



A Multidisciplinary Capstone Project Experience in a Small Liberal Arts College Setting: The Hybrid Solar Tracker

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Abstract

Over the past two decades, the overall scope and expectations for capstone projects in undergraduate engineering project has evolved. There has been an increased focus on multidisciplinary work and hands-on learning.¹ The topics of student interest have evolved as well. Studies show that an increasing percentage of students are drawn towards topics related to sustainability.² Regardless of these changes, one thing that remains true is that small engineering departments, particularly departments housed in small liberal arts colleges, are faced with additional challenges. These challenges include working with limited resources (budget, laboratory space, equipment) and the necessity for the instructor to supervise projects outside of his or her area of expertise. Thus, it can be difficult to develop capstone project ideas that are realizable in this setting. We believe the Hybrid Solar Tracker project was an example that featured many key ingredients conducive to achieving a successful experience despite these limitations.

The project team was multidisciplinary in nature. The instructor was a professor in electrical engineering. Two of the students were seniors in computer engineering, and one was a senior in mechanical engineering. The students were originally given a budget of \$300 by the department, but were encouraged to seek external sources of additional funding. To this effect, the students participated in the Xplore Contest, sponsored by the Phoenix Contact (a multinational engineering firm), and received over \$4,000 dollars in this funding from this company. In the process of this contest, the students documented their work by recording videos throughout various stages of the process and uploading them to the Internet. The contest also served as a means of external validation for their work.

The students surveyed the existing literature in solar trackers and developed their own design, with the objective of increasing tracking efficiency. Their design was a hybrid concept, combining active tracking and chronological tracking. This paper includes a detailed explanation of the design, adapted from the students' senior project report.

The Hybrid Solar Tracker ranked among the top 100 projects worldwide for the Phoenix Contact Xplore Contest and won the award for Best Senior Project in the department. While there were factors to be improved on, both in terms of planning and execution, this project was a positive example of how to achieve a successful capstone project experience in a small liberal arts college setting.

Introduction

As mentioned in the abstract, the overall scope and expectations for capstone projects in undergraduate engineering project has evolved considerably in recent years. Throughout engineering curricula as a whole, there has been an increased emphasis on multidisciplinary work and hands-on learning. The topics of student interest for projects have evolved in turn. In terms of content, studies show that an increasing percentage of students are drawn towards topics related to sustainability. Thus, faculty members need to adapt to provide guidance and mentorship in capstone experiences that reflect these changes.

However, notwithstanding the changes mentioned above, one thing that remains unchanged is that small engineering departments, particularly departments housed in small liberal arts colleges, are faced with additional challenges. These challenges include working with limited resources (budget, laboratory space, equipment) and the necessity for the instructor to supervise projects outside of his or her area of expertise. Thus, it can be difficult to develop capstone project ideas that are realizable in this setting.

Thus, for faculty members working in small engineering departments housed in small liberal arts colleges, it is a central goal to offer or help develop an array of projects that address these specific challenges. Whenever possible, the faculty member should work with the students to turn these challenges into opportunities. We believe the Hybrid Solar Tracker project was an example that featured many key ingredients conducive to achieving a successful experience despite these limitations.

The rest of the paper is organized as follows: first, we delineate the specific context of this project and identify how the general challenges apply to our particular situation. We then map our strategy for turning challenges into opportunities. Next, we take a glimpse into the process of the project itself. In the following section, we present a detailed description of the technical aspect of the project design. This section was adapted primarily from the students' work in their senior project report. Finally, we describe the outcomes and lessons learned from this project, mapping the end results to the original challenges and opportunities we identified.

The Project Setup: Challenges and Opportunities

The Hybrid Solar Tracker project was housed in the Department of Physics and Engineering at Elizabethtown College, in southeastern Pennsylvania. Elizabethtown College is a small liberal arts college (<2,000 students), and the department offers ABET-accredited programs in general engineering program with multiple concentrations (electrical, mechanical, applied physics) as well as in computer engineering. The department currently consists of 8 full time faculty, and there are roughly 120 students in the major.

The program places a strong emphasis in maintaining a project-oriented curriculum throughout all four years. Students start working on projects during their introductory courses in freshman year, continue through Sophomore Project and Junior Design, and culminate in a two-semester capstone Senior Project course. For the capstone project, students are encouraged to come up with and propose their own ideas, but faculty may suggest ideas to the students as well. Students

generally work in groups of 3-4 people.

In the specific case of the project at hand, the project team was multidisciplinary in nature. It consisted of three students. Two of the students were seniors in computer engineering, and one was a senior in mechanical engineering. The instructor was a professor in electrical engineering.

We now provide a more detailed explanation of the challenges we mentioned in the introduction, explaining how they applied to this case in particular:

-Limited budget: The department provided a maximum of \$100 per student. Anything over this amount would need to be provided either by the students or by external sources of funding.

-Small college facilities: Compared to large research universities, the college is more limited in terms of laboratory space and resources.

-Multidisciplinary team and project (students' perspective): In this case, a professor of electrical engineering with a background in controls theory mentored a project focused on sustainable engineering applications, with highly involved computer and mechanical components. This would force the students to branch out and be more independent in seeking out resources, as well as communicate effectively with each other.

-Multidisciplinary team and project (faculty perspective): Similarly, the instructor would need to grow professionally in order to mentor a project outside his field of expertise.

-Incorporating topics of interest which may not be in the curriculum: For both the mechanical engineering and computer engineering students alike, the sustainability focus of the project necessitated becoming acquainted with new material.

As mentioned at the outset, the general strategy when dealing with these limitations is to turn each challenge into an opportunity. With this mindset, we identified the following set of opportunities:

-The limited budget could increase students' motivation to seek outside sources of funding.

-Developing the project in a small college could present students with the opportunity to positively impact the college infrastructure with their work.

-Working in a multidisciplinary team with a professor outside his field of expertise could lead to student growth, increased communication skills, and increased abilities at fields outside their own concentration.

-Similarly, overseeing a multidisciplinary project outside his field of expertise could provide the faculty member with a valuable opportunity for professional growth.

-Finally, incorporating topics of interest which may not be in the curriculum could provide the students with a more tangible sense of how the theory learned in the classroom carries over to solving problems in practical applications.

In addition to the above opportunities, there were a number of unique characteristics to a small department and a liberal arts college which we considered to be advantages. Amongst them were the following:

-Lack of graduate projects for instructors to mentor: Because the instructors did not also direct graduate research, all project-oriented time is devoted to undergraduate students.

-Expectations of student-faculty interaction in the small college culture: While in a larger

institution, undergraduate students may be reluctant to approach faculty members, the culture in a small liberal arts college encourages students to reach out to faculty whenever they seek guidance.

The Process and Development

The idea for the Hybrid Solar Tracker project came from the students, not the faculty member. Interestingly, the idea originally developed not as part of any of the project-only courses, but as a class project for Control Systems, a lecture-based class.

It was the two computer engineering students that originally developed the idea, but it quickly became clear to them that, as the project itself required multidisciplinary competencies, the team needed to be multidisciplinary as well. In particular, they identified the need to add a student with mechanical expertise to the team. The students selected a faculty member with electrical engineering expertise both because complemented their skill set and because he had been the one to teach the Control Systems class that led to the original idea.

As the students started gathering information on how much it would take to design a solar tracking prototype, it quickly became clear to them that the original amount of money the department would provide (\$300, in this case) would be insufficient. Thus, the students took it upon themselves to seek out external sources of additional funding.

To this effect, the students participated in the Xplore Contest, sponsored by the Phoenix Contact. Phoenix Contact is a large multinational engineering firm that focuses on automation products. While the company's headquarters are located in Germany, the headquarters of their U.S. operations are located in Middletown, Pennsylvania, about 20 minutes from Elizabethtown College. Due in part to this close geographical proximity, as well as to a recent history of collaboration between Phoenix Contact and Elizabethtown College, the students considered tapping into the opportunities to be a logical step.

Once the students committed to participating in this contest, the deadlines set by the contest (which were generally earlier than those set by the program) forced them to work an accelerated pace. While the other students would have to have a completed project by May, this project team needed to complete their project and submit a technical report by February. Additionally, the students periodically uploaded videos to the contest's website, where their progress would be judged by Xplore's panel of judges.

The first step of the process consisted in literature review. There are many kinds of solar trackers commercially available, so the students needed to first understand the basics of the technologies and ideas already existing, so as to develop a design that hopefully improved upon them, but, at the minimum, addressed the problem in a novel way.

Once the students had decided upon a key idea, namely, the hybrid approach, they then submitted videos outlining the concept for the prototype, as well as their plan of action for its design and development. The project qualified as one of the top 100 project ideas worldwide. As a result of this, the students received over \$4,000 dollars in funding for Phoenix Contact

equipment to be used in the project.

The students continued the design through most of the fall semester, and they completed the prototype and submitted the prototype in early February. During the months between then and May (when the college course ended), the students performed additional testing and minor design tweaks to the prototype.

At the end of the semester, when all the students had completed their projects, the department selected the Hybrid Solar Tracker for the Best Senior Project Award.

The Design

We now provide a detailed description of the design of the hybrid solar tracking system. As mentioned previously, this section has been adapted from the students' senior project report.

The Design: Overview

The students surveyed the existing literature in solar trackers and developed their own design, with the objective of increasing tracking efficiency. Their design was a hybrid concept, combining active tracking and chronological tracking. Although chronological tracking has the possibility of being as efficient as active tracking, the likelihood of there being no disturbances to the light source is slim, especially in a typically cloudy place. The sun moves across the sky from East to West, 180 degrees, every day. Each year, the sun moves from low in the sky in winter to high in the summer, with a change of no more than 180 degrees in a year (from 0-90 degrees and back). Considering the rate of change in each direction, the students determined that, especially for our location (Pennsylvania), tracking the sun's movement across the sky (polar axis) was a higher priority for efficiency than tracking its vertical movement (elevation axis). Thus, the system used active tracking in the polar axis and chronological tracking in the elevation axis.



Figure 1. Polar Axis Tracking (left) and Elevation Axis Tracking (right)

The idea for a hybrid solar tracking system is one which uses chronological tracking of the elevation axis and active tracking of the polar axis. This project's active tracking used a small, independent solar panel to scan the sky for the polar axis angle with the most power output. The scanner checks the power output every 5 degrees between 20 and 160. It does this scan once every 15 minutes to ensure the system stays updated with optimal angle data. The system

measures how much power the large photovoltaic (PV) array is producing and use this and other data, such as how much power it requires to move the large array, to determine which spot would be worth moving the array to if there is one at all. Using an independent panel to find the most power output has the potential to make the system more efficient, especially on cloudy days when the sun's power is not orthogonal, because the system would have actual PV output values to look at, unlike a system using light detecting resistors (LDRs). With LDRs, the only thing that can be monitored is the direction of direct sunlight. Also, using an independent solar panel as the optimal angle sensor, power is produced to increase the overall efficiency of the system. LDRs, on the other hand, do not produce any power when subjected to light.

The system used Phoenix Contact nanoLC modules as the controllers for the tracking system. Lutron Electronics donated motors for us to use for moving the solar panels, as demo motors. The Lutron motors are normally used to move their motorized window shades. The first step with the motors was determining what method we would use to control the panels with a nanoLC. The shade motors have their own built-in controllers that move the motors based on commands that are received through an RS485 communication link. Lutron has their own protocol of commands that are sent to the shade motors from the external control devices, such as keypads and contact closure input modules. In addition to having the RS485 communication option, the shade motors also have push-buttons built in. These buttons are used for manually moving the motors one direction or the other and also for setting rotation limits.

The students' initial proposed idea for controlling motor movements from a nanoLC was to use the motors' push-button capabilities. They removed the control push-buttons and connected relay outputs of the nanoLC to the push-button contacts on the PCB. This allowed them to use the nanoLC to "push" the manual motor control buttons to move the motors. The team then switched to using a Lutron CCI (contact closure input) module to communicate with the motors, because the Lutron motors are addressable. This method used the same concept of pulsing the nanoLC relay outputs, except the relays were used to trip certain CCI inputs instead of "pushing" buttons right on the motors. This increased the amount of equipment used, but simplified the wiring of the motors and also increased the reliability of all the wire connections. The Lutron CCI module made the motor control system scalable, as it allowed for easier addition of more motors if necessary. There is no need for running more wires from the nanoLC to any additional motors, since one set of CCI's can command any motor that is set up in its group.

The Design: Mechanical considerations

The student team acquired 50 Watt solar panels, with approximate dimensions of 29"x28", from Phoenix Contact. These dimensions were decided upon after taking into account the size of the system's frame and the dimensions of the base for the Lutron motors into consideration.

Next in the design was the determination of the range of angles for the panels. Ideally, the polar axis would have 0-180 degrees of motion. However, his choice would be structurally weak, as it would feature a vertical pole supporting the panel. The students decided an A-frame would be the best course from a structural standpoint. In order to use an A-frame design direction it needed to have an angle restriction from the vertical because as the panel rotates along the polar axis, it will interfere with the frame. In the morning and at dusk, it is less imperative to be collecting

energy than midday. The horizon, trees, and structures also create barriers to the light close to sunrise and sunset. For these reasons, the panels are set to start at approximately 20° above the horizon. By proceeding in this fashion, a triangular space is created where no movement will occur, so that an A-frame can be constructed. The range of the polar axis is now from 20° to 160° . After choosing our range of angles, we were able to calculate the A-frame dimensions. We could use half of the distance of the panel to make the hypotenuse of a triangle with 20° being the minimum angle (from vertical) that the panel would move through. We also performed height and width calculations of the A-frame. As the base needed to be 22" wide, we stabilized it by using a longer bar along the base and keeping the A-frame attached at 22". The back floor bar is 60". The height of the A-frame is 32" tall, so this geometry makes a triangle of the entire structure with the bottom being the longest side by about 10". This structural design provides support from tipping over and helps with providing an area by which to attach ballasting in a roof mounted situation.

The students then determined the elevation angle range requirements. As mentioned above, this choice of angle was governed by the movement of the sun's annual height in the sky (elevation angle). The optimal elevation angle for the Harrisburg, PA area in winter is around 30° , while in summer it is around 65° from the vertical. We decided to make the structure moveable through 30° through the year. This choice results in a central angle of 50° , with motion of $\pm 15^\circ$ from this central angle. This movement is performed by a linear actuator, which is free in one axis of rotation at each end.

The next step was to determine whether to mount the actuator to the north or south side of the panel structure. Via mathematical calculations and critical thinking, the students determined it would be much more effective if the actuator were mounted in the north direction. The main reason for this was stability. When the actuator is mounted at the front, or southern end, the fully retracted position of the actuator puts the panel at the sharpest angle of 65° . When the actuator is extended, it raises the front of the panel up until it is at the minimum angle of 35° . In this extended position, the panel's center of mass is very high off the ground. This is avoided if the actuator is mounted on the back (the north end), because the panel will start with the actuator fully retracted when the panel is at 35° . Then, to obtain the 65° orientation, the actuator extends and pushes it up. In this case, the overall center of gravity is much lower. Low center of gravity is very important for stability. With a lower structure material to build and therefore is, less expensive. Figure 2 shows the design of the frame.

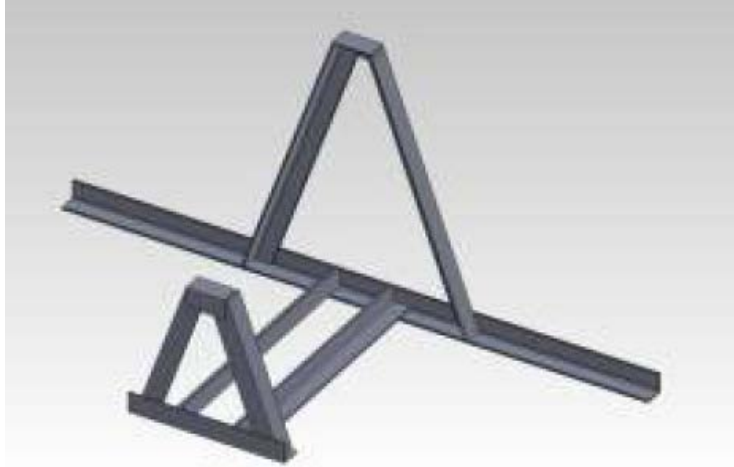


Fig. 2. Isometric view of frame

The length of the linear actuator then had to be determined. This was accomplished by using the length of the panel as the hypotenuse for two triangles with one at 35° and the other at 65° . These two triangles were then overlaid so that the base ran along the same line, and they were “pinned” at the bottom corner (a hinge in the final design). The distance between the two top corners of each triangle can then be calculated. This is the length needed for the actuation. By working through the calculations, it was determined that a 14.5 15” actuator would be required.

Aluminum was chosen as the structural material. Aluminum has a high strength to weight ratio as well as very high corrosion resistance. Steel was initially considered as an alternate possibility. However, from a structural standpoint, steel has far more strength than is required for our application, while aluminum is sufficient. Also, in the case of a roof mounting, steel would add an extra burden of weight to the roof.

The Design: Algorithms and programming

The sensor equipment used in the experiment consisted of dual-axis accelerometers and current sensors. In order to determine the orientation of the solar panel in space, the dual-axis accelerometers were used. These devices were attached to the back of each solar panel and oriented so that the X accelerometer corresponds to the polar axis of the panel, and the Y-axis on the accelerometer corresponds to the elevation axis of the panel. In the algorithm, we use accelerometers to determine when we have reached the appropriate position. We used an inductive current sensor to measure the scanner panel amperage and another to measure the overall array amperage.

Since the linear actuators we are using can only extend and retract by applying a positive or negative enable the nanoLC to switch the polarity of the voltage being supplied to them. We achieved this functionality by building an H-bridge using relays. The basic concept is shown in Figure 3. When only S1 and S4 are closed, a positive volt applied to the actuator, causing it to extend. Likewise, a negative voltage is applied to it when only S2 and S3 are closed, which causes the actuator to retract.

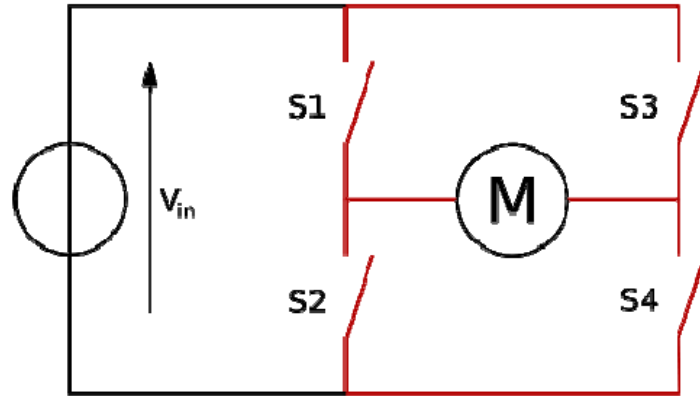


Figure 3. H-bridge using switches

As part of our algorithm for deciding when and where to move the array panels, we needed to be able to transfer sensor data from a nanoLC in one location (inverter room) to our control nanoLC in another location (the roof). We added Ethernet modules to both of the nanoLCs so they ability to communicate through a network. To transfer data between nanoLCs, a MODBUS master is required. NanoLCs cannot transfer values on their own because they can only act as MODBUS slaves. Slaves can only respond to re can't talk unless first talked to). We decided to create a Java application that would run on a PC to act as the MODBUS master. This acts as a bridge between the nanoLCs, allowing data to be transferred between them.

The Java application uses an open source MODBUS library called “jamod” to achieve the MODBUS communications. In the application, we first set up connections to both nanoLCs by specifying their IP addresses and the TCP port that they use for MODBUS. The application then enters a loop where it continuously performs actions, but waits 10 seconds between each loop iteration. At the beginning of this loop, the watchdog of each nanoLC is fed. The watchdog allows the nanoLCs to know whether or not they have a persistent connection to the MODBUS master.

Next in the loop, the “sky scan” monitor is run. This is the part of the application that checks to see if the control nanoLC needs an updated array current value. To do this, the application first gets the value of register 13 from the control nanoLC. If this value is ‘0’, no updated value is needed. If it is ‘1’, it is requesting an updated array current. To satisfy an update request, the application retrieves the array current from the specified array current monitoring nanoLC register. When creating this application, we found that 1 nanoLC register actually corresponds to 2 MODBUS holding registers. The application therefore has to read each part of the array current value and write them both to the proper MODBUS holding registers in the control nanoLC. After the application has finished transferring the array current value, it writes a ‘0’ to the request register (register 13) in the control nanoLC so that the nanoLC knows the value has been updated.

Using these sensors and devices, we controlled the positions of the panels. The first step in the control nanoLC code is to initialize all of the solar calculator values. The built in solar

calculator uses the coordinates (latitude and longitude) where the system will be placed, along with time zone, and the current year, day, and time to determine the appropriate chronologically based values for positioning the solar panels. The information collected in this step is then used to determine the appropriate position for the elevation axis in our system.

Every time the day changes and following the initialization, we run the solar calculator for the day. We also initialize the register values for sunrise, 15 minutes before sunrise, and sunset since they will be needed in future calculations. Values are being updated in the background while the rest of the program executes. Accelerometers values for both panels and the sensor panel amperage are updated continuously. After the initialization is finished, the program jumps to the loop that performs the elevation angle movement. At the beginning of this loop, a check is performed to see if the sun has come up yet, using values obtained from the sunrise and sunset registers. If the sun is not already up, the program waits until 15 minutes before sunrise to move the panels to their optimal position for the day. In order to move the panels to the appropriate position, we use the Y-axis accelerometer values for sensor feedback, which tell us the current orientation of the panels.

Once the panels have been set to their elevation angle for the day, flags are set to switch the program into the scanning loop. Like the previous loop, there is a check at the beginning of the scan loop to make sure that the sun is up. If the sun is up, the scanner panel is first moved all the way to the west. The scanner panel then begins scanning the sky by pulsing the motor every three seconds. Every time the motor pulses, we collect data for the panel's current position on the polar axis. We record the polar axis position (the X-axis accelerometer value) of the scanner panel and record the amperage that the panel is producing at that point. Using this information and the position of the array panel, we determine if the new position is better than the previously recorded position.

To determine if the new position is worth moving to, we first calculate how far the array panel will have to move in order to get to the new position. We calculate this value by checking the difference between the two X-axis accelerometer values. Then we subtract a value, corresponding to the amount of power it will take to move the panels that distance, from the new position amperage. If the adjusted amperage is better than the previously recorded amperage, the new values are stored as the best position. The scanner panel then moves to the best position after a complete scan.

Before moving the array panel, the nanoLC requests updated array currents from the server. Since we don't want to move the panels unless they will be making enough power, we look at both the amount of current the array panel is making and also the amount the sensor panel is making, and determine if our threshold has been met. If it is, we move the array panel to the same position as the sensor panel. If the request for the updated array current does not get fulfilled, there is a check to see if the Ethernet watchdog has timed out. If there was a timeout, the array amperage check is skipped and an error message is displayed. This allows the panels to continue moving even if there is an interruption in the connection to the MODBUS master.

Finally, once we have completed a single scan cycle, we wait for 13 minutes, making each scan cycle approximately 15 minutes long. The scan program then jumps back to check if the sun is still up. If the sun is not up, then flags are set to send the program back to the loop that performs the elevation movement, and if it is still up then the next scan is performed.

Lessons and Outcomes

The general feedback from the students about the project was very positive. They were very satisfied to have the external validation for their work, as well as the recognition within the department. We now discuss some of the lessons and outcomes derived from this project, in the light of the challenges and opportunities we outlined earlier.

Regarding the limited budget, we hoped this would increase the students' motivation to seek outside sources of funding. We feel this was indeed the case for this project. The students showed the self-motivation and resourcefulness to find out about the contest and take advantage of the opportunities presented by Phoenix Contact to enrich their project.

We also hoped that developing the project in a small college could present students with the opportunity to positively impact the college infrastructure with their work. In fact, the students at one point hoped that their prototype could be mounted on top of the engineering building so as to help the college with whatever power the project could save. However, in this regard, we discovered that the logistical processes for making this come to fruition were more involved than expected. In particular, getting the approval from other factions of the college to provide this service proved to be a challenge. We were unable to complete this part of the project within the one year time frame. However, the prototype remains a learning platform and can be improved upon by future generations of students.

We framed working in a multidisciplinary team as an opportunity for student growth, increased communication skills, and increased abilities at fields outside their own concentration. In this regard, the project was extremely successful. The students had to work together to overcome numerous conceptual difficulties, as well as technical challenges, such as the precision of the motors, difficulties with the Solar Calculator, and logistical limitations for testing under various conditions. The need to overcome these challenges pushed them outside their comfort zone, driving them to seek additional resources and learn from each other. The mechanical engineering student, in particular, commented on how he gained significant understanding of the interaction between mechanical devices and digital logic and how this deeper understanding allowed him to be more confident and well-rounded when embarking on the job searching process. The computer engineering students, in turn, commented on how the project heightened their appreciation for the need for the software and programming aspects of a project to be aligned with the hardware developments in a coordinated manner.

In turn, this multidisciplinary project was indeed a valuable opportunity for professional growth for the faculty member. Observing the connections between the content from the lecture classes and the mechanical and computer engineering content associated with it and such applications has provided the faculty member with a richer background both for mentoring future projects and for incorporating multidisciplinary applications into lecture-based theory courses. In particular,

the use of mechanical devices such as linear actuators provided for ideas examples to be used in place of traditional, theory-only textbook examples. After this project, the faculty member has continued to mentor more mechanical engineering students in subsequent projects, as opposed to limiting himself to primarily electrical and computer engineering students, as he had previously.

Finally, the consensus from both the students and the faculty member was that allowing students to seek out topics of interest which were not covered in the curriculum indeed successfully provided them with very tangible benefits. In particular, the students came away with an increased sense of how the theory learned in the classroom carries over to solving problems in practical applications, as well as how, in order to solve a problem effectively, it is necessary for engineers of various disciplines to collaborate and learn from each other.

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