Smart Materials and Devices

Pablo G. Caceres-Valencia,
# General Information

<table>
<thead>
<tr>
<th>Course Number</th>
<th>INME 5015 and INME 6107</th>
</tr>
</thead>
<tbody>
<tr>
<td>Course Title</td>
<td>Selected Topics in Mech. Eng. Smart Materials and Devices</td>
</tr>
<tr>
<td>Credit Hours</td>
<td>3 credits</td>
</tr>
<tr>
<td>Instructor</td>
<td>Dr. Pablo G. Caceres-Valencia</td>
</tr>
<tr>
<td>Office</td>
<td>Luccetti L-212 Phone Ext. 2358</td>
</tr>
<tr>
<td>e-mail</td>
<td><a href="mailto:pcaceres@me.uprm.edu">pcaceres@me.uprm.edu</a></td>
</tr>
<tr>
<td>Web-site</td>
<td><a href="http://academic.uprm.edu/pcaceres">http://academic.uprm.edu/pcaceres</a></td>
</tr>
<tr>
<td>Office Hours</td>
<td>T-Th 7:30-10:00am</td>
</tr>
</tbody>
</table>
Assessment

The course will be assessed in the following manner:

- 1st Partial Exam 30%
- Project 30%
- Quizzes 30% (*)
- Attendance 10% (**)

(*): Date due WebCT Quizzes (4) and class participation.

(**): After the second missed class, one point will be deducted in the final grade per each missed class (up to 8 points).
Grades

<table>
<thead>
<tr>
<th>Final Grade Range</th>
<th>Final Letter Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 – 90</td>
<td>A</td>
</tr>
<tr>
<td>89 – 80</td>
<td>B</td>
</tr>
<tr>
<td>79 – 70</td>
<td>C</td>
</tr>
<tr>
<td>69 – 60</td>
<td>D</td>
</tr>
<tr>
<td>59 – 0</td>
<td>F</td>
</tr>
</tbody>
</table>

Attendance

Attendance and participation in the lecture are mandatory and will be considered in the grading. Students should bring calculators, rulers, pen and pencils to be used during the lectures. Students are expected to keep up with the assigned reading and be prepared to answer questions on these readings during lecture. Please refer to the Bulletin of Information for Undergraduate Studies for the Department and Campus Policies.


**Exams**

All exams will be conducted during normal lecture periods on dates specified dates. The final project due date is the date for the end of classes. There will be no final exam.

Neatness and order will be taking into consideration in the grading of the exams. Up to ten points can be deducted for the lack of neatness and order. You must bring calculators, class notes and blank pages to the exams.

**Texbooks**

There is no specific textbook. My lecture notes are available in the web at http://academic.uprm.edu/pcaceres

**Recommended Reading:**

“Microstructure of Martensite” K. Bhattacharya

“Smart Materials Systems: Model Development” R.C. Smith


<table>
<thead>
<tr>
<th>Week</th>
<th>Overview of Smart Materials.</th>
<th>Week</th>
<th>Classification of Smart Materials.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Crystal Structure &amp; Microstructure</td>
<td>3</td>
<td>Crystal Structure &amp; Microstructure-Quiz 1</td>
</tr>
<tr>
<td>4</td>
<td>Piezoelectric and Electrostrictive Materials</td>
<td>5</td>
<td>Piezoelectric and Electrostrictive Materials</td>
</tr>
<tr>
<td>6</td>
<td>Magnetostrictive and Magnetoelectric Materials</td>
<td>7</td>
<td>Magnetostrictive and Magnetoelectric Materials Quiz 2</td>
</tr>
<tr>
<td>8</td>
<td>Shape Memory Alloys.</td>
<td>9</td>
<td>Shape Memory Alloys</td>
</tr>
<tr>
<td>9</td>
<td>Shape Memory Alloys - Quiz 3</td>
<td>10</td>
<td>Electrorheological and Magnetorheological Fluids</td>
</tr>
<tr>
<td>11</td>
<td>Sensor, Actuator and Transducer Technologies.</td>
<td>12</td>
<td>Sensor, Actuator and Transducer Technologies</td>
</tr>
<tr>
<td>13</td>
<td>Applications of Engineering Smart Structures and Products</td>
<td>14</td>
<td>Project Presentations</td>
</tr>
<tr>
<td>15</td>
<td>Project Presentations</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Projects

Project One

(1) Pyroelectricity
(2) Piezoelectricity
(3) Magnetostriction
(4) Thermoelectricity
(5) Shape Memory Alloys
(6) Electrochromic materials

Presentation of at least 22 slides. It must cover the following: (a) physical principles, (b) tensor analysis, (c) two slides on devices and applications and (d) four numerical examples (problems).
Background

The field of smart materials has advanced rapidly in the last 15 years, due to an increasing awareness of materials capabilities, the development of new materials and transducer design, and increasingly stringent design and control specifications in aerospace, aeronautics, industrial, automotive, bio-medical and nanosystems.

Equally important for the advancement of the field is the development of models, numerical approximation techniques, and control design which accommodate the hysteresis and constitutive nonlinearities, inherent to the material.
The attributes that provide smart materials with unique actuator and sensor capabilities are inexorably due to physical mechanisms that produce hysteresis, hence these mechanisms must be incorporated in models and control designs to achieve the unique performance capabilities offered by the compounds.

**Smart System or Structure**

Smart systems are defined as ensembles whose dynamic can be monitored or modified by distributed sensors and actuators, in accordance with an integrated control law, to accommodate time-varying exogenous inputs or changing environmental conditions.
A smart structure is a system containing multifunctional parts that can perform sensing, control, and actuation; it is a primitive analogue of a biological body.

*Smart Material Based Systems (SMBS)* are defined as electro-mechanical systems integrated with sensing, actuating, control and computational functions provided by such materials. Through system integration and compact design, systems with less complexity, lower cost and higher reliability can be built.
Actuators
- Adaptive
- Response Shape
- Memory alloys,
- Piezoelectric
- devices, MR fluids

Adaptive Response

Smart System

Electronics
- Transfer of Information
- Signal detection and control.

Sensors
- gather information
- Optical fibers
- Piezoelectric
- materials

Environment
- Stimuli

Control Function

Sensory Function
**Smart Material**

Smart materials referred to materials that will undergo controlled transformations through physical interactions. The “I.Q.” of smart materials is measured in terms of their “responsiveness” to environmental stimuli and their “agility.”

**Responsiveness:**
how large is the amplitude change with respect to small stimulus.

**Agility:**
how fast is the respond.

Smart materials are materials that respond to their environment in a timely manner. These are materials that receive, transmit or process a stimulus and respond by producing a useful effect that may include a signal that the materials are acting upon it.
**Stimuli**
- Strain
- Stress
- Temperature
- Chemicals (pH stimuli)
- Electric field
- Magnetic field
- Hydrostatic pressure
- Different types of radiation

**Effects caused by**
- Absorption of a proton
- A chemical reaction
- Integration of a series of events
- Translation or rotation of segments within a molecular structure
- Creation and motion of crystallographic defects
- Localized conformations
- Alteration of localized stress
- Strain fields

**Effects produced can be:**
- Color change
- Change in index of refraction
- Change in the distribution of stresses and strains
- Volume change

### Active Actuator/Sensor Materials
Actuator materials are those capable to convert electrical, magnetic or thermal energy to mechanical energy, whereas sensor materials are those that can provide the opposite conversion of energy. Another criterion for a material to be considered smart is that the action of receiving and responding to stimuli to produce a useful effect that must be reversible.
Materials that have been labeled as smart include:

<table>
<thead>
<tr>
<th>Material</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Piezoelectric</strong></td>
<td>Crystals which acquire a charge when compressed, twisted or distorted are said to be piezoelectric</td>
</tr>
<tr>
<td><strong>Electrostrictive, Magnetostrictive and Elastorestrictive</strong></td>
<td>The material quality of changing size in response to either an electric or magnetic field, and conversely, producing a voltage when stretched.</td>
</tr>
<tr>
<td><strong>Electrorheological &amp; magnetorheological</strong></td>
<td>Fluids that can change state instantly through the application of an electric or magnetic charge</td>
</tr>
<tr>
<td><strong>Thermoresponsive - Shape memory alloys</strong></td>
<td>the dominant smart material, change shape in response to heat or cold</td>
</tr>
<tr>
<td><strong>pH-sensitive</strong></td>
<td>these are indicators that change colors as a function of pH</td>
</tr>
<tr>
<td><strong>UV-sensitive and Electrochromic</strong></td>
<td>Electrochromism is defined as the ability of a material to change its optical properties when a voltage is applied across it.</td>
</tr>
<tr>
<td><strong>Smart polymers</strong></td>
<td>Polymers that respond strongly to small changes in the external conditions.</td>
</tr>
<tr>
<td><strong>Smart hydrogels</strong></td>
<td>Engineered response gels that shrink or swell by a factor of 1000, and that can be programmed to absorb or release fluids in response to almost any chemical or physical stimulus</td>
</tr>
</tbody>
</table>
**Classification of Smart Materials**

There are many different types of smart materials including piezoelectric, shape-memory alloys, electro-active conductive polymers, electrochromic materials, biomaterials, etc.

Commonly encountered smart materials and structures can be categorized into three different levels:

(i) **single-phase materials.** Many ferroic materials and those with one or more large anomalies associated with phase-transition phenomena.

(ii) **composite materials.** Functional composites are generally designed to combine several functional materials to make a multifunctional composite, and

(iii) **smart structures.** Integration of sensors, actuators, and a control system that mimics the biological body in performing many desirable functions, such as synchronization with environmental changes, self-repair of damages, etc.
Table 3. Stimulus-response matrix for selective responsive materials [after 16].

<table>
<thead>
<tr>
<th>Response Stimulus</th>
<th>Electrical</th>
<th>Magnetic</th>
<th>Optical</th>
<th>Thermal</th>
<th>Mechanical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td></td>
<td></td>
<td>Electrochromic Electro luminescent Electro-optic</td>
<td>Thermoelectric</td>
<td>Piezoelectric Electrostrictive ER Fluids</td>
</tr>
<tr>
<td>Magnetic</td>
<td></td>
<td>Magnetooptic</td>
<td></td>
<td>MR Fluids Magnetostrictive</td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>Photoconductor</td>
<td>Photochromic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td></td>
<td>Thermochromic Thermoluminescent</td>
<td></td>
<td>Shape Memory</td>
<td></td>
</tr>
<tr>
<td>Mechanical</td>
<td>Piezoelectric Electrostrictive</td>
<td>Magnetostrictive</td>
<td>Mechanochromic</td>
<td>Negative Poisson Ratio</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2. Property-Stimulus-Response effects [after ref.18].
**Disciplines in Smart Materials - Inter-disciplinary**

**Materials science.** Requires knowledge of composites, ceramics, metallic, alloys, gels, processing science, interface science, sensor/actuator materials, chiral materials, conducting and chiral polymers, electrochromic materials, liquid crystals, molecular-level smart materials, biomaterials.

**Sensing and actuation.** Electromagnetic, acoustic, chemical and mechanical sensing and actuation, microelectromechanical systems (MEMS), sensor/actuator signal processing, smart sensors for materials and composites processing.

**Optical and electromagnetics.** Optical fibre technology, active and adaptive optical systems and components.

**Structural.** Smart skins for drag and turbulence control, other applications in aerospace/marine structures, civil infrastructures, transportation vehicles, manufacturing equipment.

**Control.** Structural acoustic control, vibration control, adaptive structure capability, damage implications for structural control.

**Information processing.** Neural network, data processing.
Natural Sciences (Physics, Chemistry, Biology) and Mathematics

**Mechanical Engineering**
- Machine components design.
- Mechanisms & linkages.
- Thermomechanics:
  - solid & fluid mechanics, heat transfer, fracture mechanics.
- Intelligent control.
- Micro process equipment design and manufacturing.
- Assembly design.

**Materials Science**
- Materials for device components & packaging.
- Materials for signal transduction.
- Smart materials, Miniaturization,
- Materials Properties
- Materials for fabrication processes.

**Electrical Engineering**
- Power supply. Electric systems design in electro-hydrodynamics.
- Signal transduction, acquisition, conditioning and processing.
- Electric & integrated circuit design.
- Electrostatic & EMI.

**Mathematics & Modeling**