# INTEGRATING "SMART" MATERIALS INTO A FIRST-YEAR ENGIENERING CURRICULUM: A CASE STUDY

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***Abstract*** *¾ Developments in materials science are creating new possibilities for engineering designs. For example, multifunctional materials, such as shape memory alloys (SMA) or piezoelectric materials are referred to as "smart" materials since designers can use properties of these materials to construct components of adaptive mechanisms. For example, researchers are using shape memory alloys (SMA) to build biomimetic systems that mimic the behavior of biological organisms such as fish or insects. The ability of SMA components to change shape in response to thermal or electrical stimuli considerably simplifies construction of biomimetic systems. As multifunctional materials are changing the practice of engineering, providing undergraduate students with exposure and experiences with these materials and their potential for new design options should be seriously explored.*

*The proposed paper presents a narrative description of how material on SMA was integrated into a first-year engineering course and a first-year engineering project. Key partners, including an undergraduate engineering student working on a research experience and a first-year graduate student, will describe their roles in integrating material into a first-year engineering course that was taught in Fall 2001. Also, data describing the impact on students and faculty will be presented.*

*Index Terms ¾ Curriculum integration, engineering projects, first-year engineering, smart materials*

## INTRODUCTION

Developments in materials science are creating new possibilities for engineering designs. For example, multifunctional materials, such as shape memory alloys (SMA) or piezoelectric materials are referred to as "smart" materials [1] since designers can use properties of smart materials to construct components of an adaptive mechanism. For example, researchers are using shape memory alloys (SMA) to build biomimetic systems that mimic the behavior of biological organisms such as fish or insects. Smart materials are able correspond to stimuli from the surrounding environment in a unique manner. For example, SMAs are able to return to their trained shape or size when they are heated to their characteristic transformation temperature. SMAs even have the ability to recover from large deformations once heated. As multifunctional materials are changing the practice of engineering, providing undergraduate students with exposure and experiences with these materials and their potential for new design options should be seriously explored.

However, integrating knowledge of new engineering topics into engineering curricula, especially lower division curricula is a challenge, in part because the curricula are already overcrowded. There is no room to add new courses, especially in the lower division curricula, without deletion of other courses and deletion of existing courses can create heated discussions, even arguments, with charges of tampering with the fundamentals of engineering. Another alternative is to integrate material into existing courses. However, this alternative presents other challenges because the faculty members who are teaching existing courses may not have extensive knowledge of the new engineering topics and researchers with requisite knowledge may not have the time or inclination to teach an entire lower division course. Partnerships among researchers with prerequisite expertise, faculty members coordinating lower division courses, graduate students, undergraduate students, and college staff may be able to provide a solution to the challenges of integrating material into existing courses.

Funded by a Combined Research and Curriculum Development (CRCD) grant from the National Science Foundation (NSF), faculty members are cooperating to adapt research in smart research to create projects, demonstrations, and experiments that will enhance current engineering curricula. For example, students and faculty members have built a SMA torsion tube that is used to introduce the theory behind SMA phase transformation while emphasizing the concept of torsion. Another example is an adaptable wing, which elaborated upon basic aerodynamic principles by allowing the student to change the shape of the wing's airfoil with SMA wires. Similar wires can also be used to make an interactive moving robot in a first-year engineering class. This robot not only illustrates basic thermodynamic concepts and conservation principles, but design, construction, and

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testing of the robot develops teamwork skills and teaches design concepts.

In one thrust of the project, knowledge about using smart materials to design intelligent systems is being integrated into existing lower division engineering courses as researchers familiar with the cutting edge research work with faculty members who are teaching these courses. In a second thrust of the project, faculty members in aerospace engineering are developing a new curriculum track on intelligent systems emphasizing aerospace technologies. The track will offer a certificate that requires fifteen credit hours of course work, a two-semester design course, and a one-on-one directed studies course with a faculty member. Completion of the certificate will be recognized on a student's transcript. In-depth information about the project can be found at its web site: http://smart.tamu.edu/CRCD.

These are the courses that have been impacted to date.

- AERO 101 – Introduction to Aerospace Engineering (F01)
- ENGR 111/112 – Foundations of Engineering I/II (F01/S02)
- ENGR 211/213/214 –Basic engineering science courses (S02, F02)
- AERO 302 – Aerospace Engineering Laboratory I (S02)
- AERO 304/306 – Structural Mechanics I/II (F01, F02)
- AERO 401/402 – Senior design sequence (F03, S04)
- AERO 405 – Aerospace Structural Design (F01)
- AERO 489* – Special Topic: MEMS for Aerospace Engineering (F01)
- AERO 489* – Special Topic: Aerospace Intelligent Systems (S02)

The last two courses, both special topics courses, are new courses that have been developed as part of the project. The purpose of the paper is to describe how information about a set of new technologies can be integrated into existing engineering curricula without creating a large number of new courses, especially in the first three years of the engineering curriculum.

The focus of the current paper is to describe how knowledge of smart materials is being introduced to first-year engineering students within the framework of existing first-year engineering courses.

## BACKGROUND ON SHAPE MEMORY ALLOYS

Philip Ball defined smart materials as "materials that carry out tasks not as a consequence of signals or impulses passed from one component to another... but as a result of their intrinsic properties."[1] This means that these materials are able to respond to a particular stimulus from the environment in a unique way due to their internal physical structure. For example, shape memory alloys (SMAs) respond to heat in their environment by transforming to their original shape.

Shape memory alloys undergo a solid-state phase change once they have reached their transformation temperature. This type of metal has two main phases associated with the shape memory effect, austenite and martensite. Austenite, shown in Figure 1, is the high temperature phase where the alloy has a cubic crystal structure. Martensite, the low temperature phase, has a monoclinic crystal structure as shown in Figure 2. [2] SMAs are able to return to either phase by either gaining or losing heat. The specific transformation temperature varies depending upon the exact chemical composition. For example, slight variances in Nitinol's composition, which is made from approximately equal amounts of Nickel and Titanium, can cause the transformation temperatures to vary from below 0°C to above 100°C. [3]

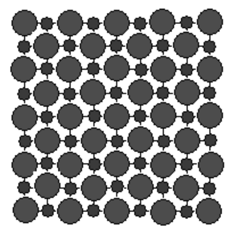

FIGURE 1
AUSTENITE PHASE

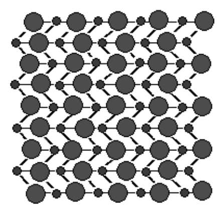

FIGURE 2
MARTENSITE PHASE

The shape memory effect in SMAs comes from the phase change in the alloy's atomic structure. As the material cools to form the martensite phase it creates alternating bands or layers. Each layer is tilted in an opposite direction from the layer above and below it. This layer opposition creates a balance in the overall structure to where there is no shape change from austenite to martensite. [3] In order to return to austenite the crystal structure uses thermal energy to unskew its atomic formation. This happens because, atomically, lower energy is preferred. At a certain temperature the cubic arrangement of austenite has a lower energy than the monoclinic arrangement of martensite. At this point the structure reverts to the austenite crystal formation. [1]

The different crystal structures of shape memory alloys allows for a rare thermo-elastic martensitic transformation. The tilted layers in the martensite phase allow for the material to undergo a shape change from an applied stress. This type of deformation does not damage the structure of the material. [3] The atomic structure only allows the stress to tilt the layers in the same direction. Because the layers can only move in one direction, the material is able to remember its previous crystal formation. [1] When heated the material springs back to its austenite phase causing it to return to its original shape. This cycle is shown in Figure 3.

## POTENTIAL FIRST-YEAR ACTIVITIES

All first-year engineering majors are required to take ENGR 111/112, Foundations of Engineering I/II. Completion of the two courses is required for admission to an engineering department as a sophomore. Since these courses are taken by all engineering majors, it was important to consider how

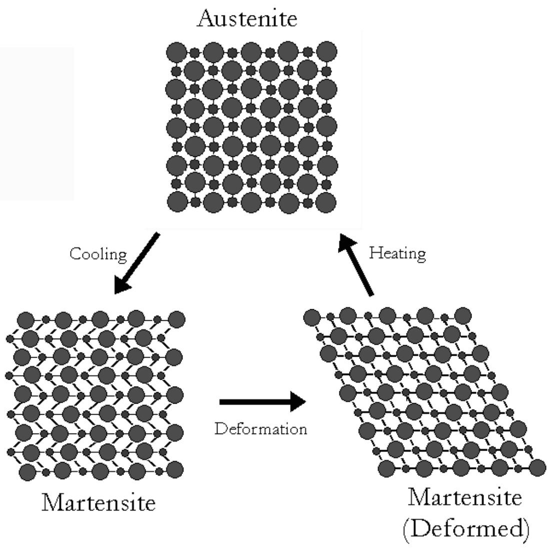


FIGURE 3
TRANSFORMATION CYCLE OF A SMA

knowledge of smart materials might be integrated into these courses. However, since these are required engineering courses, space for additional material is severely limited. At the beginning of the Fall Semester in the 2001-02 academic year, faculty members on the project approached the faculty member responsible for coordinating all the sections of ENGR 111 and asked if he would be interested in incorporating additional material on smart materials into his section of the course. Initially, he was reluctant, because his knowledge of smart materials was limited and his time to learn about these new materials was constrained. However, his enthusiasm grew when the project committed to provide a graduate student (Luke Penrod), working ten hours per week, to work with him to find ways to incorporate the material. Luke could draw upon work completed during by an undergraduate student (Diana Talley) in which she explored information about smart materials and developed demonstrations, experiments, projects and lecture material that might be used in ENGR 111/112.

Here is a list of demonstrations, experiments, and projects that were developed by Diana Talley.

- Butterfly Demonstration: SMA Linear Actuator
- Thermobile™ Demonstration: SMA Properties and Thermodynamics
- Torque Tube Demonstration: SMA Actuator and Thermodynamics
- Heat Engine Experiment: SMA Efficiency and Thermodynamics
- Stiquito Project: Application of SMA Actuators

### Butterfly Demonstration

When people first learn about SMAs they often become intrigued and start brainstorming uses for this almost "magical" material. While many ideas are very complex and involved, some will be very simple such as Dynalloy's SMA Butterfly. Dynalloy created a model butterfly that is able to mimic the flapping motion of a butterfly. The butterfly consists of a flexible plastic body with a SMA wire stretched from the head of the insect's body to its midsection, a small internal spring, a pair of flexible plastic wings, and a power cord. The SMA wire is heated when it conducts electric current. As it is heated it contracts, pulling on the two sections of the butterfly's body. The butterfly bends its head towards its rear section. This contraction movement causes part of the plastic wings to fold, bringing the wings together. Then, a switch cuts off the electric current and the wire cools to room temperature. As this happens the wire expands. The tension on the two sections of the butterfly fades and the spring causes the butterfly to straighten out. As this happens the wings come down to their original position completing the flapping motion. The demonstration raises the curiosity of viewers.

This butterfly can be used in a very simple demonstration for an introduction to engineering class. The instructor would first show the students the butterfly and illustrate how the shape memory effect, the wire contracting, leads to the flapping of the wings. The demonstration can also illustrate the concept of resistance to the students. The SMA wire acts as a resistor by restricting the electrical current. This resistance causes the heat that induces the wires transformation. This demonstration allows students to learn more about the shape memory effect while reinforcing electrical topics in the first-year curriculum such as electrical current and resistance.

### Thermobile™ Demonstration

Perpetual motion has intrigued inventors for centuries. The idea of starting a machine and having it continue forever is a fascinating idea. However, the first and second laws of thermodynamics clearly indicate that this will never be more than a whimsical idea. Through use of an illusion, the Thermobile™ (invented by Innovative Technology International) uses a SMA wire to bring this intriguing idea momentarily closer to reality in the minds of its observers.

The Thermobile™ consists of a SMA wire loop enclosing two pulleys, a metal one and a larger plastic one. To begin the demonstration the instructor would place the metal pulley of the Thermobile™ in 75°C water. At this time the instructor will start the motion by turning the larger plastic pulley. The Thermobile™ continues to turn the pulleys, giving the illusion of perpetual motion. The motion lasts as long as the metal pulley is heating the SMA wire that is surrounding it. If the Thermobile™ is removed from the water it eventually stops as the metal pulley cools to room temperature. This machine is not a perpetual motion machine because it works by absorbing energy from the heat of the water.

The motion of the pulleys occurs from the shape memory effect of the wire. The wire is trained to return to a straight shape. As the wire is heated from its contact with the hot metal pulley the wire straightens itself out. Because the wire is welded into a loop, the action of the wire straightening causes the wire to pull on the room temperature part of the wire surrounding the larger plastic pulley. This pulling force causes the pulleys to turn as the wire rotates around both of them. The motion of the machine is able to continue as long as the wire is constantly being heated and cooled at different parts.

This demonstration is an excellent way to introduce the first and second laws of thermodynamics to either first-year engineering students or students taking their first class on thermodynamics. The instructor might first discuss the principle of perpetual motion and why it is not possible due to the laws of thermodynamics. Then the instructor would demonstrate the Thermobile™ and have the class determine how the machine gets its energy. Once students have determined that thermal energy from the water is the source, the instructor will show how the force of the shape memory effect from the wire causes the motion of the pulleys.

### Torque Tube Demonstration

The torque tube demonstration consists of a SMA tube with one end attached to a load cell and the other end attached to a flywheel. Approximately 25 thermocouples measure temperature from both the inside and outside of the specimen. A coil heater is wrapped around the SMA tube and controlled by a computer program. The computer program regulates the temperature of the tube by maintaining an even temperature distribution across the locations of the 25 thermocouples.

The demonstration begins with the tube at room temperature, which means it will be in its low temperature form, martensite. A five-pound weight is attached to the flywheel causing a torque to be applied to the tube. The weight is attached to the flywheel for the entire demonstration. The applied load causes the specimen to deform by twisting. At this time the instructor begins the experiment and the coil heaters begin heating the SMA. Once the tube reaches a certain temperature the rod begins returning to its undeformed shape. This causes the flywheel to visibly turn lifting the weight. This action illustrates the shape memory effect of the specimen to the students.

Once the tube has been completely transformed, by heating the entire rod above its transformation temperature, the heater turns off. As the tube cools the students will be able to see the rod deform again from the torque due to the five-pound weight. This demonstrates that as the SMA changes into its high temperature phase, austenite, it does work by lifting the weight to return to its original shape. It also shows that once an SMA cools to its martensite phase it can easily be redeformed.

Instructors will also be able to use this demonstration to reinforce heat transfer or torsion topics. For example, the heat coming from the coil heater is transmitted by convection through the surrounding air to the tube. This subject material would be appropriate for an introduction to engineering class. Heat transfer through the tube wall would be appropriate for a basic continuum mechanics course. The continuum mechanics course could also use this demonstration to illustrate the concept of torsion to the students. The students would be able to see an actual experiment involving their classroom theories instead of an ideal model.

### Heat Engine Experiment

One of the most useful aspects of a shape memory alloy is that the force used to deform the material while it is in then martensite phase is much less than the force that can be extracted when it is heated. [3] Therefore, heat can be converted into mechanical work. This is the principle behind a SMA heat engine and can be demonstrated through a simple SMA wire heat engine experiment.

In this experiment a shape memory alloy wire is already trained to a spring or a coil. One end of the wire is attached to a fixed object and allowed to hang freely. A weight is attached to the opposite end of the wire. This weight causes the wire to stretch and deform from its original shape. A power supply is connected to the wire. As current flow through the wire heats the wire, it returns to its original coiled shape, lifting the weight. Throughout the experiment the students will be able to measure the displacement of the weight. They might also calculate the work done by the wire, the energy supplied by the power supply, and the efficiency of the wire heat engine.

This experiment is designed to teach concepts of a heat engine and efficiency to students in a basic thermodynamics course. However, the experiment could be used to teach the material in a simplified format for students in a first-year engineering course.

### SQUITO Robot Project

The goal of this project is to have every student work in teams to design and build a small walking robot that uses SMA wires. These wires are ideal for small robots because they transform almost instantaneous, the movements can be very controlled, and it produces a large force to recover its trained shape. [3] Students would be given a variety of supplies and a set of tasks that their robot has to complete. For instance, each robot must move a total distance of two feet with its only contact coming from the floor. Each robot must also be an autonomous system, meaning that the robot must be programmed to walk without assistance from someone controlling it.

A suggested design for the robot's motion is where a SMA wire is stretched tautly over each leg. The wire would be connected to body of the robot approximately 0.5 cm ahead of the leg. The opposite end of the wire would be connected to one of the furthest parts of the leg. The wire is resistance heated by creating a circuit through the SMA wire and leg. As the wire is heated it contracts causing the leg to be pulled toward the front of the insect. Immediately, the robot's controller will stop the electric current passing through each leg's circuit. Once the current has stopped, the wire begins cooling. As it cools it expands and allows the leg to return to its original position. This has allowed the robot to take one step. [4]

In order to creating a walking motion some type of controller must be attached to the robot. The controller is designed to act as a switch to all of the circuits for each of the robot's legs. By programming the robot to move its legs in a certain pattern the robot can walk. [4]

This project involves basic knowledge of SMAs, team collaboration, creativity, and a lot of patience. This is a challenging project that will give the students practical first hand design experience as well as knowledge about an advanced type of technology.

## IMPLEMENTATION

After reviewing the material that had been developed during the summer of 2001, Dr. Kohutek and Luke Penrod decided to offer a twenty-minute presentation on shape memory alloys (SMAs) and ask the students to build a Stiquito [4] robot as one of the course projects. Twenty-four four-person teams were given the following specifications:

- Must be actuated by Shape Memory Alloys (SMAs)
- Objective: maximum covered distance in 3 minutes
- Contact can only be with the ground
- Must be an autonomous system

The unique winning design (shown in Figure 4) combined a back-end supported on wheels with long front legs composed of SMA. It covered a distance of 48 cm in 3 minutes.

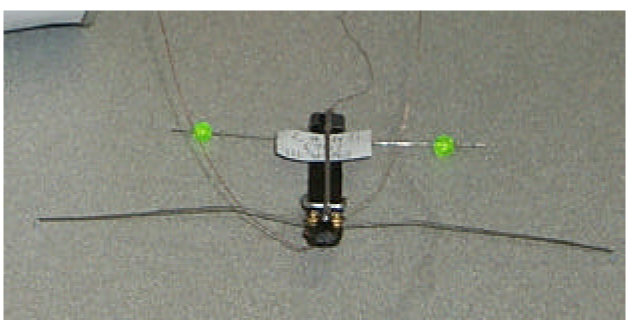

FIGURE 4
WINNING STIQUITO DESIGN

In general Terry Kohutek was very positive about the introducing of shape memory alloys (SMA) into ENGR 111. He thought students were intrigued by the Stiquito project and would remember the concept of SMA. He thought Luke Penrod made an effective presentation on SMA. He thought students enjoyed a guest speaker who was close to their own age and he thought Luke delivered an presentation that helped students to see the application of SMA as well as the basic mechanism for the SMA effect.

The contributions of Luke Penrod were essential to incorporating material from research projects into the first-year engineering course. Luke is a graduate student who works in a research laboratory on SMAs and so has the requisite content knowledge. He prepared the introduction to SMAs, a description of the project to be handed out to the students, and the grading rubrics to evaluate the project demonstrations. His description of his involvement with ENGR 111 provides some insight about the involvement of a graduate student in curriculum innovation.

*Initially, I was nervous and felt that the kids were more interested in each other than me, but once I got to the demonstrations, things got much better. I have found through this project that all people are impressed by the ability of SMA to recover macroscopic strains at such a high rate. When they see an SMA spring lift a weight for the first time or see a pair of glasses be bent around my finger, they are instantly curious. Once I finished the presentation, I asked for questions. After they got over being shy, students started raising hands all over the classroom. Some of the questions were the same ones that we were asking in the research meetings about the possibilities of SMAs in engineering. I told them that I would be giving the robot kits out after their class. I had 8 kids waiting outside my office when I got there and more in tow. Once the rush had gone, I realized that I had given nearly all the kits out, and that only 10 minutes after the project was announced.*

*My next major interaction with the kids was when they turned in the preliminary reports. This was the report where they were to discuss the ideas they had come up with for their robots. Some of the ideas were amazing. We had some with segmented bodies, some shaped like other bugs, and many with all numbers of legs. Of course there were some that were not that creative, but I think that the project was somewhat under constrained. I think that we expected a lot of first-year students to take the instructions we gave them and come up with some new and wonderful ideas. For this reason, I will be changing the project so that only the leg design will be changed, that way there are fewer things to think about and more ideas should be generated.*

## ASSESSMENT AND EVALUATION

There are three different areas of interest regarding assessment of the curriculum innovations implemented by the project. The first is the interest of the students. Several approaches will be used to examine the changes in student interest. They include retention in either engineering or, more specifically, aerospace engineering; pre- and post-attitude surveys and specific feedback about activities introduced in class. The second is the knowledge of the students about multifunctional materials. The approach used to examine changes in student content knowledge will be for faculty members knowledgeable about multifunctional materials to develop and give content questions either on assignments or examinations. Finally, the third area is the improvement in the knowledge of the engineering design process and skills associated with the design process, such as teamwork and communication. The third is very challenging and is the focus of the remainder of this section.

To determine if the project's curriculum modifications would have improve the knowledge of the students, it is necessary to find valid assessment tools and methodology for establishing baselines and measuring changes in students' design knowledge. In the course of researching engineering design learning assessment tools and methods we came upon the Mid Program Design Assessment instruments that had been developed by the Transferable Integrated Design Engineering Education (TIDEE) project. [5] Two instruments were selected: (1) Design Knowledge Assessment and (2) Reflective Essay on Team Design. Both instruments and scoring rubrics, which were available at the TIDEE website in July 2001, provided both a foundation and a point of departure for adaptations, which were developed to serve the specific assessment needs of the project. In its first year of operation, the project has targeted the assessment of design knowledge and learning at two different points in the curriculum: (1) entering level, (e.g., freshmen in their first engineering course); and (2) end-of-program level, (e.g., capstone design students). Because the TIDEE Design Assessment instruments and scoring criteria were intended for mid-program students, rather than freshmen or seniors, instruments required validity reviews, redefinition of scoring criteria, and some adaptations in scaling in order to accommodate the anticipated range of abilities and knowledge between entering and end-of-program students.

Students in one section of ENGR 111 and students in AERO 401 (the first semester of the senior capstone design sequence) completed the Design Knowledge Assessment instrument and their submissions have been scored. Post testing is planned for the end of spring semester 2002, to observe change in seniors by the end of the capstone design course, as well as to establish year-end freshman and senior benchmarks. In addition, at the end of the Fall 2001 semester, students of the targeted freshman class completed an essay in relation to their engineering class design projects. This essay assessment was modeled on the Reflective Essay portion of the Mid-Program Assessment for Entering Juniors developed by TIDEE. [5]

Both the pre and post tests and the reflective essay assessment target three major categories of design competence.

- **Design Process:** Managing, using, and improving elements of the engineering design process
- **Teamwork:** Managing, utilizing, and developing personnel engaged in the design
- **Communication:** Eliciting, distributing, extending information associated with the design, vis a vis clients, team members and other constituents.

Pre-test results for freshmen and seniors revealed superior knowledge on the part of seniors in all areas but teamwork. Nevertheless, the demonstrated superiority of the seniors with respect to the freshmen overall was not very dramatic. Comparisons will be made between freshman and senior posttest benchmarks, and pre-to-post changes in seniors will be examined.

## CONCLUSIONS

Shape memory alloys are becoming an important material to the engineering industry. These metals have been used everywhere from a coupling in the Grumman F-14 aircraft to inserts in shoes. [6] Practically every division of engineering can use some aspect of these materials. This is why shape memory alloys are an important topic for student's to learn and use. SMAs can be taught directly to the student's by using them to reinforce current course topics such as resistance or heat engines. Activities involving shape memory alloys can be used to incorporate new technologies into engineering curriculums while helping to prepare students for an evolving industry through knowledge and practical experience.

The CRCD project attempts to integrate information and experiences with the emerging technology of multifunctional materials into existing engineering curriculum while trying to introduce only a small number of new courses to minimize the effect on the overall curriculum. The approach requires cooperation among faculty members who are researching the new technology, faculty members teaching existing engineering courses, assessment specialists, graduate students, and undergraduate students. The paper has attempted to provide some insights into the process of introducing the material into first-year engineering courses.

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