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Combining smart materials for enhancing intelligent systems: initial studies, success cases and research trends

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Abstract. The combined use of smart materials, complementing each others' characteristics and resulting in devices with optimised features, is providing new solutions in many industries. The use of ingenious combinations of smart materials has led to improvements in actuation speed and force, signal-to-noise ratio, sensor precision and unique capabilities such as self-sensing self-healing systems and energy autonomy. This may all give rise to a revival for numerous families of smart materials, for which application proposals had already reached a stationary situation. It may also provide the boost needed for the definitive industrial success of many others. This study focuses on reviewing the proposals, preliminary studies and success cases related to combining smart materials to obtain multifunctional, improved systems. It also examines the most outstanding applications and fields for the combined use of these smart materials. We will also discuss related study areas which warrant further research for the development of novel approaches for demanding applications.

Keywords: smart materials; intelligent systems; sensors and actuators; energy harvesting; self sensing materials and structures; self-healing materials and structures; autonomous systems

1. Introduction

1.1 Smart materials and intelligent systems

Over the last few decades, many active, multifunctional or "smart" materials have emerged, capable of responding in a reversible and controllable manner to different external physical or chemical stimuli by modifying some of their properties. Due to their sensitivity or actuation abilities, these materials can be used to design and develop sensors, actuators and intelligent systems, with numerous applications in architecture, in information and communication technologies (ICT), in industries such as the aeronautical or the biomedical industry, in novel developments linked to automotion and machinery and in designing all kinds of consumer elements.

Some of the main advantages of integrating multiple functions in a system include related

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reductions in size, an increase in the volume of production series and fewer costs in terms of materials and processes. Active materials may play a decisive role in many future applications, since they relate electrical, thermal, chemical, optical, magnetic and mechanical magnitudes (amongst others) to each other. These materials present themselves in different forms - inorganic, metallic and organic, both natural and synthetic, being sensitive to a wide variety of physical and chemical phenomena.

Fig. 1 summarises some of the main families of smart materials and the different physical domains that they connect, being able, therefore, to act as transducers if they are integrated into more complex devices. Reference has not been made to chemical domains and specific reactions (including redox, acid-base and water absorption) responsible for the behaviour of many of these materials, in order to make classification easier and because they are intrinsically linked to the physical domains that these materials connect and have already been detailed in the main references mentioned.

Before paying attention to the possibilities and challenges derived from combining smart materials for enhancing intelligent systems, as central topic of this review, we would like to include a brief introductory state-of-the-art of the main families of smart materials and their application fields. The first decade of the 21st Century having come to an end, it is a good time to review such scientific and technological advances, as well as the most significant forthcoming study trends. Many of these materials date back to ancient times: However, the most significant progress and proposals for their application have emerged in the last three decades, as a result of concurrent progress in manufacturing, simulation and design technologies as well as progress in the field of ICT.

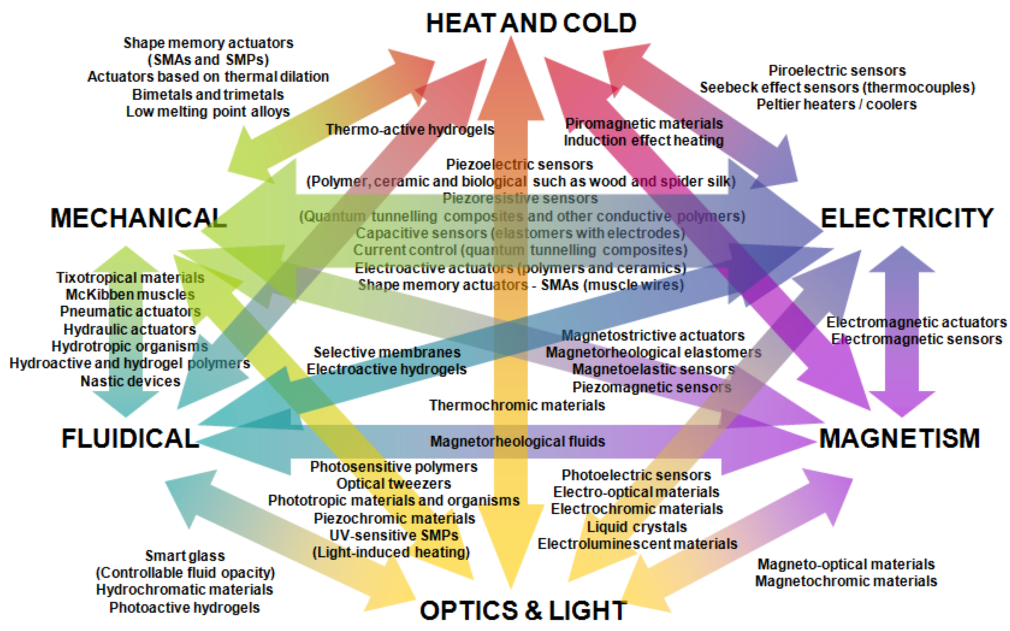

Fig. 1 Smart materials as transducers for linking different physical domains

The following figures show the results of a search made in the ISI-Web of Knowledge – Thomson Reuters ® database in January 2011, including data on the evolution of scientific documents and patents related to smart materials, information on families of materials with the largest number of applications and data on the main fields of application. Hence, the evolution of publications (extracted from the Science Citation Index, with documents from years 1945-2010, including all indexed journals in the search) shows the scientific impact of studies linked to active materials, while the evolution of patents (extracted from the Derwent Innovation Index, with documents from years 1980-2010) seeks to provide data emphasising the link to transferring technology to society and the industrial importance of this data. The search has been limited to documents published until the end of 2010.

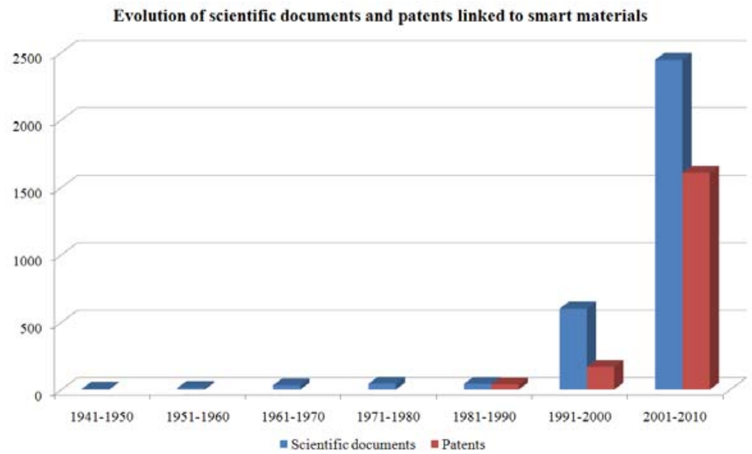

Fig. 2 Evolution of scientific documents and patents related to smart materials

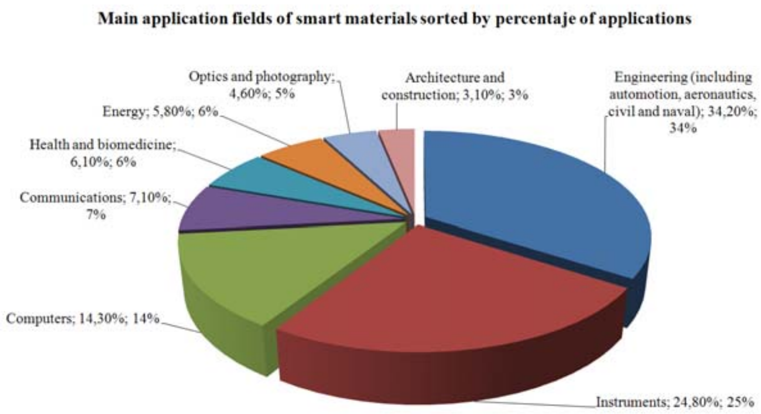

Fig. 3 Main application fields of smart materials, sorted by number of proposals

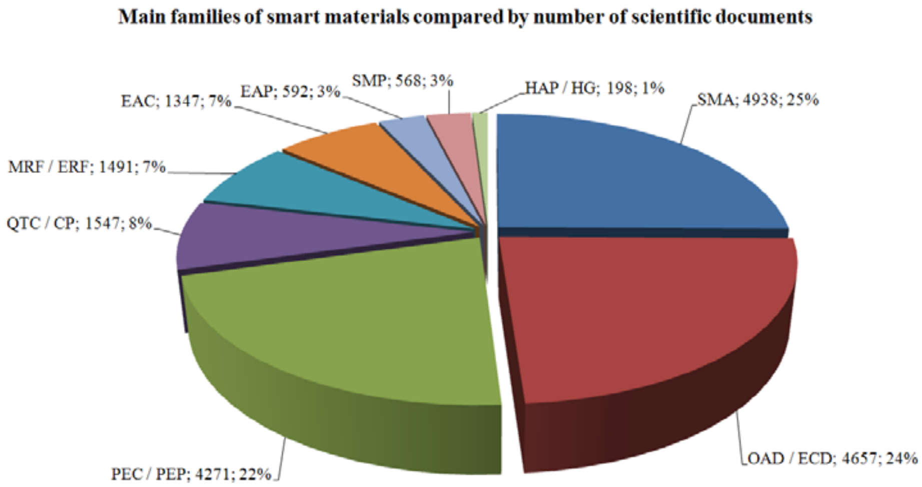

Fig. 4 Main families of smart materials compared by number of scientific documents

Acronyms used.- SMA: Shape memory alloys. OAD & ECD: Optoactive & Electrochromic devices. PEC & PEP: Pyroelectric ceramics and polymers. QTC & CP: Quantum tunnelling composites and conductive polymers. MRF & ERF: Magneto & electrorheological fluids. EAC: Electroactive (normally piezoelectric) ceramics. EAP: Electroactive polymers. SMP: Shape memory polymers. HAP & AHG/AM: Hydroactive polymers & Active hydrogels / membranes.

As regards search criteria, the character string [“Smart Materials” or “Intelligent Materials” or “Active Materials”] was entered in the information on the topic of the documents to find, bearing in mind the typical names of these materials. Thus, 3185 documents and 1816 patents were found. These were used to create Figs. 2 and 3, taking also advantage of the capabilities of ISI-WOK for information classification. For Fig. 4, which analyses different families of active materials, the search was made separately for each of them by writing the corresponding name as the search topic, although some of them have been grouped together because of their close relationship or because different names are sometimes used indistinctively to refer to the same phenomenon.

It is important to mention that many documents which discuss specific families of smart materials do not expressly refer to the term “smart material” or “active material”; these documents only use the name of the specific family. Therefore, the total number of documents on smart materials remarkably exceeds the afore-mentioned figure of 3185. However, the sample size used here is large enough to show significant data and to establish trends in the literature.

From the literature it is evident that smart materials are very useful for controlling the multifunctional nature of certain systems (e.g., implants in the human body, embedded sensors for monitoring structures and machines, actuators for minimally-invasive problem solving), thus reducing the complexity, size and in many cases, the costs of related devices, even though in most cases the expected cost reduction has to wait until the active material is commercially available and developed by several providers (for avoiding monopolies).

Among successful widespread industrial applications, typical examples of smart materials used as transducers in complex systems include: automotive injection systems, printer heads, touchpads, loudspeakers, haptic interfaces, domotic and monitoring devices, implantable pumps or active platforms for biomechanic studies, just to cite some examples, although applications are continuously growing and novel possibilities based on combining different smart materials are also proving to be of remarkable importance, as discussed in this study.

As commented, a transducer based on a smart material is normally employed for connecting two physical domains and to optimise detection or actuation tasks based on direct cause-effect relationships. Thus, each new family of smart materials is normally used for a set of similar applications, e.g., the production of movements as a response to a voltage, the generation of mechanical stresses due to heating or the generation of a load displacement caused by deformations. Therefore, most proposed applications of a new type of smart materials are normally made in the first decade after its discovery, but typically takes around two or three decades for obtaining successful industrial appliances based on a novel family of smart materials.

These new types of smart materials, many of which have already reached their limit of applications when used alone, can be revived as a result of their combined use with other smart materials, thus obtaining systems with greater functionality and higher response capacities when faced with different stimuli. The combined application of smart materials, to improve their functionality when used at the core of increasingly-complex intelligent systems, is resulting in new applications which exceed the characteristics of those from which they derive. It is worth analyzing the proposals and related trends in detail to see what synergies emerge.

2. Combining smart materials: preliminary studies and current success cases

This section describes the main success cases recorded in the last few decades in relation to the combined use of smart materials and the main advantages that these combinations have offered compared to the use of these materials alone. These success cases are generally linked to the need to improve actuation or sensing capabilities, the need to develop systems with simultaneous detection and actuation capabilities, and the importance of producing autonomous or energy harvesting systems for indefinite functioning.

2.1 Combinations for improving actuation capabilities

Typical weaknesses in certain families of smart materials that are used as actuators include the limited actuation stresses that can be developed (e.g., ionic electroactive polymers, shape memory polymers), the small deformations that can be obtained (e.g., piezoelectrics, shape memory alloys, thermal dilation-based actuators) or their slowness in response (e.g., hydroactive polymers and nastic devices). It is also difficult to develop smart materials that combine the capacity to develop actuation stresses above 25 MPa, together with significant deformations higher than 25%, and with a response speed that can be considered “fast” for actuation cycles with frequencies higher than 1 Hz. Alongside progress in materials science and engineering aimed at optimising the composition or formulation of smart polymers, alloys, ceramics as well as their transformation processes in order to improve their characteristics as actuators, it is important to mention new advances in intelligent composites or in the combined use of smart materials to obtain actuators more suited to certain functional requirements.

Thus, the combined use of shape memory alloys (smart material with thermo-mechanical coupling) together with Peltier devices (based on smart materials with thermo-electrical coupling) has helped to optimise and control the process of heat-based activation of these alloys, also improving their response time compared to the one obtained using traditional Joule effect heating, both for conventional (Luo *et al.* 2000, Abadie *et al.* 2002) and for microdevices (Wakasa *et al.* 2008). The aforementioned references explain how to design and integrate such combination of smart materials for obtaining improved systems; also verifying frequency responses up to 0.5 Hz, while previous devices based on Joule effect heating obtained responses around 1 Hz. Such use of thermoelectric heating and cooling, for controlling shape memory alloy actuators, has even been patented for aeronautic applications by relevant manufactures (Jacot *et al.* 2000). A similar association but using shape memory polymers encapsulating Peltier devices inside has made it possible to obtain shape memory polymer structures capable of modifying their geometry on more than one occasion and in a more controlled manner, even obtaining step by step actuations (Díaz Lantada *et al.* 2010). This provides a novel solution to the typical limitation of these polymers (capable of just one actuation cycle) and offering a clear alternative for other solutions based on triple shape memory formulations (Bellin *et al.* 2006).

Also, in relation to the progressive improvement of shape memory polymer capabilities, it is worth mentioning the use of nickel nanoparticles, carbon black, carbon nanotubes (amongst others), embedded inside the material, in order to obtain electroactive shape memory polymers whose heat-based activation process is faster, more controllable and more efficient, as a result of the homogeneous distribution of the heating particles. Additional information on electroactive shape memory polymers can be found consulting (Leng *et al.* 2007, Leng *et al.* 2009) for explaining the use of carbon nanoparticles, (Leng *et al.* 2007, Leng *et al.* 2008) for a description on using nickel nanoparticles and (Liu *et al.* 2009) for an specific review on the topic.

Anyway it is important to remark that in previous devices based on shape memory polymers, activated using heating resistances, temperature differences around 20ºC to 30ºC can be found within the core of the polymer, while these novel electroactive shape memory polymers provide temperature differences lower than 5ºC. Such homogeneous and more controlled behaviour has great potential for medical applications, as the references explain in depth. It is also worth mentioning the incorporation into shape memory polymeric devices or structures of micro and nanoparticles that can be heated by induction, thus achieving remote activation of the shape memory effect, with notable prospects in terms of the development of active implantable devices, as wireless devices and implants can be thus developed (Wilson *et al.* 2005, Mohr *et al.* 2006). Some devices based on the use of shape memory alloys as thermo-mechanical actuators have made use of their additional magneto-thermal coupling, in order to also enable activations resulting from remote induction heating, generally to aid improvements in prosthetic devices, with direct application in other fields (Hiroki *et al.* 1998, Müller *et al.* 2010).

The use of stack actuators is also common for improving actuation capabilities. They actuate more quickly and combine the advantages of different actuation principles to even obtain actuators that are sensitive to many different stimuli. In this sense, some research has focused on the development of actuators composed of thin layers of shape memory alloys, obtained using physical or chemical vapour deposition technologies. These stack actuators based on shape memory alloys even allow for bistable behaviour, if they are properly combined with polymeric layers whose glass transition is in the hysteresis cycle of the memory alloy (Sterzl *et al.* 2003). Shape memory polymer and alloy combinations have also been proposed in order to obtain actuators capable of performing more complex movements (Winzek *et al.* 2003).

It is important to mention that valid combinations for developing the capabilities of certain families of smart materials may also be applicable to other families with similar behaviour. It has already been mentioned that the use of Peltier devices has been useful in combination with both shape memory alloys and polymers. Likewise, recent research has shown the usefulness of developing Mc Kibben muscles with an external shape memory polymer structure in order to make actuators with thermo-pneumatic responses (Takashima *et al.* 2010). Analogous developments, substituting the polymer structure for a shape memory alloy mesh could have similar applications, if adequately controlling and limiting the current applied to the SMA wire, so that the possibility of short-circuiting is avoided.

Subsequent sections discuss other combined active material applications (many of them with stack structures) for improving not only actuation capabilities but also sensor-actuator systems, as well as for enhancing the autonomy of the associated devices.

2.2 Combinations for improving sensing capabilities

To improve sensitivity, signal - noise ratio, detection speed or the capability to sense and generate a response in the event of multiple stimuli, intelligent systems can be also based on the use of combined multifunctional or active materials, as detailed in the applications that follow. Often, the intelligent system is able to recognise itself, giving rise to self-sensing systems or structures (Ihn and Chang 2008), especially in highly-demanding structural applications in which the early detection of potential causes of error (the appearance of microcracks, local plastification, etc.) is a determining factor. Even more relevant proves to be the concept of self-sensing actuators, which will be discussed in the following subsection. There are also examples in civil engineering, in which the use of cement composites with carbon nanotubes inside are helpful in traffic monitoring tasks (Han *et al.* 2009), due to their piezoresistive properties. However, future improvements could incorporate additional smart materials, e.g., piezoelectrical elements to make other measures feasible, related to vibrations on the road itself or self-sensing structures for having increased control over the effects of the environment.

Some active material families have the ability of connecting various domains at the same time and may be sensitive to several stimuli. Thus for example, ferroelectric materials (ceramic or polymeric) have piezoelectric and pyroelectric properties, being capable of generating load displacements and associated voltages, in response to changes in stresses and temperature. This additional coupling can cause measurement errors if it is not adequately taken into consideration.

Nevertheless, it can be used for special applications that need both magnitudes to be controlled with one single sensor while being able to differentiate the causes of the voltage generated, due to the different response speed with respect to changes in the different magnitudes (Castro *et al.* 2006, Díaz Lantada *et al.* 2009). In other cases, simultaneous piezomagnetic and pyromagnetic behaviour has been utilized to develop pressure and temperature sensors based on changes in their magnetic properties, experienced by these materials when they are subjected to stresses, deformations or changes in temperature. In most cases they have been applied in the development of micro magnetic-thermo-electro-mechanical systems or “magMEMS” for active implantable devices and remote monitoring of intracorporeal phenomena (Gibbs 2005, provides a detailed review, and Bian *et al.* 2009, shows a complete development process). Furthermore, in relation to the magnetic domain, magnetostrictive and magnetoresistive behaviours have been combined to develop microsensors for measuring deformations (Duenas *et al.* 2002).

2.3 Combinations for enabling sensor-actuator systems

Amongst the main study trends in the field of intelligent systems, it is important to refer to progress in the development of devices with detection and actuation capabilities, either using combinations of smart materials for detecting different phenomena and consequently actuating, or using materials that can inherently behave like sensors and actuators (also called self-sensing actuators, instead of just self-sensing devices previously described). The concept of self-sensing actuator is traditionally linked to single transducers used both as sensors and as actuators, however nowadays several different transducers are being used in a combined way for enabling more complex sensor-actuator systems that can take advantage of the different capabilities of smart materials.

The first reported successful studies linked to the development of self-sensing actuators date back from the beginning of the 1990s and were based on the properties of piezoelectric ceramics that allow them to be used both as electromechanical sensors and actuators. The technique for concurrently sensing and actuating in a closed loop system using a single piezoelectric was developed and explained in detail elsewhere and constitutes a benchmark in the field (Dosch *et al.* 1992). More recent studies have focused on using other smart materials or combinations of materials, such as electroactive polymers or piezoelectric polymers (mainly for sensing tasks) together with piezoelectric ceramics (mainly for actuation tasks) (Bar-Cohen 2006, Hafez 2006) or microfiber composites as actuators with piezoelectric polymers as sensors in inflatable structures (Park 2002). Relevant efforts have been applied to improving modelling for helping in the design of demanding applications, especially using piezoelectric ceramics (Dunsch 2007, Janocha and Kuhner 2009), but also ionic polymer-metal composites (Porfiri 2009).

Combinations of active materials obtained on the basis of deposition or stack actuators are especially important in this area, including the use of ferroelectric polymers and ceramics, ferromagnetic materials, and even light-sensitive polymers (Bar-Cohen 2004), among others, that have the required characteristics for developing self-sensing systems. It is also important to mention stack devices based on the use of piezoelectric polymers (PVDF, P(VDF-TrFE)) as sensors and piezoelectric ceramics (PZT, $BaTiO_3$) as actuators (Frecker 2003), for promoting both systems' sensitivity and attainable actuation displacements, which could even utilise ceramic resonator properties as energy harvesters if special design steps are followed (Guyomar and Lallart 2009). These stacks can also be used in developing systems for characterising mechanical properties of materials with configurations that place the material under study between two active layers - one of them (normally ceramic piezoelectric) for providing excitation to the material and the other for obtaining a response (normally polymeric piezoelectric) for subsequent analysis (Sánchez *et al.* 2008).

In the field MEMS and magMEMS, the combination of materials with different functional features can be an ongoing source of solutions for developing an increasingly varied range of detection - actuation processes, adapted to and designed *ad hoc* for different applications. It is possible to mention combinations that link mechanical, electrical and magnetic domains based on piezoresistive detection and magnetostrictive actuation (Bourouina *et al.* 2002).

Another field of study that has been significantly nurtured through the combined use of smart materials (since it requires detection and actuation activities) is the development of haptic HMIs (human-machine interfaces) to fundamentally perform remote control handling, minimally-invasive guided surgery and virtual training tasks. In many cases, these devices combine pressure sensors, which are normally piezoelectric, in the actuator instrument. These sensors send information to the remote controller (normally a remote joystick) to control rigidity, normally using magneto-rheological damping, and to thus help control the actuator's displacements in order to avoid hazardous situations or to improve their precision (Mavroidis *et al.* 2006).

The areas of architecture, structural engineering and civil engineering stand out for their high responsibility projects and therefore the use of distributed sensing elements, in many cases based on the capabilities of smart materials, is nowadays almost compulsory. Several references can be consulted for additional details on how to take advantage of multifunctional materials, normally piezoelectric ceramics with special encapsulations, in tasks linked to concrete early-age strength monitoring (Gu *et al.* 2006), structural health monitoring (Song *et al.* 2007) and overall damage evaluation (Song *et al.* 2008).

The advances on wireless technologies provide also additional facilities, already widely used for impact detection in civil infrastructures, although the use of networks of piezoceramic transducers requires special design considerations described elsewhere in detail (Li *et al.* 2010). However present research trends on these fields are focusing on the combination of smart materials for enabling ways of sensing (for detecting problems within the buildings or structures of interest) and subsequently acting (for solving or minimizing such problems). Some of the earlier studies in this area were focused on monitoring the structure's status, using conventional piezoceramic sensors, and using the information collected by the sensors to adjust and tighten joints that might have lost rigidity with the help of shape memory alloy actuators (Park *et al.* 2001, Peairs *et al.* 2004).

More recently the concept of intelligent reinforced concrete structure (IRCS) has been presented for allowing the functions of self-structural health monitoring, self-vibration damping and self-rehabilitation. Such interesting combination of functions is enabled again thanks to the combined use of smart materials, in this case shape memory alloy actuating wires and piezoelectric ceramic sensors (Song *et al.* 2006). Besides describing the implementation of such IRCS and its main applications, the reference describes thoroughly how vibrations and damages within the structure can be controlled, with help of the information obtained from the sensors, and minimized by electrically heating the shape memory alloy wires, in the desired locations, for changing structural stiffness or closing up cracks and defects.

As the combined use of smart materials is providing remarkable results, there is also a growing concern linked to developing teaching equipment to introduce smart materials to students via demonstration and experiments. Multifunctional smart vibration platforms have already been developed and their pedagogical and research interest has been previously presented in detail (Olmi *et al.* 2007). In such systems piezoelectric ceramics (normally PZT) are used as vibration sensors and shape memory alloys and magnetorheological actuators are used for increasing the stiffness and damping ratio of the systems, based on the information obtained from the sensors.

Previously reviewed applications in architecture, structural engineering and civil engineering can benefit further on from recent advances on multifunctional concretes, normally based on the inclusion of carbon-nanofibers or carbon-nanofiber paper for changing the electrical properties of conventional concrete and enabling electrical conduction (Gao *et al.* 2009) and thermal heating (Chang *et al.* 2009). As described in the mentioned references, electrical conduction of concrete proves to be useful for enhancing monitoring and evaluation activities (in combination with sensor networks based on other smart materials, i.e., piezoceramics or piezopolymers), while thermal heating can provide structures and infrastructures with additional capabilities for adaptation to environmental phenomena, as additional research trend in the field of intelligent and environmental-friendly houses and buildings.

Anyway it is evident that, in systems with detection and actuation capabilities, the combined use of active materials is allowing several novel capabilities and promoting a shift from traditional self-sensing materials or self-monitoring structures to materials or structures which, besides monitoring the structures' own health, are capable of self-healing (Ghosh, 2009). These applications can continue to be developed and enhanced using additional combinations of smart materials to improve the autonomy of related devices, thanks to energy generation and harvesting tasks, as detailed in the next section.

2.4 Combinations for increasing autonomy and energy harvesting

Besides reasonable user behaviour, there are two complementary ways of reducing consumer product energy consumption: the use of appropriate labels to make users aware of the real consumption of different devices and to thus influence their purchasing decisions, and the imposition of energy efficiency requirements from the very first stages of design (Eco-Design EU Directive 2005). Often, devices and machines that are going to be exposed to solar light during operation include photovoltaic cells to improve energy efficiency and to increase their autonomy, not to mention progress in the automotion industry in terms of reducing and managing consumption more efficiently (multipoint injection, hybrid motors, start-stop systems, KERS devices, regenerative breaking, amongst others).

Smart materials play an essential role in terms of implementing all types of improvements related to energy efficiency and increasing autonomy and self-sufficiency in many devices. In fact, many existing multifunctional systems, based on the use of smart materials as sensors or actuators, can benefit enormously from incorporating additional smart materials that help to reduce their consumption and to increase their operating time, design modifications being very simple to implement.

There are success cases involving devices with actuation based on the use of shape memory alloys and which have managed to increase their capabilities due to a power supply based on solar energy for aerospace applications, amongst other proposals (Hull *et al.* 2004, Gao and Huang 2006, based on photovoltaic principles). This has also occurred with systems designed for tasks related to detecting problems and monitoring the condition of buildings, which are starting to be completely self-powered (Güemes 2006, Anton and Sodano 2007, Anton and Inman 2008, Anton *et al.* 2010), normally based on vibration of piezoelectric ceramics.

In many applications in machine engineering, both solar energy and vibratory energy can be available and harvesting them can boost the autonomy of the associated intelligent system. For this purpose, Midé has combined their Volture^{TM} device for vibratory energy harvesting with their Volture^{TM} Solar device for solar energy harvesting, thus implementing a new combination based on very useful piezoelectric and photovoltaic principles.

A similar combination could be to nurture recent piezo-tree developments and other systems based on energy harvesting using vibratory phenomena. These piezo-trees have been developed at Cornell University, inspired by nature and seeking to imitate the flapping of the leaves on the trees. The system developed consists of an artificial tree with piezoelectric polymer leaves (in this case PVDF), whose deformation during the movement resulting from the wind is capable of generating energy, as elsewhere explained in detail (Li *et al.* 2009, Li *et al* 2011). Nevertheless, the preliminary results show many possibilities in terms of improvement, which potentially could be obtained by using together vibratory and solar harvesting, following other pioneer designs by Samuel Cabot, CEO of Smit (http://www.s-m-i-t.com). Additional advanced proposals in the automotion industry (e.g., “symbiosis concept vehicle” – Energy Efficient Alliance, Pilkington Vehicle Design Award 2010) (Seesing 2010) seek to develop self-sufficient vehicles by including piezoelectrics in the chassis, as well as photovoltaic cells in the bodywork, as a means of supporting energy harvesting in a complex multifunctional system. It is once again important to highlight the significant potential in using combined smart materials to help improve multifunctionality and performance in all types of industry.

2.5 Summary of applications

Based on the references used to write this document, with special consideration being given to journal articles and congress proceedings included in the Science Citation Index, as well as information on manuals and text books on smart materials, we include now a brief summary of objectives and applications for combining smart materials in multifunctional systems. Data on patents have not been included in this case since they may not have gone under the rigor of the complete development, being fully validated using prototypes and tests. The main objectives for combining smart materials are summarized in Fig. 5 and the main application fields are included in

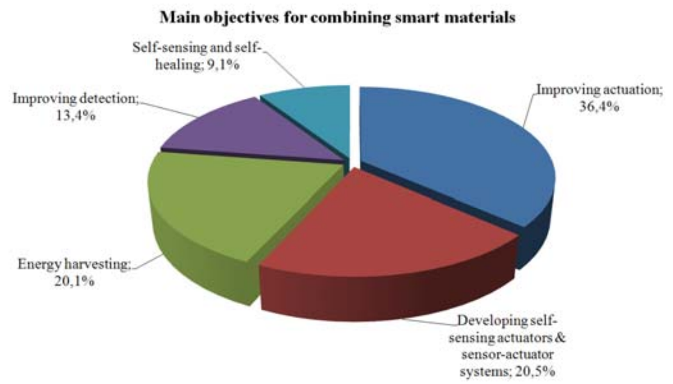

Fig. 5 Main objectives for combining smart materials, compared by percentage of proposals

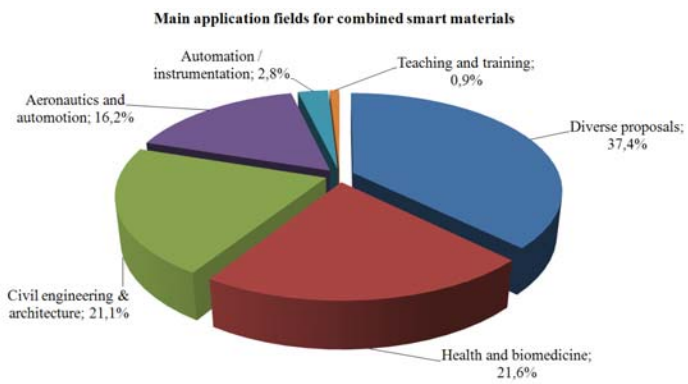

Fig. 6 Application fields for combined smart materials, sorted by percentage of proposals

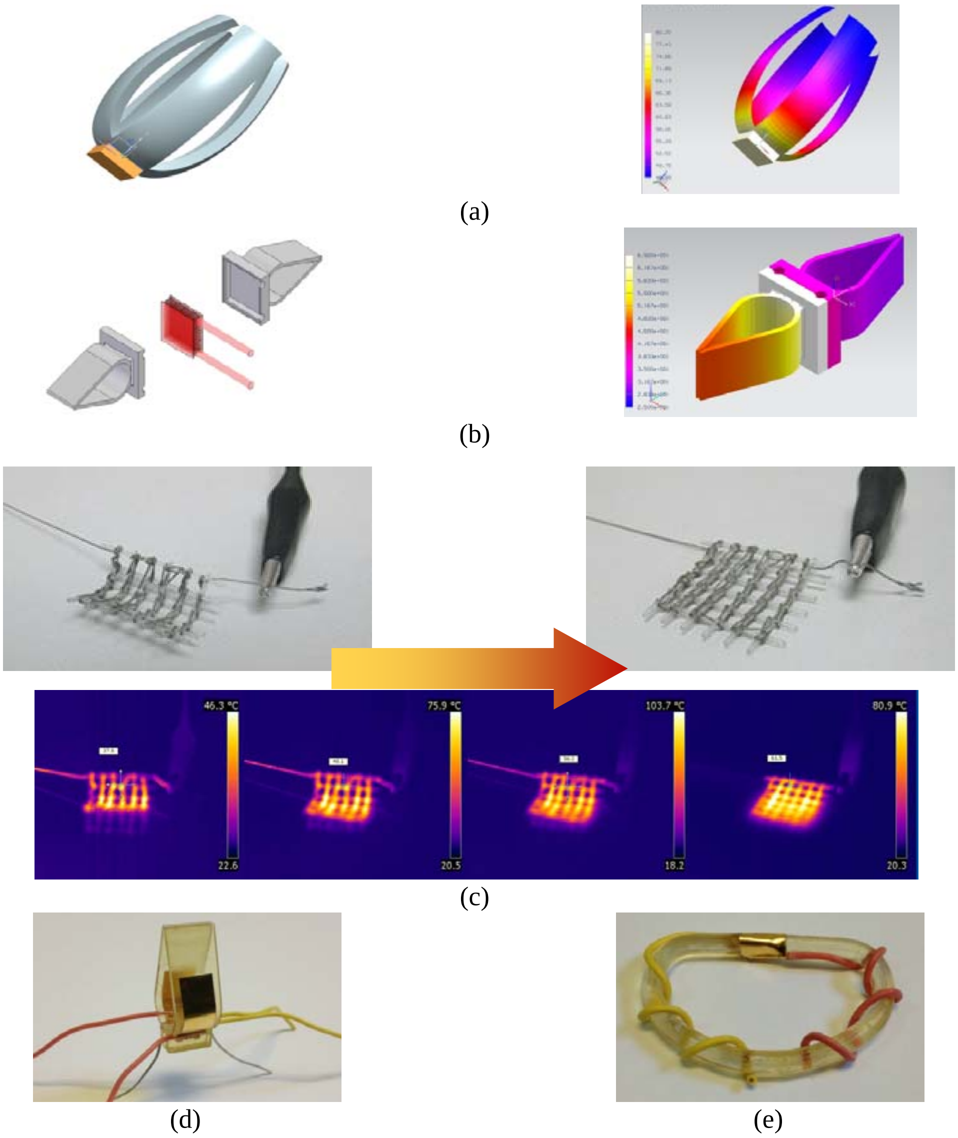

Fig. 7 Examples of some possible combinations of different smart materials for developing sensors and actuators with improved capabilities: Application to shape memory materials. (a) Design and thermal simulation of a pressure-sensitive shape memory polymer actuator by combining a shape memory polymer structure with a pressure-sensitive conductive material (orange block). The application of a pressure to the block decreases the electrical resistance and Joule effect is promoted. (b) Design and thermal simulation of Peltier device combined with a shape memory material for the promotion of step-by-step actuations, by differential heating of opposed parts of the structure. (c) Active shape memory mesh combined with conductive electrotextile for homogeneous heating. (d) Prototype of shape memory actuator coated with PVDF piezoelectric film for self-sensing ability. (e) Shape memory implantable annuloplasty ring with piezofilms for blood-pressure monitoring

Fig. 6. It can be seen that most applications seek to improve the capabilities of actuators and sensors, the development of systems with simultaneous detection - actuation capabilities, and energy management. Fig. 7 includes some examples of applications, in the field of shape memory materials, whose capabilities (possibility of actuating several times, possibility of responding to novel stimuli, actuation process and performance, self-sensing ability, among others) markedly benefit from their combination with other active materials. Likewise applications, when combining all kinds of active materials, are fundamentally related to fields such as civil engineering and architecture, biomedicine and the health sector (in vitro, in vivo, implant development, orthosis and systems for improving human performance) or aeronautical and mechanical engineering, as Fig. 6 details. A group of applications under the name of “diverse proposals” has been incorporated, which includes verified developments for which specific applications have not been described or for which diverse fields of application are simply proposed, which help to demonstrate the originality of the field in question.

3. Main challenges and future research

We have seen how the combined use of smart materials is already providing new and efficient solutions for complex systems and the need of reducing the size and costs of related devices. In terms of the future challenges, it is also important to analyse which new smart material combinations could be of interest in resolving current needs and how the process of finding and verifying these combinations is to be systematised.

The use of smart materials and their combinations is very useful for interacting with live organisms, especially in medical applications for human beings, as biological systems are especially multifunctional. Future advances can also take advantage integrated actions, which also make use of new advances in micro- and nano-manufacturing technologies and benefit from systematic design and materials selection methodologies, as discussed further on.

3.1 Exploring novel combinations of smart materials

Table 1, see Appendix I, summarizes in matrix form the combinations of different smart materials, which have been proposed and correctly validated, according to the results shown in the references mentioned and discussed in the previous sections, as a response to specific industrial requirements.

This table includes several references related to successful combinations of smart materials; due to lack of space, some of them have not been explained specifically in the section on specific application proposals. However, they are of great interest to researchers who are working on these areas and with the main fields of applying new combinations of smart materials, described previously. It would be very interesting to continue exploring the empty cells in Table 1, corresponding to possible smart material combinations whose potential has yet to be verified. Hence, it would be possible to systematically review different ways of relating different the physical domains mentioned at the beginning by using Table 1 as a checklist, and thus find new decisive principles for many applications.

By increasing the number of combined smart materials (generally two) and proceeding to triple or quadruple combinations, it is possible to develop intelligent systems capable of detecting multiple stimuli and consequently acting using different responses, continuously adapting to the effects of the environment. This is all particularly interesting if the interaction between this type of intelligent device and biological systems is studied more in depth, as analysed below.

3.2 Linking smart materials with biological systems

Over the last few decades and also as a result of advances in micro- and nano-manufacturing, attention is being given to the combined use of inorganic nanostructures and biological nanostructures to aid the development of biosensors and bioactuators with optimised responses to different stimuli or the organism's components and with huge potential for the medical and pharmaceutical industries, amongst other fields of study.

First successful developments, dating back to the 1990s, were linked to using biological motors such as units of F_1-ATPase (Montemagno *et al.* 1999, Soong *et al.* 2000, Bachand and Montemagno 2000), muscle cells (Akiyama *et al.* 2006) and more recently even bacteria (Sokolov *et al.* 2009), for improving the actuation or sensing capabilities of MEMS and NEMS.

Generally, these multi-domain and multifunctional sensors or actuators are formed by a made-to-measure, stepwise process with the following components:

- Bioreceptor or bioactuator: Normally enzymes, proteins, DNA, RNA or microorganisms capable of recognising materials and detecting the presence of any harmful elements (viruses, bacteria, antigens etc.) at molecular level, or acting on them. They are usually the organic part of the micro-/nano-biosensor or micro-/nano-bioactuator as well as being the smaller part.
- Transducer: Organic or inorganic material which receives the signal from the bioreceptor and normally transforms it into an electrical current, in the case of a nano-biosensor, or into an electrical impulse of the control unit in a stimulus that causes the actuation of the biological element. Many materials included in this study, especially their combinations, can fulfil this function in this type of device.
- Control unit: This is responsible for receiving the transducer's electrical signal and analysing it or generating a suitable electrical signal capable of activating the transducer (normally a PC, mobile phone or input/output system).

The principles of detection or actuation most commonly involved are based on piezoelectric, electrochemical, thermochemical and optical phenomena. Hence, the use of smart materials and their combinations is increasingly necessary. The most noteworthy applications are linked to tasks related to clinical diagnosis, the detection of harmful elements in the environment and quality control in the food industry or in industrial installations. Precision and speed are key factors in all of them. They are enhanced in this type of devices given the large surface-volume ratio of their components, which increases speed of reaction and interaction (Huefner 2006).

Interesting work has demonstrated the procurement of bilayer or multilayer sensors based on self-assembled nano-thin films which are simple to obtain, stable and robust, in which the combination of diverse smart materials strengthens the final results. The last layer may incorporate selective molecules which react with a specific substance for chemical analysis tasks (Ribeiro *et al.* 2009).

On other occasions, carbon nanotube electrodes with a superficial deposit of different types of enzymes have been used to detect specific biochemical reactions (Razumiene *et al.* 2009). This special type of nano and microstructured functionalisation of a device's electrodes allows for much more specific approaches and sensors that are practically designed ad hoc in terms of detecting highly-specific pathologies or phenomena more quickly.

As regards nanobioactuators, different mechanical responses of single-cell organisms are being used in the face of diverse stimuli, such as motor elements in nanoactuators and nanomachines. The level of conceptual complexity of these actuators is very low and their consumption is almost zero. However, in terms of designing nanobioactuators with an adequate response to a specific purpose, it is still important to study the modelling, simulation and characterisation of electromagnetic, electromechanical and vibro-acoustic phenomena (amongst others) in more depth (Lyshevski 2003).

Once present difficulties have been overcome, partly thanks to the gradual incorporation of combined multifunctional materials, it is expected that the use of nanomachine swarms, controlled by single-cell, interrelated organisms, make it possible to resolve many medical, biological and environmental problems, and even help the human being resolve all types of complex problems (micro and nanorobots with biological brains) (Cerutti 2008, Warwick 2008).

This gradual interaction between inorganic and organic domains and the indiscriminate use of smart materials and single- and multi-cell organisms (both vegetable and animal) in combination with improvements in terms of inert and synthetic multifunctional materials has great potential for responding to many of the uncertainties and necessities addressed by 21st century science in the report entitled "Converging technologies for improving human performance" (Rocco and Bainbridge 2002).

Collaboration between experts of different branches of knowledge and the use of systematic development methodologies will therefore be increasingly necessary when undertaking new projects of this type, as discussed in the following section.

3.3 The need for systematic methodologies

In processes related to the development of complex products (such as multifunctional devices based on combinations of smart materials discussed in this study) the use of a process or methodology that helps to achieve satisfactory solutions proves necessary. These processes or methodologies must be flexible but must also be systematically planned, optimized and verified, being the involvement of all participants necessary with a view to efficient application.

Finding the origins of what is known as "systematic design" is complicated. To give an example, anyone who studies the diagrams and drawings of Leonardo da Vinci will find it hard to overlook his depth of analysis and his use of systematic variations to suggest possible solutions to different problems and to provide methodical comparisons between them (Kaiser and König 2006, Bautista *et al.* 2010). Modern ideas on systematic development were hugely promoted by important figures in the twentieth century, as a result of scarce resources and the need for regeneration after the Second World War, (Kesselring 1951, 1954, Tschochner 1954, Matousek 1957 or Niemann 1950, 1965, 1975). Their ideas contiue to provide ways of resolving specific problems related to the process of developing consumer products and machines (Kaiser and König 2006). The principles currently commonly accepted for effectively and systematically developing new devices are based on the ideals of the previously-mentioned authors as well as the incorporation of certain design stages, the application of which has been successful on numerous occasions (Roozenburg and Eeckels 1995, Pahl and Beitz 1996, Ulrich and Eppinger 2007). In general terms, these methodologies include the following processes: preliminary studies or planning, conceptual design, basic engineering and detail engineering.

These stages are also described in design guides written by organisations such as the VDI (Verein Deutscher Ingenieure) or the ISO (International Organization for Standardization), in relation to validation as a whole and to safety and quality requirements for new products. Their gradual adaptation to the development of complex devices based on smart materials (Díaz Lantada 2009, 2011) and on their combinations may promote the efficient development of new application and the industrial expansion of this. In the specific case of devices based on smart materials or transducers, the methodology of systematic development must pay special attention to the materials selection stage and it may be useful to use common systematised procedures, such as the Asby materials selection methodology or similar (Asby 1999). This methodology was devised to help choose traditional materials based on the most relevant properties according to the performance ratio to be optimised. However, more recent improvements also include aspects related to smart materials and actuator selection (Zupan *et al.* 2002).

An additional improvement with a view towards the future consists of expanding this graphical methodology for materials selection by including new areas of interest resulting from recent combinations of smart materials, as alternatives to materials currently being used or in order to facilitate new fields of application. Fig. 8 shows a comparative between different types of actuators, according to their actuation force and speed, including traditional transducers and new actuators based on the use of combined smart materials. This sort of diagrams, comparing other additional properties, can be of help for the development of future multifunctional systems.

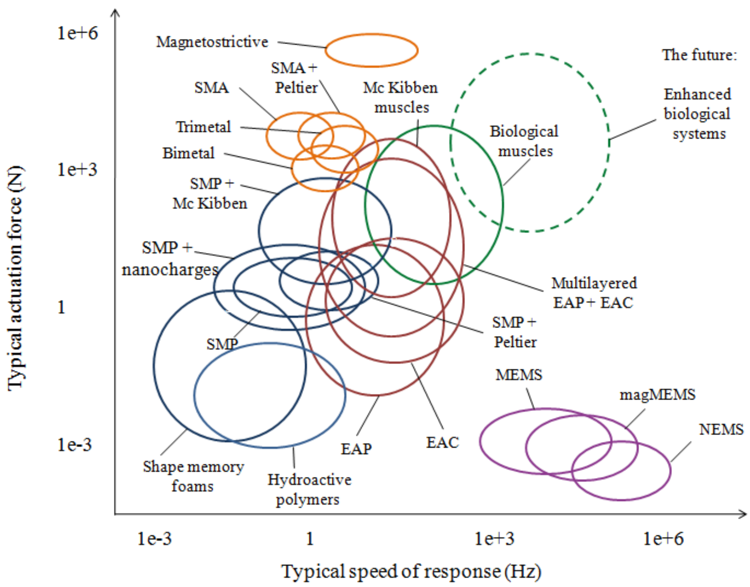

Fig. 8 Typical actuation force vs. speed of response for different actuators based on smart materials and recent combinations for improving their capabilities. Acronyms used.- EAC: Electroactive (normally piezoelectric) ceramics. EAP: Electroactive polymers. SMP: Shape memory polymers. SMA: Shape memory alloys. MEMS: Microelectromechanical systems. magMEMS: Magnetic microelectromechanical systems. NEMS: Nanoelectromechanical systems

Using information from tests on new active materials combinations, support software based on the Asby methodology, such as the Cambridge Material Selector (CES), can be enhanced. Such software is of significantly aid in terms of managing all the information in such large databases and comparing different alternatives in a simple manner, depending on the properties that are most suitable for fulfilling initial specifications. Looking towards future versions, these improvements may be an excellent complement to systematic comparative and weighting tables used in systematic development methodologies for products (Pahl and Beitz 1996).

4. Conclusions

Over last few decades, numerous smart materials have emerged, capable of responding in a reversible and controllable manner to different external physical or chemical stimuli by modifying some of their properties. Consequently, significant efforts have be made to use their characteristics to develop sensors, actuators and multifunctional systems, with the aim of optimising the response of these systems and improving their reliability, reducing aspects such as their complexity, weight or their final costs, due to the integration of functional features involving the use of smart materials as transducers. However, many types of new smart materials used alone do not provide an adequate solution to certain problems, especially if simultaneous detection and actuation requirements are combined, or some of their application proposals fail because they are not sufficiently advantageous as transducers compared with existing, fully-verified devices on the market.

The combined use of smart materials, complementing each others' characteristics and resulting in devices with optimised features, is providing new solutions for complex problems in different industries. The use of combinations of smart materials has lead to improvements in aspects related to the speed and actuating force of some actuators, the signal to noise relationship and precision of certain sensors, the capacity of self-sensing or self-healing systems and to energy autonomy as a whole. This may all give rise to the rebirth of numerous families of smart materials the proposed applications of which were practically disappearing. It may also provide the impetus needed for the definitive industrial success of many others.

Appendix 1 includes a couple of Tables with some of the most remarkable combinations of smart materials already verified, including the references that detail the advantages and challenges linked to such combinations. The blank gaps correspond to possible combinations between different families of smart materials, which will hopefully be explored in the following years and which may promote novel actuators or sensors with improved abilities. More challenging combinations, including sensors and actuators benefiting from the joint use of three or more active materials from different families, still need to be studied towards even more complex, multifunctional and integrated systems.

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References

Abadie, J., Chaillet, N. and Lexcellent, C. (2002), "An integrated shape memory alloy micro-actuator controlled by thermoelectric effect", *Mechatronics*, **14**(7), 757-775.

Anton, S.R., Erturk, A. and Inman, D.J. (2010), "Multifunctional self-charging structures using piezoceramics and thin-film batteries", *Smart Mater. Struct*., **19,** 115021.

Anton, S.R. and Inman, D.J. (Advisor) (2008), *Baseline free and self-powered structural health monitoring, Virginia Polytechnic State University*.

Anton, S.R. and Sodano, H.R. (2007), "A review of power harvesting using piezoelectric materials", *Smart Mater. Struct.*, **16**(3), doi:10.1088/0964-1726/16/3/R01.

Asby, M.F. (1999), *Materials selection in mechanical design*, *Butterworth-Heinemann* Burlington, Massachusetts.

Bachand, G.D. and Montemagno, C. (2000), "Constructing organic/inorganic NEMS devices powered by biomolecular motors", *Biomed. Microdevices*, **2**(3), 179-184.

Bar-Cohen, Y. (2004), *Biologically inspired intelligent robots, SPIE Press.*

Bar-Cohen, Y. (2006), *Electroactive polymer (EAP) actuators as artificial muscles: Reality, potential and challenges*, *SPIE Press*, 2nd Ed., Washington.

Bautista Paz, E., Ceccarelli, M., Echávarri Otero, J. and Muñoz Sanz, J.L. (2010), "A brief illustrated History of machines and mechanisms", *History Mechanism and Machine Sci*., **10**, *Springer*.

Bellin, I., Kelch, S., Langer, R. and Lendlein, A. (2006), "Polymeric triple-shape materials", *Proceedings of the National Academy of Science*, **103,** 18043-18047.

Bian, L., Wen, Y., Li, P., Gao, Q. and Zheng, M. (2009), "Magnetoelectric transducer with high quality factor for wireless power receiving", *Sensor Actuat. A – Phys.*, **150**(2), 207-211.

Bourouina, T., Lebrasseur, E., Reyne, G., Fujita, H., Ludwig, A., Quandt, E., Muro, H., Oki, T. and Asaoka, A. (2002), "Integration of two degree of freedom magnetostrictive actuation and piezoresistive detection: Application to a two dimensional optical scanner", *J. Microelectromech. S*., **11**(4), 355-361.

Castro, H.F., Lanzeros Méndez, S. and Rocha, J.G. (2006) "Separation of the pyro- and piezoelectric response of electroactive polymers for sensor applications", *Mater. Sci. Forum*, **514-516**, 202-206.

Cerutti, S. (2008), "Multivariate, multiorgan and multiscale integration of information in biomedical signal processing", *Proceedings of the International Conference on Biomedical Electronics and Devices Biostec 2008 – Biodevices*, Keynote Lecture.

Chang, C., Ho, M., Song, G., Mo, Y.L. and Li, H. (2009), "Feasibility study of self-heating concrete utilizing carbon nanofiber heating elements", *Smart Mater. Struct*., **18**(12), doi:10.1088/0964-1726/18/12/127001.

Colloza, A. (2007), *Fly like a bird*, IEEE Spectrum, Flapping wings could revolutionize aircraft design.

Díaz Lantada, A. (2012), *Handbook on active materials for medical devices: Advances and applications*, PAN Stanford Publishing.

Díaz Lantada, A. and Lafont, P. (Advisor) (2009), *Methodology for the structured development of medical devices based on smart polymers as sensors and actuators*, PhD Thesis, Universidad Politécnica de Madrid.

Díaz Lantada, A., Lafont Morgado, P., Del Olmo, H.H., Echavari, J., Lorenzo-Yustos, H., Munoz-Guijosa, J.M., Muñoz García, J. and Muñoz Sanz, J.L. (2009), "Modelling and trials of pyroelectric sensors for improving its applications for biodevices", *Proceedings of the International Conference on Biomedical Electronics and Devices - Biodevices 2009.*

Díaz Lantada, A., Lafont Morgado, P., Muñoz García, J., Muñoz Sanz, J.L., Munoz-Guijosa, J.M. and

Echávarri Otero, J. (2010), "Intelligent structures based on the improved activation of shape memory polymers using Peltier cells", *Smart Mater. Struct*., **19**(5), doi:10.1088/0964-1726/19/5/055022.

Dosch, J.J., Inman, D.J. and Garcia, E. (1992), "A self-sensing piezoelectric actuator for collocated control", *J. Intel. Mat. Syst. Str*., **3**(1), 166-185.

Duenas, T., Sehrbrock, A. Löhndorf, M., Ludwig, A., Grünberg, P. and Quandt, E. (2002), "Micro-sensor coupling magnetostriction and magnetoresistive phenomena", *J. Magnetism Magnetic Mater*., **242-245**, 1132-1135.

Dunsch, R. (2007), *Models for piezoelectric sensor-actuator systems, PhD Thesis, EPFL.*

European Commission of Energy (2005), "Eco-design of energy-using product – Eco-design EU Directive".

Franzke, L. (2013), *Touch responsive electroluminescent loudspeaker*, Materiability Research Network (http://materiability.com).

Frecker, M. (2003), "Recent advances in optimization of smart structures and actuators", *J. Intel. Mat. Syst. Str*., **14**(4-5), 207-216.

Gao, X.Y. and Huang, W.M. (2006), "Shape memory motor directly powered by solar energy for space missions", *Proceedings of the 2006 IEEE Conference on Mechatronics and Automation.*

Gao, D., Sturm, M. and Mo, Y.L. (2009), "Electrical resistance of carbon-nano fiber concrete", *Smart Mater. Struct*., **18**, 095039.

Ghosh, S.K. (2009), *Self-healing materials: Fundamentals, design strategies and applications, Wiley-VCH Verlag GmbH & Co.*, Weinheim.

Gibbs, M.R.J. (2005), "Applications of magmems", *J. Magnetism Magnetic Mater.*, **290-291**, 1298-1303, *Proceedings of the Joint European Magnetic Symposia (JEMS' 04).*

Gu, H., Song, G., Dhonde, H., Mo, Y.L. and Yan, S. (2006), "Concrete early age strength monitoring using embedded piezoelectric transducers", *Smart Mater. Struct*., **15**, 1837-1845.

Güemes, A. (2006), "Structural health monitoring", *Proceedings of the 3rd European Workshop – DEStech Publications Inc.*, Lancaster, Pennsylvania.

Guyomar, D. and Lallart, M. (2009), "Mechanical to electrical energy conversion enhancement and self-powered wireless applications", *Proceedings of the IV ECCOMAS Thematic Conference on Smart Materials and Structures* Porto, Portugal.

Hafez, M. (2006), *Polymer based actuators as artificial muscles*, FSRM Training in Microsystems Course, Teaching Resources, Zurich.

Han, B., Yu, X. and Kwon, E. (2009), "A self-sensing carbon nanotube/cement composite for traffic monitoring", *Nanotechnology*, **20**(44), doi:10.1088/0957-4484/20/44/445501.

Hassan, M.R., Scarpa, F. and Mohamed, N.A. (2009), "In-plane tensile behavior of shape memory alloy honeycombs with positive and negative Poisson's ratio", *J. Intel. Mat. Syst. Str*., **20**(8), 897-905.

Hiroki, G., Mami, T., Kentaro, H., Jiang, Z., Hidetoshi, M., Yoshikatsy, T., Seiichi, O. and Seiji, C. (1998), "Urethral valve using shape memory alloy actuators. Development of induction-heating system", *Nippon Kikai Gakkai Robotikusu. Mekatronikusu Koenkai Koen Ronbunshu*, 2AII3.3(1)-2AII3.3(4).

Huefner, S. (2006), "Nanobiosensors" (*http://www.chem.usu.edu*).

Hull, P.V., Canfield, S.L. and Carrington, C. (2004) "A radiant energy-powered shape memory alloy actuator", *Mechatronics*, **14**(7), 737-859.

Ihn, J.B. and Chang, F.K. (2008), "Pitch-catch active sensing methods in structural health monitoring for aircraft structures", *Struct.Health Monit*., **7**(5), 5-19.

Jacot, A.D., Ruggeri, R.T. and Clingman, D.J. (2000), *Shape memory alloy device and control method*, *The Boeing Company, Patent Document*, US 6499952.

Jacot, A.D. and Clingman, D.J. (2000), "Shape memory alloy consortium and demonstration", *Proceedings of the 6th SPIE Smart Structures and Materials Symposium.*

Janocha, H. and Kuhnen, K. (2009), "Solid-state actuators with inherent sensory capabilities", *Proceedings of the IV ECCOMAS Thematic Conference on Smart Materials and Structures, SMART' 09* Porto, Portugal.

Kaiser, W. and König, W. (2006), *Geschichte des Ingenieurs. Ein Beruf in sechs Jahrtausenden*, Carl Hanser Verlag München, Germany.

Kesselring, F. (1951), *Bewertung von Konstruktionen*, VDI Verlag Düsseldorf, Germany.

Kesselring, F. (1954), *Technische Kompositionslehre*, Springer Berlin, Germany.

Lelieveld, C.M.J.L. (2013), *Smart materials for the realization of an adaptive building component*, Ph.D. doctoral Thesis, Delft University of Technology.

Lelieveld, C.M.J.L. and Jansen, K.M.B. (2013), "Design and thermal testing of smart composite structure for architecture applications", *Proceedings of the 6th ECCOMAS Conference on Smart Structures and Materials*.

Lelieveld, C.M.J.L. and Voorbij, A.I.M. (2008), "Dynamic material application for architectural purposes", *Adv. Science Technol*., **56**, 595-600.

Leng, J.S. (2007), "Electrical conductivity of shape memory polymer embedded with micro Ni chains", *Appl. Phys. Lett*., **91,** 014104.

Leng, J.S., Huang, W.M., Lan, X., Liu, Y.J., Liu, N., Phee, S.Y. and Du, S.Y. (2008), "Significantly reducing electrical resistivity by forming conductive Ni chains in a polyurethane shape-memory polymer/carbon black composite", *Appl. Phys. Lett*., **92**(20), 206101.

Leng, J.S., Lan, X., Liu, Y. and Du, S.Y. (2009), "Electroactive thermoset shape memory polymer nanocomposite filled with nanocarbon powders", *Smart Mater. Struct*., **19**, 074003.

Leng, J.S., Lu, H., Liu, Y. and Du, S.Y. (2007), "Electro-active shape memory polymer filled with nanocarbon particles and short carbon fibers", *Appl. Phys. Lett*., **91**, 144105.

Li, P., Gu, H., Song, G., Zheng, R. and Mo, Y.L. (2010), "Concrete structural health monitoring using piezoceramic-based wireless sensor networks", *Smart Struct. Syst*., **6**(5), 731-748.

Li, S. and Lipson, H. (2009), "Vertical-stalk flapping-leaf generator for parallel wind energy harvesting", *Proceedings of the ASME/AIAA Conference on Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS 2009.*

Li, S., Yuan, J., and Lipson, H. (2011), "Ambient wind energy harvesting using cross-flow fluttering", *J. Appl. Phys*., **109**(2), 026104.

Liu, Y., Lu, H., Lan, X. and Leng, J.S. (2009), "Review of electro-activate shape-memory polymer composite", *Compos. Sci. Technol*., **69**(13), 2064-2068.

Luo, Y., Takagi, T., Maruyama, S. and Yamada, M. (2000), "A shape memory alloy actuator using Peltier modules and R-phase transition", *J. Intel. Mat. Syst. Str*., **12**, 721-728.

Lyshevski, L.E. (2003), "Nanoactuators: Novel synchronous reluctance nanomachines", *IEEE Nano2003*, **2**, 295-298.

Matousek, R. (1957), *Konstruktionslehren des allgemeinen Maschinenbaus*, *Springer* Berlin, Germany.

Mavroidis, C., Bar-Cohen, Y. and Bouzit, M. (2006), "Haptic interfaces using electrorheological fluids", in Bar-Cohen Y, "Electroactive polymer (EAP) actuators as artificial muscles: Reality, potential and challenges", *SPIE Press*, 2nd Ed., Washington.

Midé Technology, "Volture TM Vibration energy harvester & Volture TM Solar energy harvester" (www.mide.com/products/volture)

Mohr, R., Kartz, K., Wiegel, T., Lucka-Gabor, M., Moneke, M. and Lendlein, A. (2006), "Initiation of shape-memory effect by inductive heating of magnetic nanoparticles in thermoplastic polymers", *Proceedings of the National Academy of Science,* **103**, 3540-3545.

Montemango, C., Bachand, G.D., Stelick, S. and Bachand, M. (1999), "Constructing biological motor powered nanomechanical devices", *Nanotechnology*, **10**, 225-231.

Müller, C.W., Pfeifer, R., El-Kashef, T., Hurschler, C., Herzog, D., Oszwald, M., Haasper, C., Krettek, C. and Gösling, T. (2010), "Electromagnetic induction heating of an orthopaedic nickel-titanium shape memory device", *J. Orthop. Res*., **28**(12), 1671-1676.

Niemann, G. (1950, 1962, 1975), *Maschinenelemente*, Springer Berlin, Germany.

Olmi, C., Song, G. and Mo, Y.L. (2007), "An innovative and multi-functional smart vibration platform", *Smart Mater. Struct*., **16**(4), 1302-1309.

Park, G., Ruggiero, E. and Inman, D.J. (2002), "Dynamic testing of inflatable structures using smart materials", *Smart Mater. Struct*., **11**(1), 147-155.

Park, G., Muntges, D.E. and Inman, D.J. (2001), *Self-monitoring and self-healing jointed structures*, Center for Intelligent Material Systems and Structures – Virginia Polytechnic Institute and State University.

Peairs, D.M., Park, G. and Inman, D.J. (2004), "Practical issues of activating self-repairing bolted joints", *Smart Mater. Struct*., **13**(6), 1414-1423.

Porfiri, M. (2009), "An electromechanical model for sensing and actuation of ionic polymer metal composites", *Smart Mater. Struct*., **18**, 015056.

Razumiene, J., Gureviciene, V., Barkauskas, J., Bukauskas, V. and Setkus, A. (2009), "Novel combined template for amperometric biosensors with changeable selectivity", *Proceedings of the 2nd International Conference on Biomedical Electronics and Devices – Biodevices 2009*, Porto, Portugal.

Ribeiro, C., Gomes, P.J., Ribeiro, P.A. and Raposo, M. (2009), "Polymeric film sensors based on PAH-PAZO ionic self-assembled multi-nanolayers", *Proceedings of the 2^nd^ International Conference on Biomedical Electronics and Devices – Biodevices 2009*, Porto, Portugal.

Rocco, M.C. and Bainbridge, W.S. (2002), *Converging technologies for improving human performance: Nanotechnology, biotechnology, information technology and cognitive science*, NSF/DOC sponsored report.

Roozenburg, N. and Eeckels, J. (1995), *Product design: fundamentals and methods*, John Wiley & Sons New York, USA.

Sánchez, A.M., Prieto, R., Laso, M. and Riesgo, T. (2008), "A piezoelectric minirheometer for measuring the viscosity of polymer microsamples", *IEEE T. Ind. Electron.*, **55**(1), 427-435.

Seesing, D. (2010), *Symbiosis concept vehicle*, Energy Efficient Alliance – Pilkington Vehicle Design Award.

Sokolov, A., Apodaca, M.M., Grzybowski, B.A. and Aranson, I.S. (2009), "Swimming bacteria power microscopic gears", *PNAS*, **107**(3), 969-974.

Song, G., Gu, H., Mo, Y.L., Hsu, T.T.C. and Dhonde, H. (2007), "Concrete structural health monitoring using piezoceramic transducers", *Smart Mater. Struct.*, **16**(4), 959-968.

Song, G., Gu, H. and Mo, Y.L. (2008), "Smart aggregates: Multi-functional sensors for concrete structures - A tutorial and a review", *Smart Mater. Struct.*, **17**(3), 1-17.

Song, G., Mo, Y.L., Otero, K. and Gu, H. (2006), "Health monitoring and rehabilitation of a concrete structure using intelligent materials", *Smart Mater. Struct*., **15**(2), 309-314.

Soong, R.K., Bachand, G.D., Neves, H.P., Olkhovets, A.G., Craighead, H.G. and Montemagno, C.D. (2000), *Science,* **290**(5496), 1555-1558.

Sterzl, T., Winzek, B., Quandt, E., Mennicken, M., Nagelsdiek, R., Keul, H. and Hoecker, H. (2003), "Bistable shape memory thin film actuators", *Proceedings of the SPIE – Conference on Smart Structures and Materials 2003: Active Materials – Behavior and Mechanics*, **5053**(101).

Takashima, K., Rossitera, J. and Mukaia, T. (2010), "Mc Kibben artificial muscle using shape-memory polymer", *Sensor. Actuat. A - Phys*., **164**, 116-124.

Tschochner, H. (1957), *Konstruieren und Gestalten*, Girardet Essen, Germany.

Ulrich, K. and Eppinger, S. (2007), *Product design and development*, Mc-Graw Hill / Irwin 4th Ed., New York, USA.

Wakasa, Y., Watanabe, Y., Yoshida, A., Tanaka, T. and Ashaki, T. (2008), "Response improvement of shape memory alloy actuators with Peltier elements", *Proceedings of the 2008 IEEE International Conference on Mechatronics and Automation.*

Warwick, K. (2008), "Outthinking and enhancing biological brains", *Proceedings of the International Conference on Biomedical Electronics and Devices Biostec 2008 – Biodevices*, Keynote Lecture.

Wilson, T., Small IV, W., William, B.J., Bearinger, J.P. and Maitland, D.J. (2005), "Shape memory polymer therapeutic devices for stroke", *Smart Medical and Biomedical Sensor Technology III. Proceedings of the SPIE,* **6007**, 157-164.

Winzek, B., Sterzl, T., Rumpf, H. and Quandt, E. (2003)m "Composites of different shape memory alloys and polymers for complex actuator motions", *J. de Physique,* **4**(112), 1163-1168.

Zupan, M., Asby, M.F., Fleck, N.A. (2002), "Actuator classification and selection – The development of a database", *Adv. Eng. Mater*., **4**(12), 933-940.

Appendix: Verified combinations of smart materials

Table 1 Summary of already verified combinations of smart materials

	Bimetals, trimetals, bilayers	**Shape memory alloys**	**Shape memory polymers**	**Electroactive polymers**	**Piezoelectric polymers**	**Piezoelectric ceramics**	**Pyroelectric materials**	**Peltier devices**
Bimetals, trimetals, bilayers						Anton 2006		
Shape memory alloys		Winzek 2003	Winzek 2003, Lelieveld 2013			Song 2006, Olmi 2007		Luo 2000, Abadie 2002, Wakasa 2009
Shape memory polymers		Winzek 2003, Lelieveld 2013						Díaz Lantada 2010
Electroactive polymers				Bar-Cohen 2004, Janocha 2009, Porfiri 2009				
Piezoelectric polymers					Janocha 2009	Dosch 1992, Dunsch 2007	Castro 2006, Díaz Lantada 2009	
Piezoelectric ceramics	Anton 2006	Song 2006, Olmi 2007			Dunsch 2007	Anton 2008, Janocha 2009	Castro 2006, Díaz Lantada 2009	
Pyroelectric materials					Castro 2006, Díaz Lantada 2009	Castro 2006, Díaz Lantada 2009		
Peltier devices		Luo 2000, Abadie 2002, Wakasa 2009	Díaz Lantada 2010					
Mc Kibben muscle / inflatable			Takashima 2010		Park 2002			

actuators									
Joule effect materials		Abadie 2002	Liu 2009, Leng 2009, Díaz Lantada 2010	Watanabe 2005					
Induction effect heating		Hiroki 1998, Müller 2010	Buckley 2007, Vialle 2009, Díaz Lantada 2009			Gao 2009			
Hydropolymers				Porfiri 2009					
MR Fluids		Mavroidis 2002, Olmi 2007		Mavroidis, Bar-Cohen, Bouzit 2004	Mavroidis, Bar-Cohen, Bouzit 2004	Mavroidis, Bar-Cohen, Bouzit 2004, Olmi 2007			
Photoactive materials		Hull 2004, Gao 2006	Lendlein 2005, Leng 2010	Bar-Cohen 2004, Franzke 2013					
Photosensible materials				Kennedy, in Bar-Cohen, 2004					
Photoelectric / photovoltaic materials				Colozza 2007	Volture TM Energy harvester, Seesing 2010, Piezo Tree	Anton 2008, Seesing 2010, Piezo Tree			
Negative Poisson ratio (auxetics)		Hassan 2009	Díaz Lantada 2011						
Magneto-strictive						Bourouina 2002			

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