AC 2011-2229: BRINGING SMART MATERIALS APPLICATIONS INTO A PROJECT-BASED FIRST-YEAR ENGINEERING COURSE

Kristi J Shryock, Texas A&M University

Kristi J. Shryock is a Lecturer and Director of Undergraduate Programs in the Department of Aerospace Engineering at Texas A&M University. She received both a B.S. and M.S. in Aerospace Engineering from Texas A&M and received her Ph.D. in Interdisciplinary Engineering at Texas A&M in May 2011. Her research work focuses on engineering education.

Dr. Kaushik Das, Department of Aerospace Engineering, Texas A&M University, College Station, TX
Stephen Oehler, Texas A&M University
Jacques C. Richard, Texas A&M University
Dr. Dimitris C. Lagoudas, Texas A&M University

D. C. Lagoudas currently is the Department Head and the inaugural recipient of the John and Bea Slattery Chair in Aerospace Engineering at Texas A&M University. He also serves as the Director for the Texas Institute for Intelligent Materials and Structures (TiiMS). His research involves the design, characterization and modeling of multifunctional material systems at nano, micro and macro levels. During the past two decades he has published extensively on the subject of shape memory alloys with his students, postdoctoral associates and colleagues and several of his journal papers are now considered classic papers in the field. He served as an Associate Vice President for Research for Texas A&M University from 2001-2004, and as the first chair of the Materials Science and Engineering Program at TAMU. He has been involved with curriculum innovations and engineering education throughout his career, notably with the Foundation Coalition, where he focused on restructuring the sophomore year engineering curriculum.

Bringing Smart Materials Applications into a Project-Based First-Year Engineering Course

Abstract

Recently, aerospace engineering faculty members and graduate students at Texas A&M University (TAMU) developed a project involving smart materials and implemented it in a freshman-level engineering class to excite first-year students about material science applications. This smart materials project addresses curriculum challenges that hinder students' ability to relate mathematics and science concepts to the engineering design process. Shape memory alloys (SMAs), the specific type of smart material used in this project, provide the opportunity for explaining important engineering principles, such as energy conversion and mechanism actuation, framed within the subject of mechanics of materials. By introducing projects using SMAs, students learn about their applications and relevance in engineering designs, and the potential for material science as a future research goal. This paper will present specifications for the project developed involving SMAs, provide details on the implementation, and summarize its results.

Introduction

The smart materials project and associated curriculum introduces the development of a crane-arm mechanism actuated with shape memory alloys (SMAs). This program guides students through research, modeling, prototyping, and optimization phases of the engineering design process to discover viable methods of actuation alternative to standard electric motors or hydraulic/pneumatic systems. This new focus on material science research in engineering will address two important challenges encountered in first-year engineering courses. Specifically, these challenges include students' difficulty in associating engineering methods with some of the more conceptual topics learned in mathematics and physics, as well as students' lack of solid understanding of the engineering design process.[1] Thus, the curriculum is structured such that applied engineering methods can be directly related to aspects of mathematics and science that freshman students generally consider to be disconnected or abstract.

First-semester freshman-level engineering classes at TAMU typically include two projects, both of which exemplify an experiential learning environment. These projects are designed to resolve the same curriculum challenges, and each project regularly relates to a topic in statics and a topic in dynamics, respectively. A particularly successful statics project involves building bridge-like truss structures out of magnetic sticks and ball joints and calculating internal forces in each truss member.[2] While this statics project is consistently implemented each semester, the dynamics projects are frequently altered or redesigned to diversify the subject matter. Faculty members determined that a project should be developed to boost students' exposure to basic material science and energy conservation principles, concepts that are detailed in sophomore-level classes. The smart materials project thus incorporates these topics, as well as dynamics concepts utilized in previous second projects in the class.

The following section of this paper outlines the implementation of the project described during the fall of 2010 semester in which two sections of a first-semester freshman-level engineering course consisting of 168 total students completed the project. The next section describes the semester's schedule of tasks and displays example portions of the presented curriculum. Finally, this paper features the results from analysis of student performance and suggests changes to further refine the program's curriculum based on a conducted student survey. Future efforts to extend smart materials to projects in the second semester of the first-year engineering curriculum are also briefly discussed.

Background

First-year engineering courses can be beneficial in promoting understanding of engineering processes of design and modeling and the roles of science and mathematics in engineering. These initial courses allow for students to gradually become accustomed to science and mathematics concepts in a task-oriented environment.[2] In this way, projects motivate and guide the course content rather than simply supplement the subject matter. Courses in which first-year engineering students connect practical and technical applications with the standard curricula show good indications of having a significant impact on student retention rates.[3] Similarly, conversion of introductory engineering lecture courses into laboratory classes has had a positive effect in further generating student interest in science and mathematics.[4]

Starting in 2004, a freshman-level engineering course at TAMU was converted into a project-based learning environment in which students engaged in collaborative and cooperative learning[5] of the engineering design process. Here, student active learning is organized in a team-content centric framework that allows them to apply the design process in a meaningful way.[6] Project guidelines have been refined over the years to provide the greatest impact in encouraging growth of engineering process skills.[7] Specifications for the course include having the project: be relevant to the student’s major; emphasize the typical engineering design process and not have students use only trial and error; be within the scope of concurrent mathematics and physics courses; have a graphics component to address communication issues; not rely on fabrication ability of students; and be conducted within a suitable time period for the class.[8]

All new projects developed must include the following elements[2] from the engineering design process:

1). *Needs Identification:* What is to be accomplished?
2). *Conceptual design*: How might the need be met? What alternatives should be considered?
3). *Analysis and modeling*: What is involved in determining whether the conceptual design will meet the need? Technically feasible? Can it be modeled mathematically?
4). *Verifying and assessing:* Can the predictive models be validated through physical testing?

With these guidelines in mind, a new project involving smart materials was implemented during the fall of 2010 semester.

Project Summary

Course Details

At the start of the semester, multidisciplinary teams of four students are formed in the class. Students then work together in their teams during class on a daily basis and outside of class as well. Typically, many of the students in the team are taking the same mathematics and physics courses that semester, so it is not uncommon for instant study groups to be formed to assist with courses even outside of this one.

The beginning of the semester primarily covers basic physics concepts as they apply to fundamental engineering methods: free-body diagrams and static equilibrium, calculating moments and forces on a rigid body, and the determination of internal forces in truss members.[9] These topics also correlate well with the first project. Course content in the remainder of the semester can vary based on the project implemented but are consistently dynamics in nature. In the course, students also develop an extensive knowledge of design visualization and graphical engineering communications through instruction and assignments in engineering drawing and computer-aided drafting. Grading in the course is based on individual work, which includes homework assignments, daily work, and exams, and accounts for approximately 75% of the total points. The remaining 25% is earned through the portion of daily work completed as a team and components of the projects, such as weekly technical memorandums and final reports. The technical memorandums are quite useful in the course as they assist in guiding the teams through the design process and require them to reflect quite often on their progress with the design.

New Project

For the final five weeks of the semester, the smart materials project is introduced to the class teams in the form of a "request for proposal." In summary, design requirements are outlined and specified for each team to design and build a supporting structure and lifting crane arm that can lift its own weight, while actuating through an angle change of at least 45^{o}. Each team uses LEGO Mindstorm kits as a resource for constructing the crane's main structure and arm.

The only method for actuating the arm allowed in the requirements is the uniaxial contraction of Nitinol SMA wire via thermally induced transformation. Therefore, the electric motors that normally come packaged with the provided LEGO kits are explicitly banned from use. Each team is provided 50 cm of SMA wire from MuscleWire, a provider of commercially-available Nitinol wires and springs,[10] to study, test, and integrate into their crane designs. For reference, each meter of low-temperature, 150 μm diameter SMA wire costs $18.95, as of October 2010. For this project, 15 meters are ordered for distribution over 24 teams, totaling approximately $285 for the class. Excess wire is provided for those teams that request it in the event of burnout, breaking, or loss.

The students are tasked with four deliverables, one for each week following the introduction of the project. Each deliverable is associated with specific assignments and requires a separate technical memorandum that includes information regarding team progress and results with hand-calculations and visualizations of selected designs.

Implementation

The following section provides a more detailed description of the request for proposal and the requirements for each deliverable. As mentioned previously, the smart materials project consists of four tasks, each associated with a week in the latter portion of the semester's timeframe following the introduction of the project.

Week One

During the first week of the second project, a technical memorandum summarizing the project and current applications of SMAs in the biomedical and aerospace industries is presented in the course. The memorandum (see Appendix, Figure A1) also provides practical reasons for utilizing SMAs as an alternative to standard actuators from a design engineer's perspective, which leads into a discussion about their use in mechanisms such as a crane arm.

The memorandum thus highlights the purpose for building a scale-model crane arm and structure that could meet the following minimum design criteria:

1. Power is only derived from the contraction of the SMA wire. No motors or other materials may be used to move the crane arm.
2. Wire burnout must be avoided. Burning out the wire is equated with burning out a necessary component.
3. The Lego structure must never disassemble itself (i.e. come apart) during crane arm actuation.
4. Additional weights must remain fixed to the end of the crane arm.
5. The crane arm must actuate through an angle change of at least 45^o.

Bonus criteria are offered, to encourage each team to design an assembly that exceeds the minimum criteria. Students are instructed to attempt to minimize their system's cost-benefit ratio during the iterative design process, a concept which is explained in detail during the third and fourth weeks. In this case, cost and benefit are defined as:

1. Benefit – Calculated as the change in potential energy of the crane arm (plus any additional weight). For additional weight to be considered valid, the crane arm must continue to actuate through an angle change of at least 45^o.
2. Cost – Considered to be the amount of transformed wire used to "power" the crane arm.

Accompanying the technical memorandum, a lecture presentation defines active materials as a subset of multifunctional materials and describes the material property coupling they exhibit. It is explained that the transformation (contraction) of SMAs, a category of active materials, is an effect of the changes in crystal orientation when subjected to thermal or mechanical loads.[11] Thus, wires consisting of the same active material can be used as actuators, only providing contracting uniaxial motion along the direction of the wire, and can be controlled with applied resistive joule heating.

With these ideas in mind, each team is then given a week to create a technical memorandum outlining concepts they developed for integrating the material into a crane design for use as an actuator. Each student submits their individual concept by writing a short paragraph describing the mechanisms involved and including supporting visualization of the concept by means of AutoCAD or hand-sketches.

Week Two

After testing, teams calculate the average uniaxial transformation strain of the wire over three test runs by completing a provided datasheet (see Appendix, Figure A2). It quickly becomes apparent to the students that the relatively small motions resulting from the thermally induced transformation of the wire provides the primary challenge in satisfying project criteria; students would need to attach the entire length of wire to achieve minimal actuation. This, of course, would not be conducive to effectively minimizing the cost-benefit ratio of the system. To resolve this issue, a lecture is then given to describe power transmission and conversion of linear to angular motion. The lecture emphasizes the necessity of using mechanisms that convert linear motion, caused by the change in length of transforming SMA wire, into augmented angular motion.

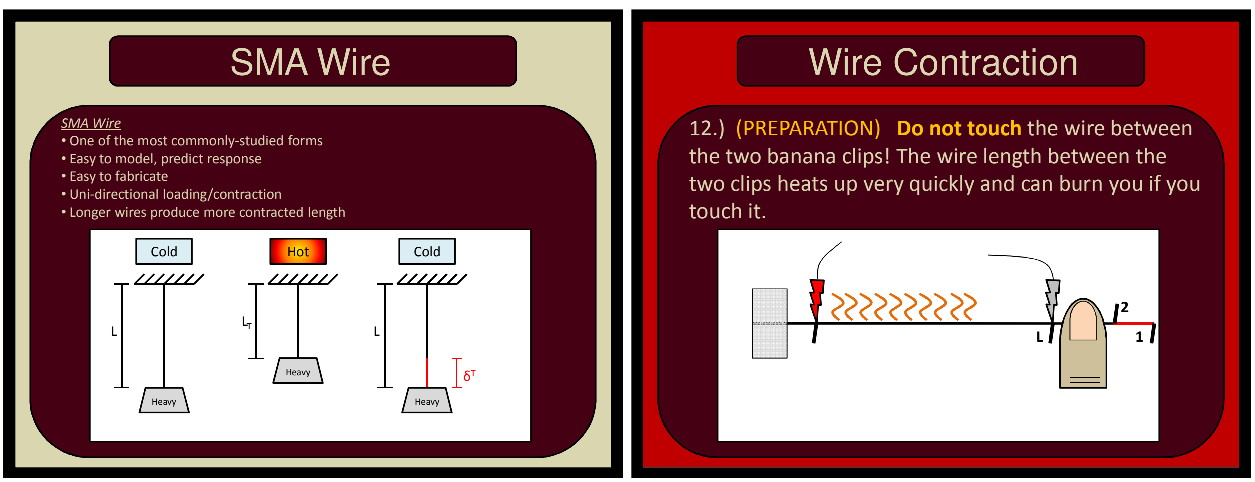

Figure 1. *Example presentation slides outlining: main points for the use of SMA wires as actuators (left) and personal safety issues when measuring wire contraction in a lab setting (right).*

An example design is illustrated with crane arm actuation directly connected to the rotation of the smallest gear in a mesh and its motion increased by the ratio relationship between gears of differing diameters. The SMA wire is then installed by fixing one end and connecting the other to the circumference of the largest gear. Thus, during transformation the wire spooled around the largest gear contracts and causes augmented crane arm actuation. In theory, knowing the overall gear ratio, one can then back-solve to find the minimum-required length of SMA wire to effect minimum crane arm actuation.

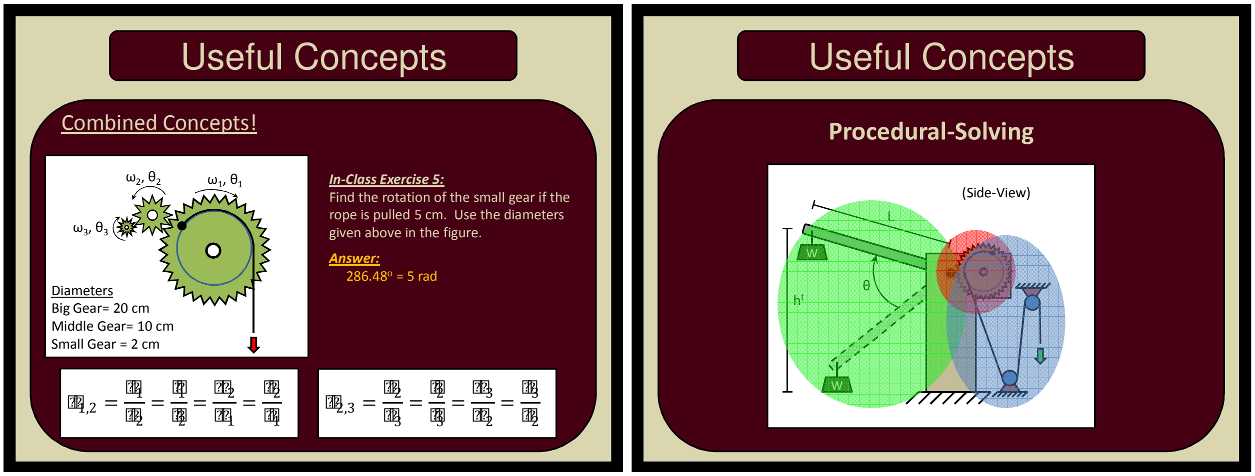

Figure 2. *Example presentation slides outlining: gear relationships and linear-to-angular motion (left) and suggestions for using known parameters to back-solve for required initial conditions (right).*

Considering this example, each team then measures the diameters of the different gear sizes available in their LEGO kits. Selecting one of the designs completed individually the previous week in their assignment, gear systems are then applied by the entire team working together on the selected design. The technical memorandum for the week includes calculations predicting the required length of SMA wire based on the average transformation strain data from the lab and a standard three-view visualization of the full assembly. In addition, teams begin physical construction of prototype crane structures in preparation for the following week's iterative optimization phase.

Week Three

The third week of the project marks the beginning of the iterative design phase. This phase requires each team to have built a working prototype model that can at least satisfy minimum design criteria. The iterative optimization methods are then applied to make changes to the working models' foundation, supporting structure, and interacting mechanisms. Each team attempts to alter their designs to determine how the cost-benefit ratio can be minimized. All teams are required to document any alterations and the reasons associated with them in this week’s project technical memorandum.

As previously mentioned, the cost of the project is considered to be the length of the SMA wire used to actuate the crane arm. Conversely, the benefit of the system is measured as the change in potential energy of the crane arm, including any additional weight. To reinforce understanding of gravitational potential energy of a rigid body (with the crane arm as an application), the class is taught how to determine the mass of a component and the location of its center of mass. With this information, each team then calculates their crane arm's vertical displacement at the center of mass and determines its change in potential energy based on measured change in angle.

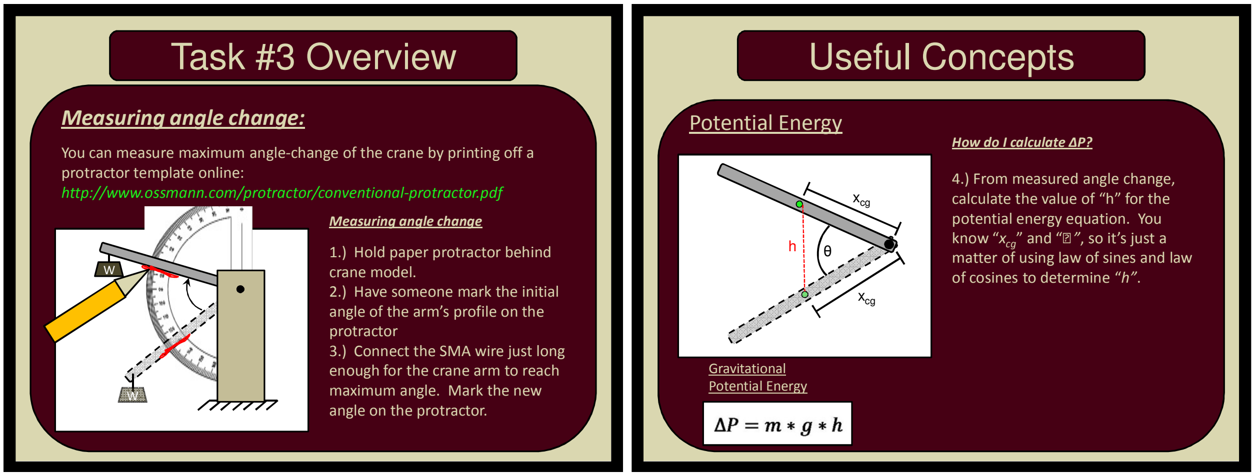

Figure 3. *Example presentation slides outlining the suggested procedures for measuring the change in angle of a crane arm (left) and calculating the change in potential energy of a rigid body (right).*

Week Four

During project week four, the engineering teams are given time to test their crane designs in a setting that resembles the final tests scheduled for week five. These "dry run" sessions are ungraded, but they give students a sense of what to expect for the next week. The teams have until the following week to make changes to their designs to meet any criteria in which they lacked during the dry run. In addition, they are assigned their fourth and final memorandum, which includes design specifications and visualizations up to this point and their final recommendations. Finally, each student is required to individually conduct research on SMAs as they apply to projects related to their own engineering discipline and write about their findings in a single-page technical memorandum. This final step is intended to help solidify the students' understanding of current discipline-specific interest in smart materials.

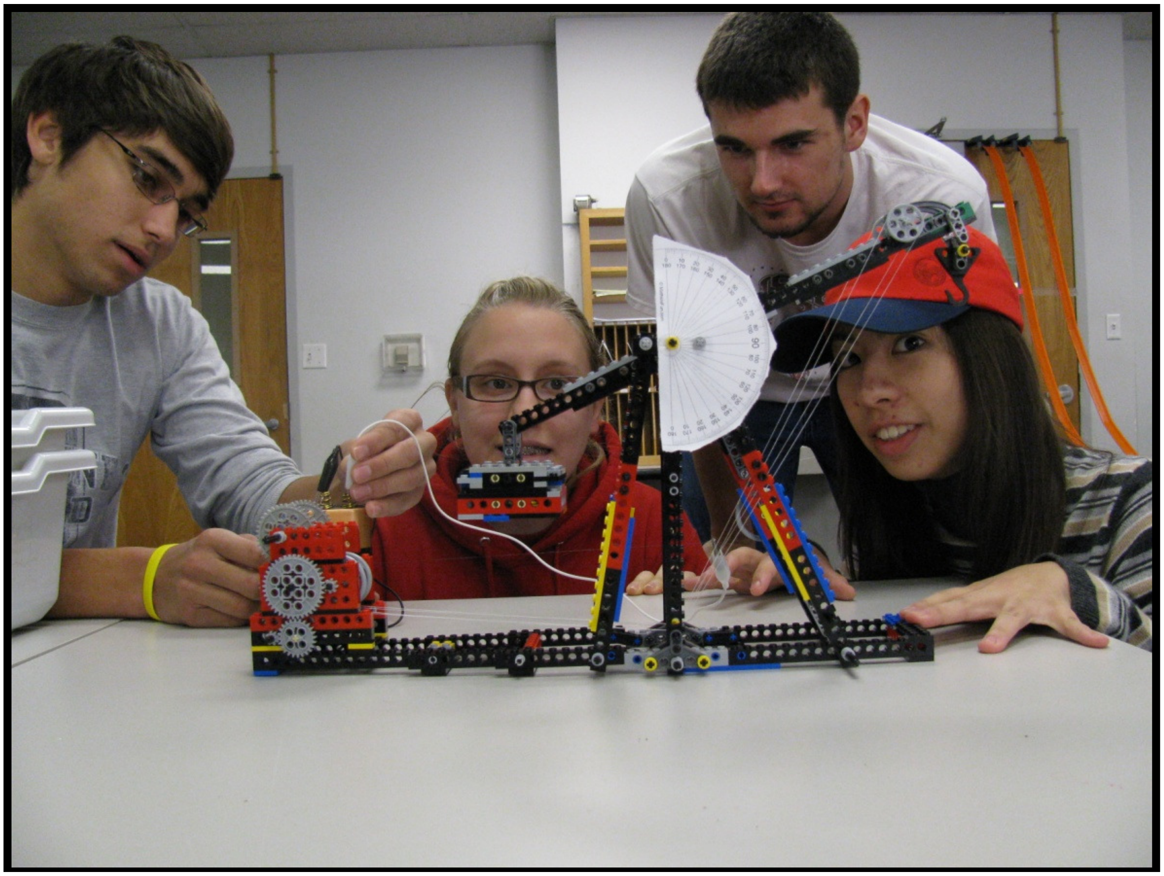

Figure 4. *A particular crane design, ready for testing during the dry run sessions.*

Week Five

During the fifth and final week in the project, the final test runs are conducted, and all materials, such as team final technical memorandum, LEGO kits, and class-available resources (batteries, banana clips, etc.) are collected. In order for a team's project to be considered complete, an instructor is required to sign off on the datasheet (Figure 4), which was introduced to them at the dry run in week four, by visually confirming each point on the checklist.

Be sure to include appropriate units.

Minimum Requirements Checklist
These must be checked off during the first test with a Professor/TA/PT supervising.

1.) Is the crane structure only powered by SMA wire actuation? Yes/No
2.) Is the wire intact for second testing (no wire burnout)? Yes/No
3.) Is the LEGO structure intact (no disassembling during actuation)? Yes/No
4.) Did the crane arm actuation at least 45^{o} without additional weight? Yes/No
5.) (*Optional*): Was additional weight added to the crane arm? Yes/No

Data Table

	Test 1	Test 2	Test 3
1.) Maximum Angle Change			
2.) Maximum Total Weight to Reach Max Angle			
3.) Length of Transformed Wire Used ("L")			
4.) Mass of Crane Arm			
5.) Calculated Change in Potential Energy of Crane Arm (including added weight)			
6.) Calculated Benefit/Cost Ratio			

Figure 5. *Datasheet used in recording crane design measurements.*

Results and Suggested Changes

At the end of the semester, all students are asked to complete an online survey. This survey contains six questions and inquires about the effectiveness of the smart materials project in terms of knowledge gained from the lessons, work motivation, and recommendation of the project for future classes. Following these questions, an essay area allows students to verbally suggest changes to the project or to mention some of the program's highlights. Of the 168 students who took part in the SMA project, 110 respond to the survey, resulting in a 65% return rate. The data from the survey are collected and summarized in Figure 6.

Overall, participating students from the two sections favor the project in all areas of the survey. The first two questions relate to student difficulty in understanding engineering processes. The answers to these questions indicate positive feedback with approximately 84% of students reporting at least "above average" understanding of basic engineering concepts after the class, compared to 29% before the class. In addition, most participating students reply that they took time to meet with their group outside the class to discuss design changes and complete calculations. This indicates students' growth in personal motivation and maturity in managing projects as members of engineering teams. The majority of students also respond with increased interest in material science following the program, and at least 82% recommend continuation of this project in future classes.

Question	Well Above Average	Above Average	Average	Less Than Average	Needs Serious Improvement
How would you rate your knowledge of basic engineering concepts (Free-Body Diagrams, Method of Joints, etc.) before the class?	6%	23%	31%	32%	8%
How would you rate your understanding of basic engineering concepts after the class?	22%	62%	15%	1%	0%

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
The Shape Memory Alloy (SMA) crane project motivated me to learn more about multi-functional materials, such as SMAs.	21%	48%	26%	4%	1%
I utilized team work outside the class to complete the project.	42%	45%	9%	1%	3%
I believe the crane project motivated me to actively analyze and solve the problem as a team.	25%	55%	15%	2%	3%
I would recommend this project for use in future ENGR 111 classes.	47%	35%	14%	4%	1%
Total Responses = 110					

Figure 6. *End-of-semester survey for fall of 2010 students who participated in the smart materials project.*

Many of the students also include several comments suggesting project changes for future implementation. Some students indicate that handling the provided SMA wire is too difficult and in some cases is too weak to support higher loads. This problem can be solved by using a larger diameter wire. However, from an administrator's viewpoint the inverse proportionality of wire diameter to resistance needs to be considered when arranging for voltage sources to be used. Other students suggest that a lack of proper incentive for taking time to optimize designs encourages teams to apply the entire length of the given SMA wire just to meet the minimum criteria for success. Obviously, this issue is avoided if proper incentive is provided, perhaps in the form of bonus points on graded technical memorandums. Finally, students recommend connecting this research project with their engineering disciplines, as a method of further increasing personal motivation by assigning the SMA research technical memorandum in the first project week instead of the last.

In addition to these suggestions from students, faculty members suggest focusing more on detailing the process of iterative design. While this concept is discussed verbally during the third project week, it is never outlined in a presentation for students to reference in the following weeks. Faculty members also recommend teaching students how to determine the energy input required for the wire to transform. This information can then be used to find the efficiency of the system with respect to the measurable work output of the crane arm. Then, students can compare their design's energy efficiency with that of a standard electric motor. This would further reinforce the concept of conservation of energy and emphasize the importance of considering alternative aspects of design.

Future Efforts

The overall success of this project has motivated the initiation of a second semester robotics project using smart materials. In a similar manner, students will be expected to incorporate SMA wires into existing LEGO land rover designs that are automated by an RCX programmable controller. Pending successful integration of these wires with the controller, students will be able to create programs to "throttle" the contraction of the wires to actuate a claw mechanism for picking up detectable objects. The introduction of smart materials alongside robotics-themed projects is expected to generate interest in material science and help keep engineering students engaged past the first year.[3]

Conclusion

The introduction of smart materials applications early in the undergraduate engineering curriculum addresses student difficulties in associating conceptual subject matter with engineering work. This program incorporates the engineering research and development processes into the existing freshman-level engineering curriculum to accomplish this goal. Topics in material science and principles of energy conservation are discussed and applied to the design of a crane mechanism with SMA actuators. The use of SMAs as actuators, instead of standard electric motors or hydraulics/pneumatics, encourages students to search for alternative methods to accomplish the given task. Following a rigid program schedule, students complete the outlined tasks and submit deliverables that detail their design specifications and visualization process. At the project's completion, participating students complete an online survey as an opportunity to provide feedback on the effectiveness of the program. The majority of students surveyed recommends the continuation of the program and also indicates the project helped provide a better grasp of basic engineering concepts. Faculty members and participating students suggest minor changes to the provided resources, overall objectives, and curriculum to improve student motivation and to promote easier connection of topics to the hands-on learning experience. Finally, future efforts are underway to extend the study of smart materials into a second semester engineering course in order to enhance the experience of building programmable autonomous robots.

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Appendix

Memorandum

To: Engineering Staff
ENGR 111 Design Teams

From: Project Supervisor

Subject: Design of a Crane Using Smart Materials

Purpose and Background:

Design and production of mechanical actuation devices have historically been limited by a combination of factors. As engineers, you will encounter many design constraints such as manufacturing complexity, eventual maintenance costs, and device weight and volume. In other words, in designing a sub-assembly, all engineers must account for how difficult it will be to manufacture the separate parts, how much time and money is required for the labor involved in replacing used parts, and how the assembly will fit into the physical space given in the master assembly.

Shape Memory Alloys (SMAs), special metals that can change shape and contract/expand when subjected to temperature changes, have been considered as an alternative actuation device to traditional hydraulic and pneumatic systems because of their obvious design benefits. Historically, SMAs have been mainly applied in biomedical devices such as self-expanding arterial stents, or as bone screws that secure themselves once they reach internal body temperature. However, SMAs are slowly finding their way into mechanical, aerospace, and civil engineering designs, with applications as thread-less pipe couplings, morphing wing structures, and bridge vibration-dampers. SMAs have no moving parts so they are very simple load-bearing systems. SMAs are also extremely light in weight and take up much less room than hydraulic or pneumatic actuation systems.

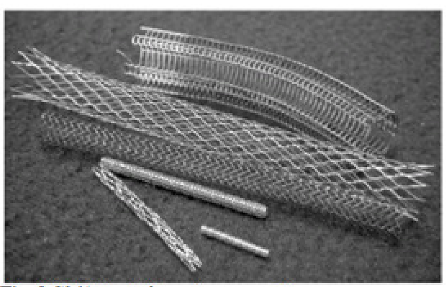

Fig. 1 *SMA stents for artery expansion*

Fig. 2 *Morphing chevrons for decreasing engine noise*

Figure A1. *First page of the smart materials introductory technical memorandum.*

Follow the SMA wire procedure 3 times to get multiple measurements for the lengths.
For data from the table, refer to the **150 LT** *SMA wire type.*

Team Data

	L_1	L_2	L	$\Delta L = \delta^T = L_1 - L_2$	$\varepsilon_t = \Delta L/L$ (transformation strain)	Max Load *P (from table)*
Measurement 1						
Measurement 2						
Measurement 3						

Calculate the transformation strain error based on the literature values (table).

Collaborative Data

	ε_t (measured)	ε_t (table)	Error (%)
Measurement 1			
Measurement 2			
Measurement 3			

Average Transformation Strain (measured):_______________

Figure A2. *Datasheet provided for each team for recording SMA wire measurements during testing. Homework exercises are also assigned.*