INTELLIGENT

STRUCTURES

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Preface

An International Workshop on Intelligent Structures was held on 23–26 July 1990 in Taipei, Taiwan. The main objective was to bring together world-leading experts and active researchers in the field, to exchange technical information and to interact with each other in this emerging field of research.

The emphasis was placed on the development, application and modification of active/hybrid control theories, through innovative materials processing and systems concepts, to achieve designed intelligence of civil engineering structures. The Workshop served as an open forum to look into the future research and development needs, and to stimulate cooperative research efforts among investigators of different countries.

The technical program of the Workshop was organized around the following three major theme areas:

- Sensing and monitoring techniques
- Structural control
- Intelligent systems

Included in the program were four keynote lectures which set the stage for over twenty technical presentations of a multidisciplinary nature. The keynote papers were presented by C. A. Rogers (Virginia Polytechnic Institute and State University), T. Kobori (Kajima Corporation), G. W. Housner (California Institute of Technology) and B. K. Wada (Jet Propulsion Laboratory).

The Workshop was developed jointly by the Chinese–American Association for Natural Disaster Reduction and the National Central University, Taiwan. Financial support was provided by the National Science Council in Taiwan (Republic of China) and the Sino-American Foundation.

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An Introduction to Intelligent Material Systems and Structures

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ABSTRACT

Man has always used nature as a source of inspiration for his engineering, both in design and process. The development of ideas within the area of intelligent material systems structures and systems is no exception. Zuk and Clark, in the book *Kinetic Architecture*, write "Life itself is motion, from the single cell to the most complex organism, man ... It is these attributes of motion, mobility, of change, of adaptation that place living things on a higher plateau of evolution than static forms. Indeed, survival of these living species depends on their kinetic abilities: to nourish themselves, to heal themselves, to reproduce themselves, to adapt to changing needs and environments ...". It is this concept of creating a higher form of material systems and structures by providing 'life' functions of sensing, actuation, control and intelligence to materials and structures which has inspired and motivated the initiation of this "new" field of endeavor.

This paper includes a somewhat historical account of the field of intelligent material systems and structures and describes the various concepts, definitions and classifications of materials and structures associated with intelligent systems. A brief survey of some of the actuator and sensing materials being utilized in the field of intelligent material systems will be given to illustrate the progress being made and concepts under investigation.

INTRODUCTION

'Intelligent', 'Smart', 'Sense-able', 'Adaptive' and many other terms have all been used to describe and/or classify materials and structures which contain their own sensors, actuators and computational/control capabilities and/or hardware. One of the proposed definitions of intelligent materials is materials possessing adaptive capabilities to external stimuli such as load or environment with inherent or integral intelligence. The

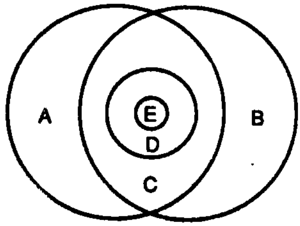

Figure 1. Proposed Framework (after Wada, Fanson, Crawley, 1990)

control or intelligence of the material could perhaps be 'programmed' by material composition, processing, defect and microstructure, or conditioning to adapt in a controlled manner to various levels of stimulus. Intelligent structures may simply be constructed of intelligent material systems or may have dedicated or integrated actuators, sensors, and intelligence in a more discrete form. The early 'Smart Materials' contained, for the most part, embedded and/or distributed sensors for strain and temperature. However, the complexity and utility of intelligence material systems has increased rapidly to the present time where major advancements seem to be occurring on a monthly basis in the areas of materials, actuators, sensors, and controls. Although intelligent material systems and structure concepts may be applied to the design and implementation of buildings, dams, bridges, pipelines, ships, and ground-based vehicles, recent research efforts have been concentrated on potential aerospace applications in advanced aircraft, launch vehicles, and large space-based platforms.

To gain an understanding of the concept and diversity of the sciences involved, two specific definitions will be presented. The first is from a paper by Wada, Fanson, and Crawley (1990) in which they attempt to develop a framework to classify structural systems. The second concept definition will be that of Takagi (1990) which is a very detailed description of the Japanese concept of intelligent materials. These two concepts will show the consensus in the paradigms but will illustrate the contrast in the scientific and engineering approach.

The performance requirements of advanced structural systems of the future, i.e., space systems, aircraft and marine vessels, have motivated a new approach to structural and material design. Wada, Fanson and Crawley use this fact to motivate an attempt at proposing a general framework for categorizing various approaches being pursued to add intelligence to structural systems. Their primary interest is of structural systems for precision space structures. Their proposed general framework is illustrated in Figure 1, which embraces a broad context of structural control approaches. The following explanation of their definitions and concept is taken from their paper:

The two most basic categories are the *sensory* structures, those which possess sensors that enable the determination or monitoring of system states or characteristics, and the *adaptive* structures, those which possess actuators that enable the alteration of systems states or characteristics in a controlled manner. A sensory system may possess sensors for health monitoring, but possess no actuators. Conversely, an adaptive system may possess actuators for a controlled deployment, but have no sensors.

The intersection of sensory and adaptive structures are the *controlled* structures, those with both sensors and actuators in a feedback architecture for the purpose of actively controlling system states or characteristics. It is somewhat arbitrary (and may expose the predisposition of the authors) to call such systems *structures*, since in principle a controlled structure may be composed of a conventional structure and a separate and distinct control system, such as a proof mass actuator attached to a truss structure. Perhaps the main utility in such a definition is to distinguish such conventional approaches from the next category: the *active* structure.

The *active* structure is a controlled structure that contains sensors and/or actuators that are highly integrated into the structure and have structural functionality in addition to control functionality. The hybrid nature of the active structure is the point of departure from conventional approaches, and characterizes a truly integrated control/structural system. Taken to the logical extreme, the *intelligent* structure contains highly integrated control logic and electronics that provide the cognative element of a distributed or heirarchic control architecture.

Structures can be controlled in a number of different senses. For example, the objective of the control system may be to influence the mechanical properties of the structure. This includes the mechanical states (position, velocity, etc.). A structure which uses rate feedback to an actuator to increase damping is a mechanically controlled structure. Alternatively, other types of controlled structures can be contemplated. A thermally controlled structure would include a control system to influence its thermal states (temperature), or thermal properties (conductivity, absorptivity, etc.). A structure with distributed heaters and thermocouples would be an example. One might even envision a structure whose surface optical properties (hue and intensity) were controlled, or whose surface electromagnetic properties were controlled.

Japan's Concept of Intelligent Materials

Dr. Harumitsu Yoshimura of the Japan Science and Technology Agency gave a brief introduction to Japan's interest in intelligent materials at the First International Workshop on Intelligent Materials held in March 1989 at Tsukuba Science City. He stated that a few years ago the Agency began investigating the feasibility of developing "materials which can manifest their own functions intelligently depending on environmental changes". The concept and definition of intelligent materials has since been extensively studied by the Agency and the Council for Aeronautics, Electronics and Other Advanced Technologies, and the results of this study were presented by Dr. Toshinori Takagi, chairman of the Workshop.

Dr. Takagi presented the paper entitled "A Concept of Intelligent Materials in Japan" which was in essence an interim report detailing the discussion and conclusions as prepared by the members of the Materials Technology Committee and Subcommittee, Council for Aeronautics, Electronics and Other Advanced Technologies, Science and Technology Agency, Government of Japan. The interim report is a complete position paper on the motivation of and concepts for intelligent material implementation and research in Japan (a slightly modified paper was also published in the *Journal of Intelligent Material Systems and Stuctures*; Takagi, 1990). The report begins: "The science and technology, in the coming 21st century, will rely heavily on the development of new materials ... We consider "Intelligent Materials" as leading candidates for such new materials ...".

The motivation for the initial investigation of the concept of intelligent materials seems to have come from an assessment of the history of material science and mere postulation of the future of the science that the Japanese have come to dominate. "The history of materials science shows that there is a distinct trend in development from structural materials to functional materials". The effort in research and development will therefore be directed toward creation of "hyper-functional materials which surpass even biological materials in some respects. The concept of using biological materials or systems is not new to the area of intelligent materials, however, the specific interest in duplicating and mimicking biological materials is quite different to the approach being taken in the United States. In fact, it is the common philosophy of the Japanese researchers that "biological materials can be regarded as the ultimate materials". Whereas the focus within the Japanese science community appears to be in materials development, the focus in the United States has been on purpose, function, and application. The primary difference between these two approaches is that the United States scientific community is looking at nature for ideas on how to perform various functions, i.e., how does the arm perform both slewing and vibration control tasks with such high authority and precision?, whereas the Japanese scientific community is looking at nature for ideas on new synthetic materials able to perform the same adaptive functions as biological materials, i.e., can organic muscle fibers be synthesized?

The report is impressive in its scope and depth of evaluation of the future of material sciences in Japan. The description of the concept of intelligent materials begins with their definition:

- "Intelligent Materials may be defined as materials which manifest their own functions intelligently depending on environment changes."

However, their definition of 'environment' was never particularly clear. The 'concept' was explained by classifying the 'intelligence' of materials into three catagories as shown in Figure 2.

- Primitive Functions - this level constitutes essentially adaptive (which were referred to as 'primitive') functions related to sensor, effector, and processor capabilities.
- Macroscopic Functions - this level contains the intelligence inherent in materials.
- Social Utility - this level considers the intelligence of materials from the viewpoint of human beings and refers to material 'properties' that are to be classified as 'friendly', 'rational or irrational', and are 'harmonious'.

These three catagories have a hierarchy of intelligence and presumably, utility. The primitive functions are the foundation on which the macroscopic functions are realized by a step called "Incorporation of Software Systems into Materials". However, "even if the macroscopic functions' category fulfills its function successfully ... these functions

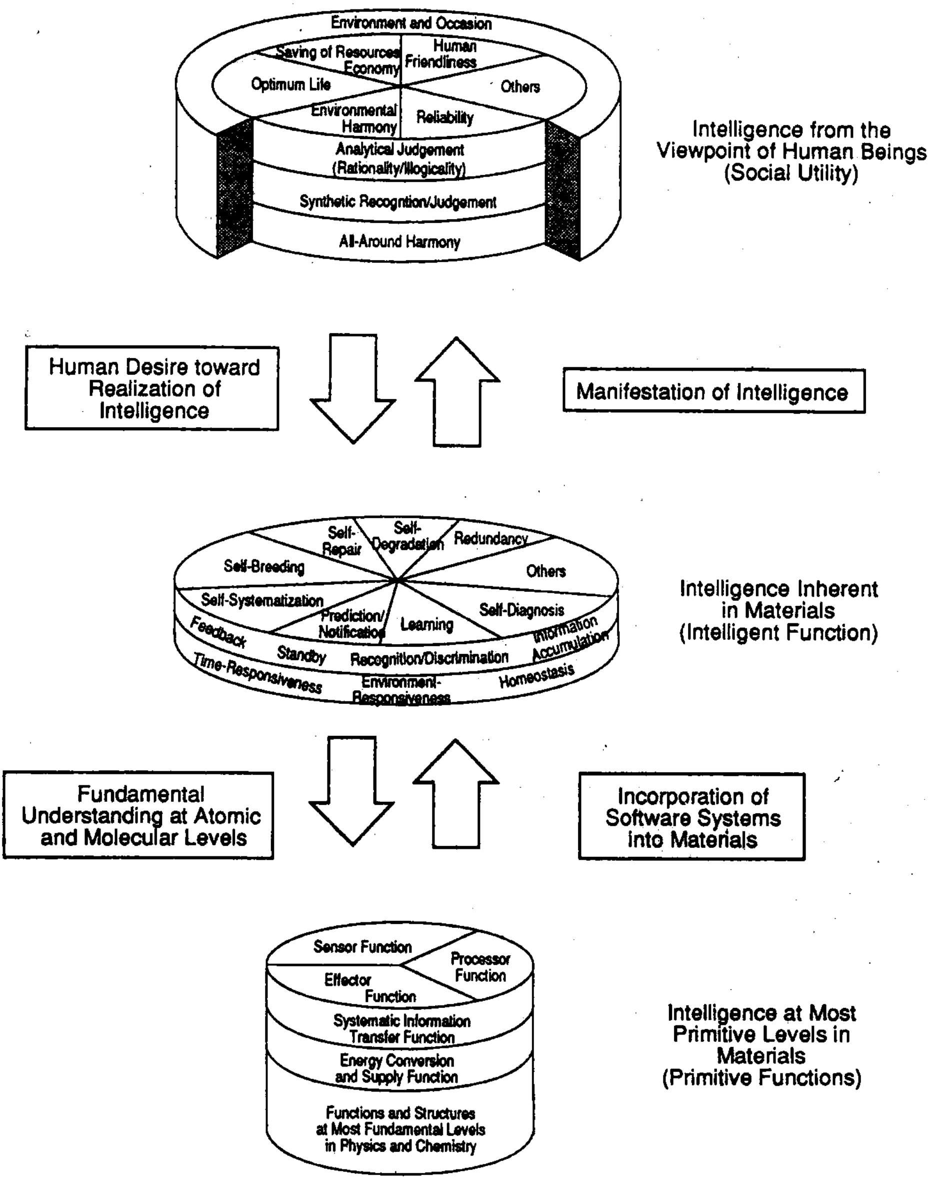

Figure 2. Schematic Representation of Intelligent (after Takagi, 1990)

may not appear to be intelligent from the viewpoint of human beings". In order to instill human-like intelligence in a material, a step called "Manifestation of Intelligence" is employed to impart functions such as:

- Human friendliness
- Reliability
- Harmony
- Optimum Life (not necessarily infinite life)
- Saving of Resources - Economy
- Intensiveness
- Analytical Judgment
- Synthetic Recognition/Judgment
- Rationality/Illogicality

One of the most impressive elements of this concept is that a committee of scientists under the authority of a government agency has defined a new technology in terms beyond those generally used in science and technology. The goals and objectives as described in this concept paper refer more to the philosophy of materials science in the future than in short term technical gains. It is clear that one of the objectives of this workshop was for the committee to begin a long-range educational program to motivate material scientists towards these goals of 'social utility'.

"The intelligence at the most primitive levels in materials consists of three functions. They are sensor functions, the effector or actuator functions, and the processor functions including the memory function". This is essentially the same definition that has been widely accepted in the United States for several years to describe the area of smart or intelligent materials. However, even with this definition, the concept is not entirely clear (and perhaps never should be). To illustrate the confusion that exists between defining the technology and actually trying to implement the concept, consider the "typical examples of intelligent materials" identified as a part of the concept paper. It is generally agreed that intelligent materials of the future may be feasible "if the materials can have built-in intelligence such as self-diagnosis, self-learning, prediction/notification, ability to standby, stimulus-reactiveness, and the ability to recognize/discriminate." Examples included:

- materials whose surface color or luster varies according to the applied load ...
- materials whose appearances vary according to the internal degree of damage ...
- materials whose mechanical and/or electrical properties vary according to its surroundings ...
- materials whose mechanical and/or electrical properties vary according to the applied load ...

- materials whose chemical composition varies according to its surroundings and/or operating conditions, thus being able to decompose by itself or to restore the degraded properties ...

These examples of materials seem to describe sensor materials which are but one of the primitive functions that act as the foundation of the concept. The concept paper even assesses the utility and feasibility of biomaterials with self-adjustable functions. Examples of such materials are:

- biomaterial which has a self-adjustability function to promote the growth of bone in the human body
- biomaterial which has a self-adjustability function to substitute for human skin, liver, kidney, pancrease, etc.
- drug delivery systems

The concept as presented by Dr. Takagi was generally well accepted by the invited participants. However, the focus of the committee's concept that individual materials may contain all of the primitive functions as well as the abstract social utility functions was not necessarily a view shared by all those present, as will be illustrated in the discussion below. It is also important to note that the Japanese concept does not favor any structural concepts or even "composite" systems, but relies primarily on the material science of essentially monolithic materials to provide these intelligent functions.

The following section will describe many of the definitions and concepts used through the workshop as well as many of the definitions that have been discussed in the United States over the past few years. The importance of such discussions is founded in perhaps the only area of mutual agreement between the diverse groups of researchers; "functions must lead the development of intelligent material systems". Whereas the objective of an intelligent material system is to perform a given function efficiently and adaptively, earnest development of this area of science will not be efficient until the function (definition) of the area is well stated and understood. The definition may, and probably should, be adaptive to allow be molded by the evolution of the science and technology.

WHAT'S IN A NAME?

In September of 1988, a workshop entitled "ARO Smart Materials, Structures, and Mathematical Issues Workshop" (Rogers, 1988), was held at Virginia Polytechnic Institute and State University. A small number of nationally recognized engineers, scientists, and mathematicians were invited to discuss the past and present state of smart materials and structures research. This workshop marked the first attempt to formally define the technology and science commonly termed smart or intelligent materials. Upon the conclusion of that workshop, the author wrote a summary paper which contained a section entitled "What's in a Name?". This section was inspired by the discussion at the workshop concerning the proper name for this new area of research. During the course of the Workshop in Japan, a similar parade of definitions and concepts for the area they call intelligent materials was discussed. For the sake of completeness, excerpts from the

ARO Workshop summary are included to allow comparisons of yet several new definitions and concepts as presented at the Workshop in Japan.

ARO Smart Materials & Structures Workshop

Materials and structures which incorporate environmental and material sensors, mechanical actuators, and electronic signal processing and adaptive control systems to produce either appropriate readouts or actuator responses for particular sensor inputs have been termed "smart", "intelligent", "sense-able", or "organic" during the past several years. In a recent cover article published in NASA Tech Briefs (Rogowski et al., 1988) on the evolution of smart materials, a much different definition was presented ... "The smart materials concept is based on the integration of sensors with materials, so that the material has its own 'nervous system', able to both sense and communicate with an outside intelligence". Recent literature contains many other definitions generally focusing on the technology or science the author is presently investigating. During the course of the workshop, all of these terms were used and defined by several of the invited participants.

Professor C. A. Rogers (1989) began the parade of definitions by defining smart/intelligent materials as "containing distributed and/or integral actuators, sensors, and microprocessors capabilities", and differentiating between smart and adaptive materials by stating that adaptive materials and structures are but a subset of smart materials and structures. For example, a structural member made of shape memory alloy (SMA) reinforced composites can compensate for deterioration in absorptivity and thermal expansion properties which result in excessive change in length of that or other members, as well as control the motion, vibration, acoustic transmission, strength, and stiffness of the structure. The same material can be used to change load paths in a structure or within the material so that the component can be replaced or repaired before it causes catastrophic failure of the system or unacceptable degradation of performance – all adaptive capabilities but not smart unless coupled to sensor and control information. Integrating adaptive technologies, with sensing technologies and control techniques result in 'smartness'.

Professor M. V. Gandhi (1989) followed with a report on a "revolutionary ultra-advanced intelligent composite material" which consists of a hollow graphite epoxy beam filled with an electro-rheological fluid. "Changes in the electrical field imposed upon the electro-rheological fluids can dramatically alter the rheological characteristics of the fluids and hence the global mass, stiffness and dissipative characteristics of the ultra-advanced composite structures. ... The revolutionary capabilities of these materials can be exploited by integrating fundamental phenomenological theories with intelligent sensor technologies and modern control strategies in order to significantly accelerate the evolution of this innovative class of multi-functional, dynamically-tunable, ultra-advanced, intelligent composite materials ...". Professor Gandhi's classification of a structural member filled with an adaptive material (ER fluid) contains at least four qualifiers or adaptive descriptors including "intelligent". Several other invited participants used the term "intelligent" in place of smart.

Another term was introduced by Professor E. I. Rivin (1989) – "passive self-adaptive