur by one of the other chromic phenomena such as photochromism, thermochromism, ionochromism or gasochromism [101].

Design of systems is constructed to allow the changes in their colours to occur over a predetermined period using pH indicators, leuco dyes and photochromic materials placed in surroundings. One example of regarding application is the usage in toothpaste. That kind of toothpaste is obtained by using sodium ascorbate and Methylene Blue. While brushing the teeth, the two chemicals interact with each other, and therefore, the dye is transformed into a colourless product. Thus, the entire disappearance of the original blue colour at the beginning indicates that the time spent brushing teeth is enough. [108]. Especially for kids, it is a helpful and practical application. Another application field to be used chronochromic products is as visual measurement tools, so-called ‘‘time-temperature indicators’’ (TTI), for determining the duration history of packaged foodstuffs, pharmaceutical and medical products regarding response to temperature over a time period [109, 110].

g) Hydrochromism is a phenomenon that covers colour change on the interaction of bulk water or humidity with a substrate [111]. It is possible to classify the humidity-sensitive materials into four groups, porous ceramics, organic polymers, electrolytes and zeolites. Among these, functional ceramics have a crucial role due to their superior mechanical strength, high chemical resistance against most environments, and good reproducibility [112, 113].

Hygrochromic materials change colour in response to moisture or contact with water. Humidity sensors are used extensively in industry and to monitor environmental conditions. It also has across-the-board applications, such as in the food packaging industry. Moisture existing inside the package can accelerate the deterioration of food. Because of that, desiccants are often added to the package to extend the shelf-life of food products [114]. One of the most successful commercial hydrochromic products involves the conversion of an opaque white layer, containing a white pigment of low refractive index, into a transparent clear layer on interaction with water. The process is reversible. The layer becomes opaque again after becoming dry [115, 116]. The papers coated with hydrochromic materials enable it to rapidly and precisely map human sweat pores of feet, fingers, and palms [117]. Designing an umbrella with that material for the fashion field can lead to an aesthetic outlook on rainy days [118]. Systematic studies of dyes exhibiting hydrochromic behaviour have still been undertaken to produce a printing system which uses rewritable, water-jet paper [119, 120].

h) Solvatochromism is a phenomenon associated with the changes in position, intensity, and shape of the chromophore's UV–VIS absorption spectrum in a solvent of different polarity.

Positive solvatochromism refers to the chromophore's absorption, which has a neutral ground state showing a red shift with increasing solvent polarity. The blue shift in the absorption with increasing solvent polarity is called negative solvatochromism [121].

In applying solvatochromic materials, different detectors of chemical agents, which contain selectively soluble pigments in these agents, can also be added. Paper chemical agent detectors were designed during the 1960s and have been widely used in military applications. These detectors consist of a paper incorporating dyes. Each dye is sensitive to a distinct family of chemical agents. When chemical agent react with the specific dyes embedded on the paper surface, colour changes on the paper are generated. Thus, the type of chemical agents can be detected depending on colour changes [122, 123]. In another application of paper chemical agent detectors, paper chemical detectors are attached to personnel's clothing or equipment. Thus, personnel are immediately determined whether any liquid contamination is exposed. [124]. Another possibility is the production of textile materials containing chemical agent detectors by layer coating, allowing a short reaction time for the detector [125].

i) Biochromism is is a phenomenon associated with changes in the specifically created molecules subjected to a chromic transition on interfacing with a biological substance. Most studies in this field cover the utilisation of modified conjugated polymers, polydiacetylene and polythiophenes as biosensors in the form of membranes, mono and bilayer lipids, and vesicles [126]. The phenomena of colour changes when interacting with polydiacetylenes are often called affinochromism. On the other hand, the colour change phenomenon is often called affinitychromism, if the colour change is observed in polythiophenes. Polydiacetylenes (PDAs) form the basis of many biochromic sensors for diverse applications, including the detection of enzymes, antibiotics, viruses, bacteria and heparin, showing the usual rapid colour change from blue to red [127].

2.1.8. Self healing Properties

One of living organisms' most fascinating and valuable features is their self-healing ability after damage. When we look at human skin, it has been known that it heals after wounds of various degrees. Contrary, synthetic materials tend to degrade over time due to operation conditions such as fatigue, corrosion or damage. Self-healing materials are being intensively investigated by inspiring nature. Studies aim to get them to acquire self-repair ability by mimicking biological systems [128]. The considerable materials group exhibiting self healing is polymeric materials. The ample design capacity of polymeric systems allows too many creative ways to stimulate their self-healing qualifications [129].

Self-healing materials are classified into two classes, depending on the strategy of the self-healing process. They are called autonomics and non-autonomics. Non-autonomic forms of healing need a stimulus, such as heat, chemicals, and light, to initiate the healing procedure. The autonomic self-healing materials do not need external stimuli; the occured damage or crack is enough to start the healing procedure. This concept is attributed to a self-adaptive system because the detecting and repairing process happens autonomously and simultaneously in the structure. In this structure, the damage is detected by sensors while actuators execute the repairing process [130]. Another classification relevant to the self-healing process is also used to distinguish characteristics of self-healing materials. They are called 'extrinsic' self-healing and 'intrinsic' self-healing. Extrinsic means that material does not have an inherent ability to heal itself. The healing is executed by intentional components, like microcapsules or nanocapsules, implanted into the structure of materials to provide healing [131]. Capsule-based and vascular methods inspired by biological systems are the principal approaches to acquiring healing functions. Various agents are broadly researched to satisfy the needs for challenging applications of smart materials. Inner self-healing, on the other hand, does not require additional healing agents [132].

The first fully automatic self-healing material was reported in 2001 [133]. An encapsulated agent is implanted into the structure in that study. The composite structure also includes catalysts to lead the polymerization with the healing agent. When damage occurs within the material structure, the fracture breaks the embedded microcapsules. Then, the healing agent is released into the crack zone through capillaries caused by the crack. As soon as the healing agent contacts the catalyst, polymerization is triggered. As a result of the polymerization process, the crack starts to heal. Thus, the damage arising from any external conditions is healed.

Applications concerning self-healing materials include electronic skins (E-skin) [134], field effect transistors (FETs) [135], capacitive touch screen sensors [136], humidity sensors [137], motion sensors [138], biosensors, wire-shaped supercapacitors [139], coating for photovoltaic devices [140]. As self-healing materials continue to be developed rapidly, devices including these kinds of materials will finally be applicable in more difficult working environmental conditions, such as deep sea or outer space. More importantly, these material groups have the possibility to lessen electronic waste through their autonomous repairing functions and assist sustainability [128].

3. CONCLUSIONS and OUTLOOK

Many social events, such as health, poverty, prosperity, decentralized renewable energy networks, easy access to food and clean water, prevention of natural disasters, gender equality, E-learning systems, and smart agriculture practices are handled in UN SDGs. Circular economic growth, smart waste management systems, new working models, sustainable and more efficient production, , and reasonably and sustainably infrastructure systems are suggested for everyone regardless of sex, age, language, and region for a new human-centred society. In order to have a high quality of life in the surrounding environments in which they live for all people, it is clear that it should be considered economic and social factors along with climate and environmental issues. To reach the esteemed society, the future society mentioned here plans that the big data gathered from cyber-physical systems (CPS) (via sensors and devices) through the Internet of Things (IoT) are processed by Artificial Intelligence (AI). As actuators and sensors, smart materials play an essential role in operating the Internet of Things (IoT) and Artificial Intelligence (AI), such as robotics and human−computer interaction. The developments in smart technologies will help solve and support worldwide societal challenges and global environmental issues.

Conflict of Interest Disclaimer

There is no personal or business interest.

REFERENCES

[1] Mourtzis, D., Angelopoulos, J. and Panopoulos, N., 2022. A Literature Review of the Challenges and Opportunities of the Transition from Industry 4.0 to Society 5.0. *Energies*, *15*(17), p.6276.
[2] Lu, Y. Industry 4.0: A survey on technologies, applications and open research issues. J. Ind. Inf. Integr. 2017, 6, 1–10.
[3] Fukuyama, M., 2018. Society 5.0: Aiming for a new human-centered society. *Japan Spotlight*, *27*(5), pp.47-50.
[4] Onday, O. Japan's Society 5.0: Going Beyond Industry 4.0. Bus. Econ. J. 2019, 10, 1000389
[5] United Nations Do you Know All 17 SDGs? Available online: https://sdgs.un.org/goals (accessed on 05 August 2023).
[6] Keidanren. Society 5.0—Co-Creating the Future. Available online: https://www.keidanren.or.jp/en/policy/2018/095.html (acccessed on 5 August 2023).
[7] Dantas, T.; De-Souza, E.; Destro, I.; Hammes, G.; Rodriguez, C.; Soares, S. How the combination of Circular Economy and Industry 4.0 can contribute towards achieving the Sustainable Development Goals. Sustain. Prod. Consum. **2021**, 26, 213–227.
[8] Zengin, Y., Naktiyok, S.,., Kavak, O. and Topçuoğlu, E., 2021. An investigation upon industry 4.0 and society 5.0 within the context of sustainable development goals. *Sustainability*, *13*(5), p.2682.
[9] Li, Y.; Qian, X.; Zhang, L.; Dong, L. Exploring spatial explicit greenhouse gas inventories: Location-based accounting approach and implications in Japan. J. Clean. Prod. 2017, 167, 702–712.
[10] Michna, A.; Kmieciak, R. Open-Mindedness Culture, Knowledge-Sharing, Financial Performance, and Industry 4.0 in SMEs. Sustainable 2020, 12, 9041.
[11] Fukuda, K. Science, technology and innovation ecosystem transformation toward society 5.0. Int. J. Prod. Econ. 2020, 220, 107460
[12] Taniguchi-Matsuoka, A.; Shimoda, Y.; Sugiyama, M.; Kurokawa, Y.; Matoba, H.; Yamasaki, T.; Morikuni, T.; Yamaguchi, Y. Evaluating Japan's national greenhouse gas reduction policy using a bottom-up residential end-use energy simulation model. Appl. Energy 2020, 279, 115792.
[13] Kroschwitz, J. (ed.) (1992) Encyclopedia of Chemical Technology. New York: John Wiley & Sons.

[14] Schwartz, M. ed., 2008. *Smart materials*. CRC press.
[15] R. Bogue, Smart materials: a review of capabilities and applications, Assem. Autom. 34 (2014) 16–22.
[16] See Akhras, G., “Smart Structures and their Applications in Civil Engineering”, *Civil Engineering Report*, CE97-2, RMC, Kingston, Ontario, Canada, 1997.
[17] Culshaw, B., *Smart Structures and Materials*, Artech House Inc, 1996 and Bank, H. T., Smith, R.C. and Wang, Y., *Smart Material Structures, Modelling, Estimating and Control*, John Wiley and Sons, 1996.
[18] Fortuna, L. and Buscarino, A., 2022. Smart Materials. *Materials*, *15*(18), p.6307.
[19] Bahl, S., Nagar, H., Singh, I. and Sehgal, S., 2020. Smart materials types, properties and applications: A review. *Materials Today: Proceedings*, *28*, pp.1302-1306.
[20] Addington, M. and D. Schodek, Smart Materials and Technologies in Architecture: For the Architecture and Design Professions. 2012: Routledge.
[21] Qader, I.N., Mediha, K.Ö.K., Dagdelen, F. and AYDOĞDU, Y., 2019. A review of smart materials: researches and applications. El-Cezeri, 6(3), pp.755-788.
[22] Shanthi, M., Sekhar, E.S., Ankireddy, S., Shah, S.G., Bhaskar, V., Chawla, S. and Trivedi, K., 2014. Smart materials in dentistry: Think smart!. *Journal of Pediatric Dentistry/Jan-Apr*, *2*(1).
[23] Heywang, W., Lubitz, K. and Wersing, W. eds., 2008. *Piezoelectricity: evolution and future of a technology* (Vol. 114). Springer Science & Business Media.
[24] A. Shafik, R.B. Mrad, Piezoelectric Motor Technology: A Review, in: C. Ru, X. Liu, Y. Sun (Eds.), Nanopositioning Technologies, Springer International Publishing, Switzerland, 2016, pp. 33–59.
[25] Wang, S., Rong, W., Wang, L., Xie, H., Sun, L. and Mills, J.K., 2019. A survey of piezoelectric actuators with long working stroke in recent years: Classifications, principles, connections and distinctions. *Mechanical Systems and Signal Processing*, *123*, pp.591-605.
[26] V.A. Bardin, V.A. Vasil’Ev, Combining measurement and control functions in the structure of a multilayer piezoelectric actuator of nano- and micromotions, Meas. Tech+ 60 (2017) 711–716.
[27] Y.B. Ham, W.S. Seo, W.Y. Cho, D.W. Yun, J.H. Park, S.N. Yun, Development of a piezoelectric pump using hinge-lever amplification mechanism, J. Electroceram. 23 (2009) 346–350.
[28] J.W. Lee, Y.C. Li, K.S. Chen, Y.H. Liu, Design and control of a cascaded piezoelectric actuated two-degrees-of-freedom positioning compliant stage, Precis. Eng. 45 (2016) 374–386.
[29] Y. Peng, Y. Peng, X. Gu, J. Wang, H. Yu, A review of long range piezoelectric motors using frequency leveraged method, Sensor. Actuat. A-Phys. 235, (2015) 240–255.
[30] Gautschi, G. and Gautschi, G., 2002. *Background of piezoelectric sensors* (pp. 5-11). Springer Berlin Heidelberg.
[31] Kulkarni, H., Zohaib, K., Khusru, A. and Aiyappa, K.S., 2018. Application of piezoelectric technology in automotive systems. Materials Today: Proceedings, 5(10), pp.21299-21304.
[32] Ölander, A., 1932. An electrochemical investigation of solid cadmium-gold alloys. *Journal of the American Chemical Society*, *54*(10), pp.3819-3833.
[33] Vernon, L.B. and Vernon, H.M., VERNON BENSHOFF Co, 1941. *Process of manufacturing articles of thermoplastic synthetic resins*. U.S. Patent 2,234,993.

[34] J. Damodharan, A. Sreedharan, T. Ramalingam, A review on smart materials, types and applications, Int. J. Eng. Technol. Sci. Res. 5 (2018) 5.

[35] Jani, J.M., Leary, M., Subic, A. and Gibson, M.A., 2014. A review of shape memory alloy research, applications and opportunities. *Materials & Design (1980-2015)*, *56*, pp.1078-1113.

[36] Buehler, W.J., Gilfrich, J.V. and Wiley, R.C., 1963. Effect of low-temperature phase changes on the mechanical properties of alloys near composition TiNi. *Journal of applied physics*, *34*(5), pp.1475-1477.

[37] Kauffman, G.B. and Mayo, I., 1997. The story of nitinol: the serendipitous discovery of the memory metal and its applications. *The chemical educator*, *2*, pp.1-21.

[38] Furuya, Y., 1996. Design and material evaluation of shape memory composites. *Journal of intelligent material systems and structures*, *7*(3), pp.321-330.

[39] Kohl, M., 2004. *Shape memory microactuators*. Springer Science & Business Media.

[40] Duerig, T., Pelton, A. and Stöckel, D.J.M.S., 1999. An overview of nitinol medical applications. *Materials Science and Engineering: A*, *273*, pp.149-160.

[41] Okotete, E., Osundare, A., Olajide, J., Desai, D. and Sadiku, E., 2020. Shape Memory Nanomaterials for Damping Applications. In *Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications* (pp. 1-32). Cham: Springer International Publishing.

[42] Bil, C., Massey, K. and Abdullah, E.J., 2013. Wing morphing control with shape memory alloy actuators. *Journal of Intelligent Material Systems and Structures*, *24*(7), pp.879-898.

[43] Kheirikhah, M.M., Rabiee, S. and Edalat, M.E., 2011. A review of shape memory alloy actuators in robotics. *RoboCup 2010: Robot Soccer World Cup XIV 14*, pp.206-217.

[44] Wahi, S.K., Kumar, M., Santapuri, S. and Dapino, M.J., 2019. Computationally efficient locally linearized constitutive model for magnetostrictive materials. *Journal of Applied Physics*, *125*(21).

[45] Joule, J.P., 1842. On a new class of magnetic forces. *Ann. Electr. Magn. Chem*, *8*(1842), pp.219-224.

[46] E. Villari, Intorno alle modificazioni del memento magnetico di una verga di ferro e di acciaio, prodotte per la trazione della medesima e pel passaggio di una corrente attraverso la stessa, Il Nuovo Cimento 20 (1) (1864) 317–362.

[47] Dapino, M.J., 2002. On magnetostrictive materials and their use in smart material transducers. *Struct. Eng. Mech. J*, *17*, pp.1-28.

[48] Olabi, A.G. and Grunwald, A., 2008. Design and application of magnetostrictive materials. *Materials & Design*, *29*(2), pp.469-483.

[49] Clarisse Ribeiro, V. Correia, P. Martins, F.M. Gama, S. Lanceros-Mendez, Proving the suitability of magnetoelectric stimuli for tissue engineering applications, Colloids Surf. B Biointerfaces 140 (2016) 430–436.

[50] S.D. Bhame, P.A. Joy, Enhanced magnetostrictive properties of CoFe2O4 synthesized by an autocombustion method, Sensor Actuator Phys. 137 (2) (2007) 256–261.

[51] Xuegen Zhao, Nigel Mellors, D.G. Lord, Magnetomechanical performance of directionally solidified Fe–Ga alloys, J. Appl. Phys. 101 (9) (2007), 09C513.

[52] T Toby Hansen, Magnetostrictive materials and ultrasonics, Chemtech 26 (8) (1996) 56–59.

[53] Hal R. Holmes, Andrew DeRouin, Samantha Wright, M Riedemann Travor, Thomas A. Lograsso, Rupak M. Rajachar, Keat Ghee Ong, Biodegradation and biocompatibility of mechanically active magnetoelastic materials, Smart Mater. Struct. 23 (9) (2014), 095036.

[54] Murzin, D., Mapps, D.J., Levada, K., Belyaev, V., Omelyanchik, A., Panina, L. and Rodionova, V., 2020. Ultrasensitive magnetic field sensors for biomedical applications. *Sensors*, *20*(6), p.1569.
[55] Vranish, J.M., Naik, D.P., Restorff, J.B. and Teter, J.P., 1991. Magnetostrictive direct drive rotary motor development. *IEEE Transactions on Magnetics*, *27*(6), pp.5355-5357.
[56] Bushko, D.A. and Goldie, J.H., 1991. High performance magnetostrictive actuators. *IEEE Aerospace and Electronic Systems Magazine*, *6*(11), pp.21-25.
[57] Arani, H.K., Shariyat, M. and Mohammadian, A., 2020. Vibration analysis of magnetostrictive nano-plate by using modified couple stress and nonlocal elasticity theories. *International Journal of Materials and Metallurgical Engineering*, *14*(9), pp.229-234.
[58] Shin-ichi Yamaura, Microstructure and magnetostriction of heavily groove-rolled Fe-Co alloy wires, Mater. Sci. Eng., B 264 (2021) 114946.
[59] Shuai Ren, Dezhen Xue, Yuanchao Ji, Xiaolian Liu, Sen Yang, Xiaobing Ren, Low-field-triggered large magnetostriction in iron-palladium strain glass alloys, Phys. Rev. Lett. 119 (12) (2017) 125701.
[60] Newnham, R.E., Sundar, V., Yimnirun, R., Su, J. and Zhang, Q.M., 1997. Electrostriction: nonlinear electromechanical coupling in solid dielectrics. *The Journal of Physical Chemistry B*, *101*(48), pp.10141-10150.
[61] Damjanovic, D. and Newnham, R.E., 1992. Electrostrictive and piezoelectric materials for actuator applications. *Journal of intelligent material systems and structures*, *3*(2), pp.190-208.
[62] Coutte, J., Dubus, B., Debus, J.C., Granger, C. and Jones, D., 2002. Design, production and testing of PMN–PT electrostrictive transducers. *Ultrasonics*, *40*(1-8), pp.883-888.
[63] Uchino, K. 1986. "Electrostrictive Actuators: Materials and Applications", Am. Cer. Soc. Bull., 65(4):647-652.
[64] Ganet, F., Le, M., Capsal, J. *et al.* Development of a smart guide wire using an electrostrictive polymer: option for steerable orientation and force feedback. *Sci Rep* **5**, 18593 (2016).
[65] Rabinow, J., 1948. The magnetic fluid clutch. *Electrical Engineering*, *67*(12), pp.1167-1167.
[66] Ginder, J.M., Davis, L.C. and Elie, L.D., 1996. Rheology of magnetorheological fluids: models and measurements. *International journal of modern physics b*, *10*(23n24), pp.3293-3303.
[67] De Vicente, J., Klingenberg, D.J. and Hidalgo-Alvarez, R., 2011. Magnetorheological fluids: a review. Soft matter, 7(8), pp.3701-3710.
[68] Rabbani Y, Ashtiani M, Hashemabadi SH. An experimental study on the effects of temperature and magnetic field strength on the magnetorheological fluid stability and MR effect. Soft Matter. 2015;11(22):4453–60.
[69] Rabbani, Y., Hajinajaf, N. and Tavakoli, O., 2019. An experimental study on stability and rheological properties of magnetorheological fluid using iron nanoparticle core–shell structured by cellulose. Journal of Thermal Analysis and Calorimetry, 135, pp.1687-1697.
[70] Milecki, A. and Hauke, M., 2012. Application of magnetorheological fluid in industrial shock absorbers. *Mechanical Systems and Signal Processing*, *28*, pp.528-541.

[71] Okui, M., Iikawa, S., Yamada, Y. and Nakamura, T., 2018. Fundamental characteristic of novel actuation system with variable viscoelastic joints and magneto-rheological clutches for human assistance. *Journal of Intelligent Material Systems and Structures*, *29*(1), pp.82-90.
[72] Nakamura, T., Midorikawa, Y. and Tomori, H., 2011. Position and vibration control of variable rheological joints using artificial muscles and magneto-rheological brake. *International Journal of Humanoid Robotics*, *8*(01), pp.205-222.
[73] Christie, M.D., Sun, S., Deng, L., Ning, D.H., Du, H., Zhang, S.W. and Li, W.H., 2019. A variable resonance magnetorheological-fluid-based pendulum tuned mass damper for seismic vibration suppression. Mechanical Systems and Signal Processing, 116, pp.530-544.
[74] Yildirim, G. and Genc, S., 2013. Experimental study on heat transfer of the magnetorheological fluids. *Smart materials and structures*, *22*(8), p.085001.
[75] Donado, F., Carrillo, J.L. and Mendoza, M.E., 2002. Sound propagation in magneto-rheological suspensions. *Journal of Physics: Condensed Matter*, *14*(9), p.2153.
[76] Alekhina, I., Kramarenko, E., Makarova, L. and Perov, N., 2022. Magnetorheological composites for biomedical applications. In *Magnetic Materials and Technologies for Medical Applications* (pp. 501-526). Woodhead Publishing.
[77] Munteanu, A. and Sedlacik, M., 2023. Progress in Surface Functionalized Particle-based Magnetorheological Composites. In *Magnetic Soft Matter: Fundamentals and Applications* (pp. 85-106). The Royal Society of Chemistry.
[78] Winslow, W.M., 1949. Induced fibration of suspensions. *Journal of applied physics*, *20*(12), pp.1137-1140.
[79] Electrorheological Fluids: Mechanisms, Properties, Technology and Applications, ed. R. Tao and G. D. Roy, World Scientific, Singapore, 1994.
[80] Wen, W., Huang, X. and Sheng, P., 2008. Electrorheological fluids: structures and mechanisms. *Soft Matter*, *4*(2), pp.200-210.
[81] Ma, H., Wen, W., Tam, W.Y. and Sheng, P., 1996. Frequency dependent electrorheological properties: origin and bounds. *Physical review letters*, *77*(12), p.2499.
[82] Tam, W.Y., Yi, G.H., Wen, W., Ma, H., Loy, M.M. and Sheng, P., 1997. New electrorheological fluid: theory and experiment. *Physical review letters*, *78*(15), p.2987.
[83] Lin, C.J., Lee, C.Y. and Liu, Y., 2017. Vibration control design for a plate structure with electrorheological atva using interval type-2 fuzzy system. *Applied Sciences*, *7*(7), p.707.
[84] Lin, C.J.; Lee, C.Y.; Cheng, C.H.; Chen, G.F. Vibration Control of a Cantilever Beam Using a Tunable Vibration
Absorber Embedded with ER Fluids. Int. J. Aerosp. Ind. Mechatron. Manuf. Eng. **2013**, 7, 1412–1418.
[85] Sun, Y.; Thomas, M. Control of torsional rotor vibrations using an electrorheological fluid dynamic absorber. J. Vib. Control **2011**, 17, 1253–1264.
[86] Chen, W., Pan, Y., Chen, J., Ye, F., Liu, S.H. and Yin, J., 2018. Stimuli-responsive organic chromic materials with near-infrared emission. *Chinese Chemical Letters*, *29*(10), pp.1429-1435.
[87] Jiang, Y., 2014. An outlook review: Mechanochromic materials and their potential for biological and healthcare applications. *Materials Science and Engineering: C*, *45*, pp.682-689.
[88] Bar, N. and Chowdhury, P., 2022. A brief review on advances in rhodamine B based chromic materials and their prospects. *ACS Applied Electronic Materials*, *4*(8), pp.3749-3771.

[89] El-Khodary, E., Gebaly, B., AlSalmawy, A. and Rafaat, E., 2020. Critical review on smart chromic clothing. *Journal of Design Sciences and Applied Arts*, *1*(1), pp.90-95.
[90] Aburas, M., Soebarto, V., Williamson, T., Liang, R., Ebendorff-Heidepriem, H. and Wu, Y., 2019. Thermochromic smart window technologies for building application: A review. *Applied Energy*, *255*, p.113522.
[91] Zhang, J., Zou, Q. and Tian, H., 2013. Photochromic materials: more than meets the eye. *Advanced Materials*, *25*(3), pp.378-399.
[92] Tian, H. and Yang, S., 2004. Recent progresses on diarylethene based photochromic switches. *Chemical Society Reviews*, *33*(2), pp.85-97.
[93] By controlling the intensity of the light, it is possible to manipulate the photokinetics of the colour-switching reaction. Thus, The photokinetics of the colour-switching serves information technologies such as recording, erasing, and rewriting.
[94] Photochromism has attracted significant attention after the invention of photochromic glass. Sunglasses that protect human eyes from UV light or intense sunshine can be given as an excellent example of the application of photochromic material.
[95] Li, X.N., Tu, Z.M., Li, L., Wang, Z.H. and Zhang, H., 2020. A novel viologen-based coordination polymer with multi-stimuli responsive chromic properties: photochromism, thermochromism, chemochromism and electrochromism. *Dalton Transactions*, *49*(10), pp.3228-3233.
[96] Wang, X.; Wang, S.; Gu, C.; Zhang, W.; Zheng, H.; Zhang, J.; Lu, G.; Zhang, Y.; Li, M.; Zhang, S. X. A. Reversible Bond/Cation Coupled Electron Transfer on Phenylenediamine-Based Rhodamine B and Its Application on Electrochromism. *ACS Appl. Mater. Interfaces* 2017, *9* (23), 20196−20204.
[97] Platt, J. R., (1961). Electrochromism, a possible change of color producible in dyes by an electric field, *The Journal of Chemical Physics*, *34*(3), 862–863.
[98] Chang, I. F., Gilbert, B. L., & Sun, T. I., (1975). Electrochemichromic systems for display applications, *J. Electrochem. Soc*., *122*(7), 955–962.
[99] Monk, P. M. S., Mortimer, R. J., & Rosseinsky, D. R., (2007). *Electrochromism and Electrochromic Devices*, Cambridge University Press, Cambridge.
[100] Mortimer, R. J., Dyer, A. L., & Reynolds, J. R., (2006). Electrochromic organic and polymeric materials for display applications, *Displays*, *27*, 2–18.
[101] Peter, B.; Michael, H. *Chromic Phenomena; technological applications of colour chemistry*, 3rd ed.; Royal Society of Chemistry: 2018.
[102] Gillaspie, D.T., Tenent, R.C. and Dillon, A.C., 2010. Metal-oxide films for electrochromic applications: present technology and future directions. *Journal of Materials Chemistry*, *20*(43), pp.9585-9592.
[103] Wang, W., Fan, X., Li, F., Qiu, J., Umair, M.M., Ren, W., Ju, B., Zhang, S. and Tang, B., 2018. Magnetochromic photonic hydrogel for an alternating magnetic field-responsive color display. *Advanced Optical Materials*, *6*(4), p.1701093.
[104] Ge, J., Lee, H., He, L., Kim, J., Lu, Z., Kim, H., Goebl, J., Kwon, S. and Yin, Y., 2009. Magnetochromatic microspheres: rotating photonic crystals. *Journal of the American Chemical Society*, *131*(43), pp.15687-15694.
[105] Kim, J., Choi, S.E., Lee, H. and Kwon, S., 2013. Magnetochromatic microactuators for a micropixellated color-changing surface. *Advanced Materials*, *25*(10), pp.1415-1419.
[106] J. Ge, Y. Hu, Y. Yin, *Angew. Chem., Int. Ed.* 2007, **119**, 7572.

[107] J. Ge, L. He, J. Goebl, Y. Yin, *J. Am. Chem. Soc.* 2009, **131**, 3484.
[108] Roch Romeo, Eur. Pat., 298839A1, 1987
[109] Intelligent Packaging, C. Nithya, 2011, http://www.slideshare.net/nithyac12/intelligent-packaging-41285755 (accessed October, 2016).
[110] A. Pavelkova´, Acta Univ. Agric. Silvic. Mendelianae Brun., 2013, 61, 245–251.
[111] T. Okawa and S. Imai, U. S. Pat., 4,810,562, 1989.
[112] Yamazoe, N., & Shimizu, Y., (1986). Humidity sensors: *Principles and Applications*, *Sensors and Actuators*, *10*, 379–398.
[113] Sohrabnezhad, S., Pourahmad, A., & Sadjadi, M. A., (2007). New methylene blue incorporated in mordenite zeolite as humidity sensor material, *Materials Letters, 61,* 2311–2314.
[114] Esse, R., & Saari, A., (2008). In: *Smart Packaging Technologies*, Kerry, J., & Butler, P., (ed.), John Wiley & Sons, West-Sussex, pp. 130–149.
[115] T. Okawa and S. Imai, U. S. Pat., 4,810,562, 1989.
[116] www.sfxc.co.uk
[117] D.-H. Park, W. Jeong, M. Seo, B. J. Park and J.-M. Kim, Adv. Funct. Mater., 2016, 26, 498-506.
[118] www.smarol.com (accessed Nov. 2017).
[119] L. Sheng, M. Li, S. Zhu, H. Li, Y.-G. Li, Y. Wang, Q. Li, S. Liang, K. Zhong and S. X.-A. Zhang, Nat. Commun., 2014, 5, 3044.
[120] S. X.-A. Zhang, L. Sheng and M. Li, U. S. Pat. Appl., 20160168797.
[121] Reichardt, Ch., & Welton, T., (2011). *Solvents and Solvent Effects in Organic Chemistry*, 4th edn., Wiley-VCH Verlag, Weinheim. pp. 4–140
[122] Thoraval, D., Bets, R. W., Bovenkamp, J. W., & Dix, J. K., (1988). Development of paper, chemical agent detector, 3-way liquid containing non-mutagenic dyes. *I-Replacement of the Yellow Dye Thiodiphenyl-4,4'-diazo-bis-salicylic Acid (A2),* Defense Research Establishment Ottawa, Report No. 962.
[123] Sata, T., (2004). *Ion Exchange Membranes, Preparation, Characterization, Modification and Application*, The Royal Society of Chemistry, Cambridge. pp. 276–280.
[124] Thoraval, D., & Bovenkamp, J. W., (1989). Paper chemical agent detectors, *EP 0334668 A1*, *27*.
[125] Vik, M., & Viková, M., (2011). *Identification Methods for Evaluation of Amount of Dangerous Substances in Air and on the Surface* (in Czech), Report for National Authority for Nuclear, Biological and Chemical Protection Czech Republic.
[126] D. Charych, in Biosensors and Their Applications, ed. V. C. Yang and T. Ngo, Springer, Berlin, 2000.
[127] S. Lee, J.-Y. Kim, X. Chen and J. Yoon, Chem. Commun., 2016, 52, 9178.
[128] Yu Jun Tan, Jiake Wu, Hanying Li, and Benjamin C. K. Tee, *ACS Applied Materials & Interfaces* **2018** *10* (18), 15331-15345
[129] Yang, Y.; Urban, M. W. Self-Healing Polymeric Materials. Chem. Soc. Rev. 2013, 42, 7446.
[130] Hager, M.D., Greil, P., Leyens, C., van der Zwaag, S. and Schubert, U.S., 2010. Self-healing materials. *Advanced Materials*, *22*(47), pp.5424-5430.

[131] Bekas, D.G., Tsirka, K., Baltzis, D. and Paipetis, A.S., 2016. Self-healing materials: A review of advances in materials, evaluation, characterization and monitoring techniques. *Composites Part B: Engineering*, *87*, pp.92-119.

[132] Zwaag, S. ed., 2008. *Self healing materials: an alternative approach to 20 centuries of materials science* (Vol. 30). Dordrecht, The Netherlands: Springer Science+ Business Media BV.

[133] White, S., Sottos, N., Geubelle, P. *et al.* Autonomic healing of polymer composites. *Nature* **409**, 794–797 (2001).

[134] Tee, B. C.-K.; Wang, C.; Allen, R.; Bao, Z. An Electrically and Mechanically Self-Healing Composite with Pressure- and FlexionSensitive Properties for Electronic Skin Applications. Nat. Nanotechnol. 2012, 7 (12), 825−832.

[135] Lu, C.-C.; Lin, Y.-C.; Yeh, C.-H.; Huang, J.-C.; Chiu, P.-W. High Mobility Flexible Graphene Field-Effect Transistors with Self-Healing Gate Dielectrics. ACS Nano 2012, 6 (5), 4469−4474.

[136] Li, J.; Liang, J.; Li, L.; Ren, F.; Hu, W.; Li, J.; Qi, S.; Pei, Q. Healable Capacitive Touch Screen Sensors Based on Transparent Composite Electrodes Comprising Silver Nanowires and a Furan/ Maleimide Diels−Alder Cycloaddition Polymer. ACS Nano 2014, 8 (12), 12874−12882.

[137] Guo, K.; Zhang, D. L.; Zhang, X. M.; Zhang, J.; Ding, L. S.; Li, B. J.; Zhang, S. Conductive Elastomers with Autonomic Self-Healing Properties. Angew. Chem., Int. Ed. 2015, 54 (41), 12127−12133.

[138] Yang, Y.; Zhu, B.; Yin, D.; Wei, J.; Wang, Z.; Xiong, R.; Shi, J.; Liu, Z.; Lei, Q. Flexible Self-Healing Nanocomposites for Recoverable Motion Sensor. Nano Energy 2015, 17, 1−9.

[139] Sun, H.; You, X.; Jiang, Y.; Guan, G.; Fang, X.; Deng, J.; Chen, P.; Luo, Y.; Peng, H. Self-Healable Electrically Conducting Wires for Wearable Microelectronics. Angew. Chem., Int. Ed. 2014, 53 (36), 9526−9531.

[140] Banerjee, S.; Tripathy, R.; Cozzens, D.; Nagy, T.; Keki, S.; Zsuga, M.; Faust, R. Photoinduced Smart, Self-Healing Polymer Sealant for Photovoltaics. ACS Appl. Mater. Interfaces 2015 , 7 (3), 2064 −2072