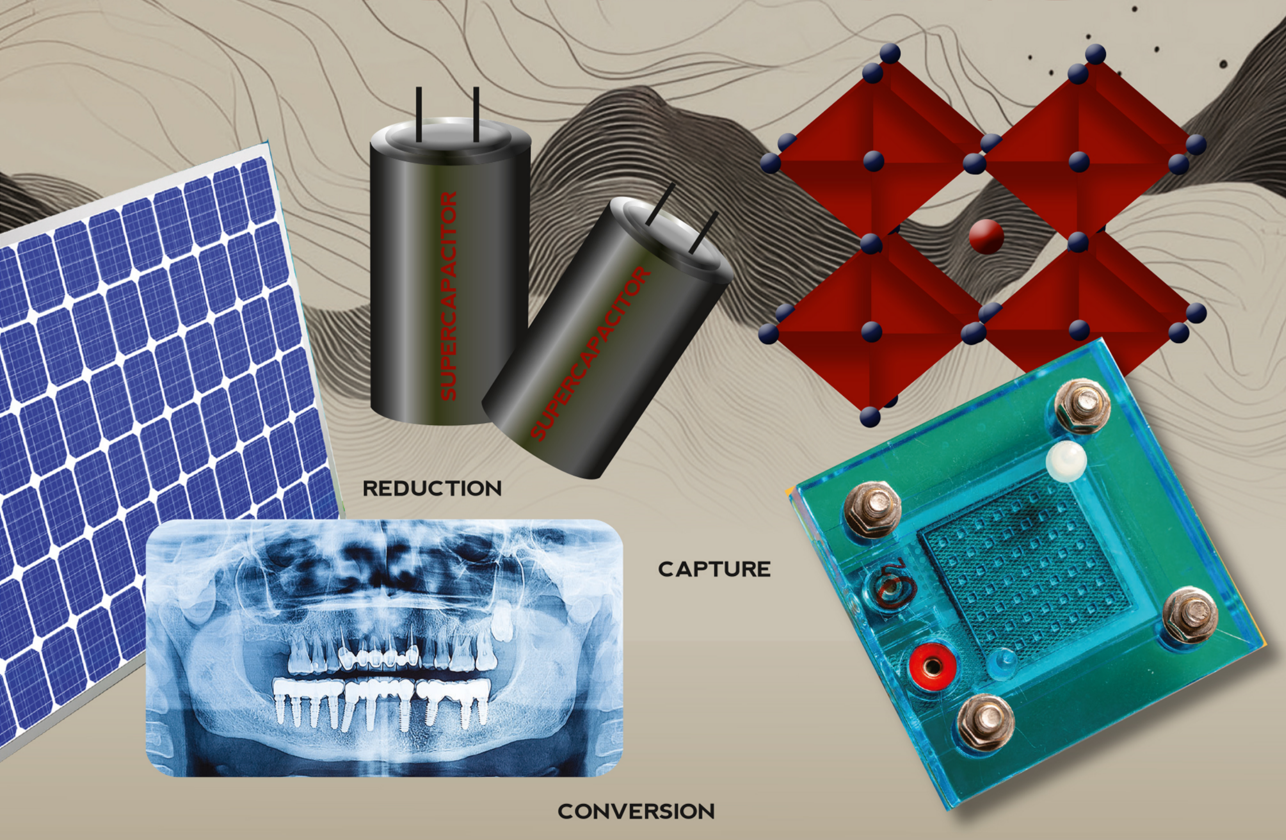
SMART MATERIALS FOR SCIENCE AND ENGINEERING



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Dedicated
to ours
Authors, Collaborators
&
Beloved Parents

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Preface

Advanced and creative materials are other names for smart materials. They can be described as advanced materials that react intuitively to environmental changes or as materials that can return to their original shape in response to certain stimuli. Based on their characteristics, such as active or passive response, smart materials are classified. There are two types of active materials; the first kind cannot change its characteristics when subjected to outside stimuli, such as photochromatic spectacles, which only alter their colour when exposed to sunlight. The other kinds, like piezoelectric materials, can change one sort of energy (thermal, electrical, chemical, mechanical, and optical) into another. When subjected to external pressure, it can generate an electric charge. As an example, optical fibers can transmit electromagnetic waves. In contrast, passive smart materials can transmit a specific sort of energy. They have some amazing qualities that set them apart from other materials, such as transiency—they can react to different kinds of external stimuli, immediacy—the response time is much shorter, self-actuation—the capacity to change their appearance and shape, selectivity—the response is divided and expected, directness—the response is limited to the activating event, shape-changing—the material can change its shape to external stimuli, self-diagnostic—their ability to determine their own health, and self-healing – their ability to recover and fixed issue by themselves.

The ability to synthesize novel materials has substantially progressed thanks to science and technology over the past 20 years. They fall mostly into the following four categories: polymers, ceramics, metals, and smart materials. Among these, smart materials are gaining in popularity since they have more uses than conventional materials. Smart materials are unusual substances that have the ability to alter their properties, such as those that can immediately change their phase when placed near a magnet or their shape simply by applying heat. The human race will be significantly impacted by this new era of smart materials. For instance, some of them can adapt their properties to the environment, some have sensory capabilities, some can repair themselves automatically, and some can degrade themselves. These extraordinary properties of smart materials will have an effect on all facets of civilization. There are many different types of intelligent materials, including magnetorheological materials, electro-rheostat materials, shape memory alloys, piezoelectric materials, and more. This book describes many forms of smart materials and their possible uses in various fields. Thus, this book titled "*Smart Materials for Science and Engineering*" cover most of the significant areas of smart materials and useful for the readers.

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Scope of the Book

The present book gives a complete description about the different types of smart materials. In this book, a literature survey discusses the different types of smart materials such as based ceramics, polymers, organic compounds, etc., and their need, advantages, disadvantages, and applications will be comprehensively discussed. In this book, the discussion about the well investigated smart materials including piezoelectric, Magnetostrictive, shape memory alloys, electro-rheological fluid, and magnetorheological fluid will be discussed with their present prospects and current literature survey.

This book covers the various aspects of the smart materials. Chapter 1 describes the detailed introduction of the smart materials, historical overview and future prospective. Fabrication and characterization of the smart materials are discussed in Chapter-2. Chapter-3 and Chapter-4 provides the details about medical application in dental science and tissue engineering. The various application and preparation strategies of the smart materials are discussed in the Chapter-5 to Chapter-8. The energy storage applications of the smart materials are discussed in Chapter-9 to Chapter-12. The fuel cells and biofuel cell applications are discussed in Chapter-13 and Chapter-14. The CO_2 reduction, capture and semiconductor application from the smart materials are discussed in Chapter-15 and Chapter-16, respectively. Further, the futuristic microelectronics from the smart materials are discussed in Chapter-17. Hence, this book is quite beneficial for undergraduate, post-graduate, Ph.D. scholar, Post-Doc fellow, faculty and scientist working in interdisciplinary areas to understand fundamentals of smart materials, their advantages, disadvantages, and applications in various societal and smart city problems.

1

Introduction: Historical Overview, Current and Future Perspective

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Abstract

Human civilization was dependent on the use of materials in the ancient era as it is today. Humans started using stone before progressing to functional nanomaterials; today, humans benefit from using new advanced materials named smart materials. In the present scenario, humans develop different types of smart materials like piezoelectric materials, magnetostrictive materials, dielectrics, thermoelectric materials, nano-medicines, shape-memory alloys, and rheological fluids. These types of smart materials are applicable for sensing devices, data storage, fast commutation, cloud computing, and different engineering as well as medical tools and equipment. Biodegradable and low-cost smart materials will develop due to the synthesis of different amalgamation of materials in the future. The newly developed smart materials may be rapidly used in the engineering, medical, and the information technology sectors.

This book chapter aims to promote awareness on smart materials for the extensive research and knowledge enhancement for new applications in the future. Historical views and modern and future perspectives of smart materials are discussed in this chapter.

Keywords: Historical overview, smart materials, current prospective, future prospective, application of smart materials

1.1 Introduction

In ancient times, humans used different materials for various purposes, due to which there was an enhancement in their living standards. Civilizations were categorized on the basis of their invention of material; the primary age was the Stone Age. Bronze Age was the most radical and was more sustainable. The development of bronze signified the start of a new metallurgical age, which saw the synthesis of numerous materials. Engineering and technology have made significant advancements in the manufacture of novel materials during the last two decades. They could be subdivided primarily into four groups: polymers, ceramics, metals, and smart materials. Because they have more applications than traditional materials, smart materials are among them and are growing in popularity. Smart materials

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are unique materials with the capability of changing their properties, such as substances that may instantly change their phase when placed near a magnet or their shape by simply reheating. These unexpected abilities of advanced material will have an effect on every aspect of civilization [1].

The terms "smart," "intelligent," and "adaptive" were first used to describe the newly developing field of research that involved incorporating electro-active efficient materials in massive structures as in actuators and *in situ* sensors in the beginning of the 1980s. Tiny and microstructure transducers and precise mechatronics (mechanical + electrical) controllers constituted the only applications for electro active materials in the past [2].

Mecha, which signifies mechanical, and tronics are terms from the fields of electrical and electronic engineering, etc. Also included is digital engineering. In the other meaning, as produced items and technologies are advanced, it will become gradually difficult to distinguish the electronics between how deeply and naturally they are incorporated into processes. When seen in the context of systems design, the field of mechatronics could be characterized as the intersection of these three main domains rather than just the total of the three. Figure 1.1 [3] depicts mechatronics' multidisciplinary approach. "The effective integration of electronic control, systems thinking, and precision mechanical engineering in the design of goods and industrial processes" [4].

During the 19th century, mechanical engineering as a popular discipline saw a burst in growth as it established the groundwork of successful and quick advancement for the revolution of the industry. Mechanical, electrical, civil, and chemical engineering were the four main engineering disciplines of the 20th century. These disciplines still have their own bodies of knowledge, textbooks, and professional journals since they are thought to have separate intellectual and professional domains. Entrants might evaluate their unique intellectual abilities and select one of the fields as a career. The information revolution is a current scientific and social change that we are currently witnessing, and oddly, engineering expertise appears to be both concentrating and diversifying. The advancement of engineering electronics that has sparked communication and information that revolutionized people is what gave rise to this modern revolution. One of the newest and most fascinating areas of engineering is mechatronics, which incorporates elements of more established disciplines

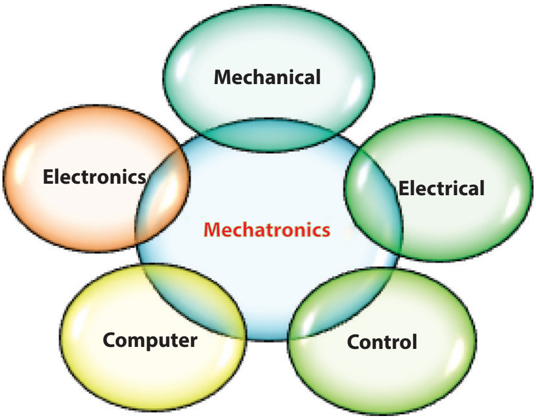

Figure 1.1 Mechatronics: a multi-disciplinary approach [4].

and necessitates a more comprehensive approach to the design of what we can properly refer to as mechatronic systems. So, exactly what is mechatronics? The word "mechatronics" refers to a multidisciplinary subject of engineering that is currently in rapid development. The term "mechatronics" was first used in Japan in the late 1960s; it later gained popularity in Europe and is now widely used in the US. Mechatronic system design primarily draws on the fields of mechanics, semiconductors, controls, and computer engineering.

An engineer of mechatronic systems must be capable of construction and choose digital and analogical circuitry systems, micro-processor-based elements, mechanical components, actuators, and sensors so that the finished result meets the necessary objectives. Smart devices are another name for mechatronic systems. Although a specific definition of the word "smart" is elusive, in the context of engineering, we refer to the incorporation of aspects like computing, logic, and feedback system that are combined in a complex design, which may appear to emulate human thought procedures. The engineering of mechatronic systems requires knowledge from numerous domains, making it difficult to encapsulate within a traditional field of engineering. The designer of mechatronic systems needs to be a generalist who is eager to learn from a variety of sources and apply it to their work. The learner may initially feel intimidated by this, yet it has many advantages for originality and lifelong learning. Nowadays, almost all mechanical machines come equipped with electrical parts and some kind of computer monitoring or control. As a result, a widespread array of system and components fall under the mechatronic systems. Microcontrollers are being included into electromechanical devices increasingly frequently, giving system designers far greater flexibility and control. All the components of an engineering mechatronic system are shown in Figure 1.2. The interface circuit between the input/output and control circuits are controlled by the digital devices [3].

The engineering disciplines that deal with the design of controlled electromechanical systems are currently in a process of evolutionary transformation. A mechanical system that is computer controlled is referred to as mechatronic. Control decisions are frequently made by an embedded computer rather than a general-purpose computer. Yaskawa Electric Company engineers originally used the term "mechatronics" Nowadays, an embedded computer controller is almost built into every electromechanical system. As a result, concerns with computer hardware and software are included in the discipline of mechatronics when applied to the control of electromechanical systems. The field of mechatronics as we know it today would not exist if cheap microcontrollers were not widely available for the

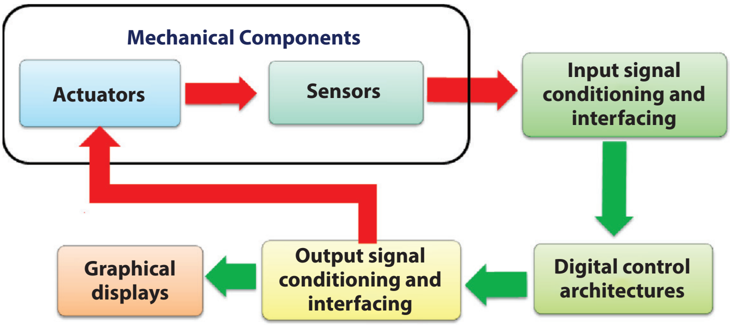

Figure 1.2 Mechanical components in mechatronics system.

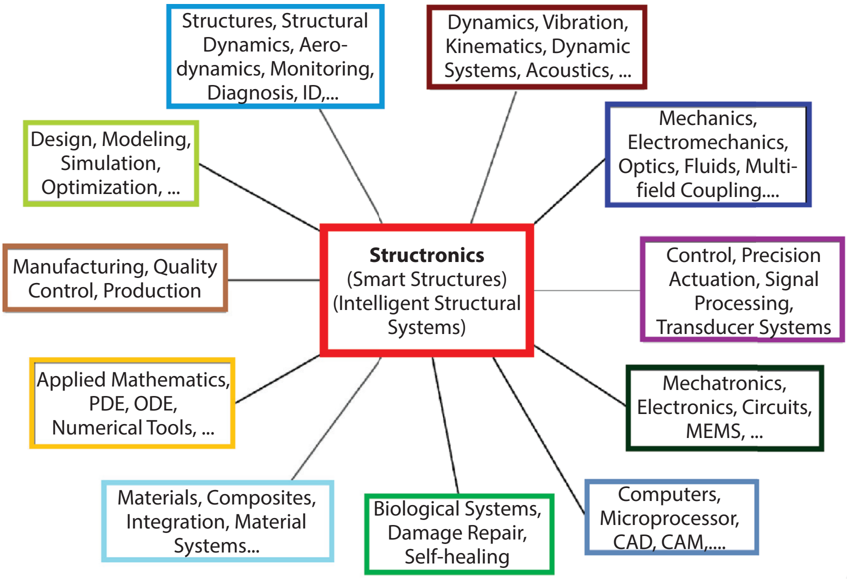

Figure 1.3 Structronics—A multidiscipline integration.

mainstream market. The application of computer control in countless consumer products is made possible by the accessibility of embedded microprocessors for the mass market at continually decreasing cost and rising performance. The preceding model [3] is the outdated model for an electromechanical product design team.

(i) Engineers who design a manufacturer's mechanical parts;
(ii) Engineers who create a product's electrical parts, including actuators, sensors, amplifiers, and other devices, as well as the control logic and algorithms;
(iii) Computer hardware and software developers who design the real-time controls for the product.

Adaptive materials or structures, and smart and intelligent materials are generally thought to have the capacity to be sophisticated, trendy, and active. In Figure 1.3, the structronic system is depicted. As a consequence, the objective of this study is to discuss the fundamental properties, design concepts, and real-world uses of the major smart materials listed in Table 1.1, the smart materials that have been studied. Also covered are the specifications for multifield optothermoelectro mechanical systems, which are used to solve various challenging field control problems coupling thermal, magnetic, electric, magnetic, and optical interactions [2].

1.2 Historical Overview of Smart Material

In 1880, quartz crystals were subjected to mechanical forces and the Curie brothers (Jacques and Pierre) detected the creation of electric fields on the crystals (the Greek

Table.1.1 Different eras smart materials [2].

Smart materials	Time periods
Pyroelectrics	315 B.C.
Piezoelctric	1880
Electro and Magneto-rheological Fluids	1784/1947
Superconductors	1911
Electro and Magneto-strictive Materials	1954/1840
Shape-memory Material	1932
Polyelectrolyte Gels (pH muscles)	1949
Photostrictive Material	1974

word piezo means "push"). When the crystal was exposed to electric fields and they also saw strain formation. In general, the piezo-electricity is an electro-mechanical phenomenon that couples the electric (static coupling) and elastic (dynamic coupling) fields. The direct piezoelectric effect is a piezo-electric material that responds to stresses or pressures of mechanical property by producing voltages. The inverse piezoelectric effect is the ability of electric charges or fields to cause mechanical stresses or strains in a material.

Chang and Read discovered shape-memory-like behavior in a gold cadmium (AuCd) sample for the first time in 1932. Later on, in 1938, brass underwent this shape change, and in 1951, an AuCd bend bar did as well. Buehler, Gilfrich, and Wiley did not discover the whole shape-memory effect in various nickel–titanium alloys until 1962. The most popular shape-memory alloy (SMA) is commercially manufactured as nitinol (NiTi). Military high-performance hydraulic systems used the Cryofit hydraulic pipe coupling, which Raychem successfully manufactured in 1969. In Japan, demand for SMA goods significantly rose during the 1970s.

The ER feature was first noted by Winkler in 1784. The Winslow effect is occasionally used to refer to the ER phenomenon because Winslow continued to rigorously study ER property variations in 1947. Colloidal suspensions known as ER fluids undergo significant property changes in response to an appropriate electrical field.

Polymeric solutions known as ionic polymeric gels have the capacity to change their physical characteristics in response to external environmental factors like pH, electrical charge and field, and so on. A paper on the ionization-induced swelling and contraction of polymeric acids is published in 1949 by Katchalsky and Kuhn. Although many novel polymers were found between 1988 and 1991, little work was started until the early 1990s theoretically. To ascertain characteristics of several of the older polymers, tests had to be conducted. Some gel qualities still need to be determined experimentally because not all gels are now covered by theories that can predict polymer bf.

Michael Faraday demonstrated in 1845 that polarized light's polarization angles may be altered by passing through a thick glass sheet fastened to the poles of a strong magnet. The magnetooptical effect is sometimes known as the Faraday effect.

The disappearance of mercury wire's resistance as the temperature approaches zero degrees Fahrenheit was originally noticed by Kamerlingh Onnes in 1911. A new era of superconductivity began as a result of this observation. At room temperature, ion oscillations within the lattice structure of metallic conductors and material impurities, flaws, and imperfections cause electrical resistance. The resistance brought on by the vibrating ions, however, reduces as the temperature of some materials rises. When the temperature falls below a specific level, known as the critical temperature. Various nonmagnetic elements, alloys, and compounds transform into a superconductive state [2].

1.3 About Smart Materials

Any new material that can be controlled and experiences a macroscopic change in one of its physical and mechanical properties as a result of a non- mechanical external stimuli is described as a smart material [5]. Advanced or intelligent materials are other names for smart materials. They can be described as sophisticated materials that react intelligently to environmental changes or as materials that can return to their basic shape in response to certain stimuli. Intelligent materials are categorized into two parts: active and passive smart materials. Active smart materials can transport electromagnetic waves; examples of passive smart materials are fiber optics. Additionally, there are two categories for active materials. For example, photochromatic spectacles only change colour when placed in sunlight; they cannot modify their attributes when subjected to external stimuli. The capability of intelligent material to change their shape in response to external stimuli is self-diagnostic; they are capable of automatically detecting cracks on their surfaces, and are self-healing when damaged [1].

Table 1.2 Type of smart materials [5].

Stimulus	Active materials	Semi-active materials
Thermal Field	Shape Memory Alloys (SMAs) Shape Memory Plymers (SMPs);	• Magnetorheological Fluid (MRF) • Electrorheological Fluid (ERF) • Magnetorheological Elastomers (MRE)
Magnetic Field	Magnetic Shape Memory Alloys (MSMAs); Magnetostrictive Materials;	
Electric Field	Electrostrictive Materials; Piezoelectric Materials; Dielectric Materials; Photomechanical Materials;	