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An Update to a Multidisciplinary Hydroelectric Generation Design Project

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Abstract

A two-semester freshman course sequence at Norwich University brings Mechanical Engineering (ME), Civil and Environmental Engineering (CEE) and Electrical and Computer Engineering (ECE) students together during the first semester for a general Introduction to Engineering course. They complete the second introductory course in the sequence in their respective disciplines. A final project in the second semester that could bring the students back together to make discipline-specific contributions to a multi-disciplinary project was implemented in the spring of 2012. The chosen project was a hydroelectric generation project in which the ME students designed a waterwheel to work in a laboratory flume, the ECE students designed a permanent-magnet generator with wireless monitoring, and the CEE students designed a structure to support the wheel and generator. Throughout the course of the project students designed their respective components and communicated with others among the various disciplines to define design interface requirements. The first year of the project was successful in that the student teams were able to design working components that functioned together in a system to generate electricity. That design experience and several lessons-learned were previously reported at the 2013 ASEE Annual Conference. Many of the lessons learned were adopted to enhance the experience for the next class of freshmen in the second annual iteration of the project. The scope of work for each of the respective disciplines was narrowed and the project test platform was modified—replacing the waterwheel with a turbine to afford the students the opportunity to test, measure, and analyze the performance of differing mechanical turbine designs. A number of new challenges were present in the second iteration of the project, including the absence of the CEE students from participating in the experience. This paper is an update to the previous report presented at this conference and will present the scope of the design problem, summarize the project modifications that stemmed from the lessons learned in the previous iteration, address the instructional coordination challenges and successes, and discuss the value of the multidisciplinary project to student achievement of course specific outcomes related to the freshman engineering sequence.

Introduction

This paper details the implementation and evolution of a multidisciplinary design project that serves as a capstone activity for freshman engineering students among the Mechanical Engineering (ME) and Electrical and Computer Engineering (ECE) disciplines. All students from an engineering discipline at Norwich University complete a common, general introduction to engineering course that introduces them to various fundamental skills and tools of the engineering profession in the fall semester. The concepts introduced include the technical and non-technical aspects of engineering design, graphical communication skills, data collection, and statistical analysis. Following this course, the students complete the sequence by following a course of study introducing them to discipline-specific tools during the spring semester.

This curricular configuration provides an opportunity to thrust the students into an engineering design project with realistic non-technical constraints and parameters early-on in their academic careers. After spending one semester working to develop a common understanding of the engineering profession, the students diverge and learn discipline-specific techniques, tools, and terminology. The various disciplinary groups are then required to reconnect during the spring semester through this project to design and implement a hydroelectric generator to instructor- ("customer-") provided resource, operational, and temporal constraints. This creates a rich educational platform that requires small groups of students to form teams and take ownership of pieces of the larger design project, while simultaneously requiring them to work with other teams of students from other disciplines to reinforce the interdependency of their respective roles. Through this project experience, students have the opportunity to connect their specific disciplinary background to a larger, interdisciplinary topic; they also have the potential to recognize the value that multi-disciplinary technical and non-technical perspectives bring to the challenge of solving a realistic problem. Both of the aforementioned opportunities have been identified as major learning barriers to cross-disciplinary learning[1].

The opportunity for teaming and the collaboration of engineering students with others outside their respective domains are the primary motivation for, and thus the primary emphasis of the project. The technical scope was constrained such that freshman students with little experience would have a high probability of succeeding at the endeavor. This resulted in a relatively low performance expectation—an expectation that their design merely result in a functioning power generator and accompanying monitoring system for measuring the generator's power output. Constructing and constraining the project in this manner is critical to the perception of the project as a "mastery experience" by most of the participants. Mastery experiences have been noted[2] as key to shaping many students' self-efficacy beliefs; it has also been noted that a student's self-perception of content mastery is highly linked to their self-reported enjoyment, interest, and satisfaction. These factors are also commonly linked to one's motivation for learning. The next section presents how the scope of the project was appropriately constrained for the technical level of its constituency.

Design Project Overview

The hydroelectric power generation project with associated power monitoring was inspired by an overseas aid project involving the construction of a permanent magnet generator used with a small wind turbine[3]. The hydroelectric application of a PMG was originally selected because it provides a platform that introduces students to electrical, computer, mechanical, civil, and environmental engineering concepts. The initial instantiation of this design project was previously reported at the 2013 ASEE Annual Conference—where the electromechanical aspects and associated model equations for the generator are described in full detail[4]. A brief presentation of the necessary attributes is provided below.

The hydroelectric generator plant can be divided into three main components: the generator, turbine, and hydro source. A diagram of the plant and these components is shown in Figure 1. For the purpose of the project, each of these main components was mapped to one of the constituent engineering disciplines for completion by a student team. The generator became the primary responsibility of the electrical and computer engineers, the turbine became the wheelhouse of the mechanical engineers, and the hydro source became the focus of the civil and environmental engineers. For the project iteration detailed in this paper, the civil and environmental engineering group opted out of the project, and a team of faculty and staff took responsibility for providing information related to the hydro source.

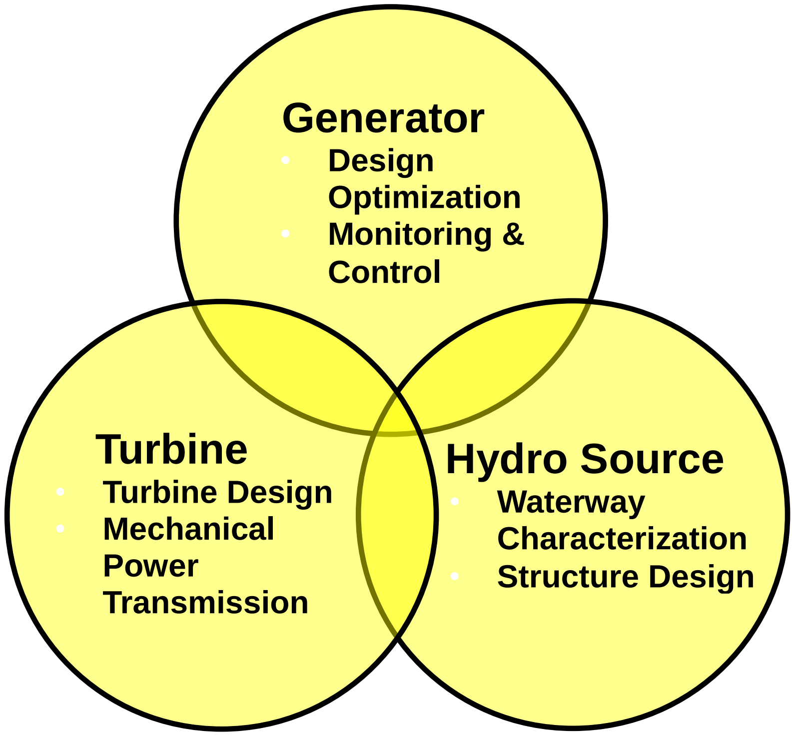

Figure 1 - A Venn diagram of the primary components of a hydroelectric generator plant which were mapped to the respective *(engineering discipline)*: the generator *(ECE)*, the turbine *(ME)*, and the hydro source *(CEE)*.

The interdependency of the plant components as represented in Figure 1 created an opportunity for the small mono-disciplinary teams of engineering freshman to interact with groups from others disciplines outside of the normal classroom and lab hours. Many were hesitant to do so and they soon realized that in order for their project to succeed this was less of an opportunity and more of a necessity.

The sub-components listed in each of the elements of the diagram in Figure 1 were the responsibility of their respective engineering teams during the first iteration of the project. Based on the lessons learned from that project execution, a number of refinements were made to this initial vision and division of labor. However, all constituent elements of the diagram were essential components to the execution of the project. As a result, a fourth constituency, a team of faculty and staff, designed and implemented the pieces of the overall power generation system that were no longer in the per-view of the student teams. The interfacing requirements to those subsystems became a design constraint for the overall project as presented to the students. Details on this modification and other project changes follow in the next section.

Project Evolution

A concise summary of the previously reported[4] lessons learned in the first implementation of the project is provided below in Table 1. For convenience, a letter has been assigned to each of the insights. In the discussion that follows laying out the modified execution of the project in the Spring of 2013, each change that is detailed will reference the associated lesson that motivated the change by listing the corresponding letter afterward in parentheses.

Table 1 - Lessons learned from the initial execution of the hydroelectric generator design project.

Identifier	*Lesson Learned / Insight*
LL-a	Narrow the problem definition
LL-b	Multiply component design options to increase tasks for added engagement
LL-c	Start earlier in the semester
LL-d	Everyone doesn't have to do everything; focus on the process
LL-e	Being part of something bigger than the individual project has a positive effect on the work ethic of some students

Electrical and Computer Engineering Teams

The permanent magnet generator's (PMG) design is that of a rotor comprised of two quarter-inch thick steel plates with permanent magnets mounted on each plate with alternating north-south orientation, and a stator with enamel coated magnet-wire coils mounted in the gap between the rotating magnet plates. Solid models of the rotor were created in SolidWorks and machined on an automated machining center. Three reference rotor designs were created by the team of faculty and technicians based on the use of eight 1" square, twelve ¾" square, and sixteen ½" square rare-earth magnets. As the magnets of the rotor pass over the coils of the stator, current will flow and a potential difference will develop across the coil. The peak magnitude of the electromotive force or voltage difference that develops is described by equation (1) when the constituent components of the relationship: the relative velocity between the magnetic field and the coil (u), the segment of the wire bundle (l) with N turns that interacts with the field, and the orientation of the magnetic field (B_o), are all taken to be orthogonal.

$$V_{emf} = uB_o lN \quad [V]. \tag{1}$$

By fixing the design of the rotors and removing the need for the students to fabricate them, the rotor component of the generator effectively became a commercial-off-the-shelf (COTS) component with a bad datasheet. The scope was thus narrowed (LL-a) to increase the number of overall generator designs that were implemented and tested (LL-b), and the electrical and computer engineering students were sub-divided into five groups each responsible for a different core component of the overall generator (LL-d). The division of responsibility was as follows:

- one group was tasked with designing an electric circuit that supported AC waveform rectification of the signals from all three different stator designs, variable loads for power dissipation, and voltage and current monitoring by a microprocessor;

- one group was tasked with developing an embedded system and the relevant signal conditioning and display technology to monitor the voltage and current output of the loaded generator and to display the overall power output of the system;
- three groups were required to characterize the magnetic field of the provided rotors as a function of the air gap between the rotor magnet and the stator coils, and to design and implement a stator (number of turns, wire gauge, coil thickness / air gap, number of series coils) with the required number of coils to match the geometry of the reference rotor and to meet the target voltage specification given the expected torque and rpm output from the mechanical turbine. Each of the three groups was to develop a custom stator for one of the three reference rotor designs.

Mechanical Engineering Teams

Previously, the mechanical engineering teams were responsible for designing the turbine and the transmission required to harness the power in the flow and transmit it to the rotating shaft of the generator at an appropriate torque and speed. The initial implementation resulted in the students generating a large, wooden undershot water wheel and a primitive drive train directly connecting a 138 tooth gear to a 10 tooth gear. It was noted that the availability of source materials and the size of the undershot wheel required for the water source (a 12" wide weir capable of producing a 20" head and a variable flow rate of up to 12 gal/s) greatly limited the number of designs that the mechanical engineering students could complete.

As a result, the team of faculty and staff decided that the mechanical turbine design would be required to be a Kaplan turbine. The team implemented a drive train to transfer / transform the energy from the turbine to a rotor based on the chain and sprocket drive of a ten-speed bike. In the process, the mechanical specification for the turbine shaft was also defined. The properties of the transmission system became constraints for the design project that were provided to both the generator and turbine design groups. This modification narrowed the scope of the mechanical project (LL-a), and by focusing on the Kaplan turbine design, it greatly increased the number of turbines that could be designed and implemented by three sections of mechanical engineering students (LL-b). An image of the transmission system implemented is shown in Figure 2.

Figure 2 - Headstock, turbine, transmission system, and PMG for the hydroelectric generator plant.

As a result, the mechanical engineering students teams designed, simulated, analyzed, redesigned, and rapid-prototyped several turbine designs. The mechanical teams designed multiple turbines in SolidWorks, varying the blade pitch, shape, and number with the goal of maximizing the rotational velocity based on their model. A few of the fabricated designs are shown in Figure 3. Due to the transmission system specification, these turbines were designed in such a fashion that they could be quickly interchanged and evaluated based on the peak and average power that the turbines transferred—as measured by the generator. This added an element of competition to the project as well as the opportunity to give the students experience with another key area of multi-disciplinary engineering, the engineering of tools used for measurement and scientific discovery. The flexibility of the turbine-transmission interconnection combined with the generator enabled the completed system to function as an alternative means of evaluating the power output of a mechanical turbine under test.

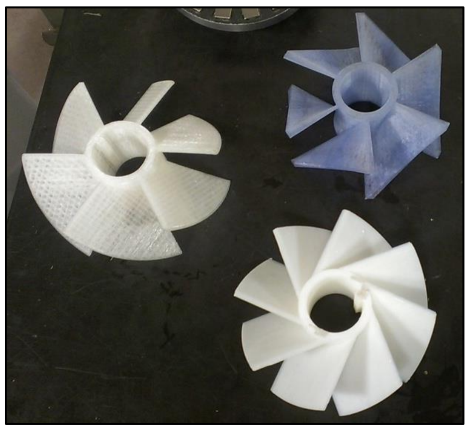

Figure 3 - Three Kaplan turbine designs for the hydroelectric generator plant.

Civil and Environmental Engineering Teams

In the original project execution, the civil engineering students were responsible for characterizing the flume and designing all of the support structures necessary to accommodate the turbine, generator, and transmission system. In the second iteration of the project, the goal was for the CEE students to maintain this role, with the problem being constrained by the instructor specification of the transmission system, rotor design, and Kaplan turbine. These constraints (a) would allow for more creativity in the design of the structural support and reduce the tendency for the design teams to converge on a massive support structure because of the possible turbine variations that may result from the mechanical engineering groups or a general breakdown of intergroup communication. Additionally, these modifications would allow for further subdivision (b) of effort and provide the opportunity for some CEE teams to design earthen dams or other apparati to funnel the flow of the weir to the turbine. Opportunities also exist for the CEE students to engage with the project in an overall project management capacity.

Unfortunately, the CEE class opted out of the project in its second year due to a unique opportunity that presented itself on the Norwich University campus. Construction was beginning on a new biomass generation plant, and the CEE freshman class had the opportunity to take part in a number of experiential learning opportunities as the site development and construction of the facility took place on a timeline and in a location convenient to the freshman course.

Cross-disciplinary Interactions

With the project constructed as stated above, the multidisciplinary nature and coordination aspect of the project was designed to take the following form:

- The electrical teams required knowledge of the mechanical power output of the system which directly relates to the generator's speed and torque. They were required to work with the mechanical engineering teams to converge on a torque and speed input that their generator design could accommodate.
- The mechanical teams negotiated with the electrical groups for a torque and speed output from the turbine that they could achieve with the available materials, based on the project constraints, the weir operating parameters, and the mechanical torque induced by the electrically-loaded generator.

Beyond the ME-ECE interdisciplinary structure, the development of the electrical engineering teams was in itself structured as a cross-disciplinary endeavor of small teams working on one small piece of a larger project or subsystem. Remembering that the students involved in the project are freshman who had yet to be introduced to the details of many of the elements required to produce a rigorous design, the components selected for each ECE team were carefully constructed and guided. The division of labor for the generator design was such that the electric circuit team was required to interface with the stator team to define the range of power output and the maximum voltages and currents that could be accommodated. The electric circuit team was also required to interface with the power monitoring team to agree upon a technology and interface that would allow for an embedded system to sample, analyze and display the system operating parameters. Through the beauty of the conservation of energy, all of the electrical operating parameters were related to the operating point of the mechanical systems and the ability for the mechanical designs to meet those specifications.

Instructional Challenges and Successes

The students in this introductory course were required to complete a large, "real-world" project that required them to become experts in their respective domains so each team could deliver a functional subsystem that was essential to the overall success of the entire endeavor. As freshman, the students were far from experts—but in working through the project they had to become efficacious in their own domain and familiar with the high level concepts and limiting factors in the other disciplines to effectively communicate responsibilities and requirements as they worked to complete the project.

The student teams spent approximately 5 weeks of the 15 week semester working on the hydroelectric generator project. It poses quite the instructional challenge to design the rest of the course in such a way that discrete laboratory exercises intended to introduce the students to a breadth of fundamental, discipline-specific tools and concepts scaffold in such a way that they accomplish that goal and simultaneously support the capstone course project. In the electrical engineering course, the students completed a series of lab exercises that introduced them to Arduino-based microcontrollers, embedded system programming, digital and analog I/O, power and energy conversion, and simple electric motors. Similarly, the mechanical engineering course addressed this challenge through a series of labs that introduced the students to data analysis in MATLAB as well as 3D solid modeling and simulation in SolidWorks. Despite the recognized need to introduce the project earlier in the semester, and all efforts of the instructors to do so (LL-c), the need to introduce fundamental concepts in support of the project and the additional burden on the instructors to develop and implement subsystems to further constrain the design prevented that from happening. Additionally, the absence of the civil engineering group from the project added an additional design and implementation burden as a rudimentary head stock and support system was needed to interface the mechanical and electrical subsystems to the existing weir.

With respect to the project overall, the participants were successful at achieving the modest performance expectation of creating a hydroelectric generator plant with power monitoring in 5 weeks time as a part of an introductory freshman engineering course. A number of intermediate successes and challenges surfaced throughout the process presenting future opportunities for further project improvement.

The time spent introducing the concepts of analog and digital I/O, the use of embedded systems for monitoring and control, and basic circuit theory to the electrical and computer engineering students prior to beginning the project was effective at providing the load/rectification circuit and monitoring teams with sufficient background information to support the inquiry and design required to complete their tasks. The supporting laboratory experience based on the use of the electric motor and the lecture materials covering the high level principles behind a permanent magnet electric generator were sufficient at getting the stator teams to understand the high level functionality required of their designs. However, they were insufficient at supporting the students to the point that they could effectively construct and conduct intermediate design tests for verification. Additionally, the stator teams needed significant instructor intervention as they worked to optimize the reduced set of stator design parameters—further constraint of the allowed stator coil design variables is likely necessary. Two of the three stator groups implemented a design that was successful at interfacing with the load/rectification, power monitoring, and mechanical turbine teams to achieve power generation. Of the five final project reports submitted by the electrical engineering teams, two communicated their designs and findings in a manner far superior to anything that was previously submitted throughout the course.

The preliminary exercises introducing the mechanical engineering students to data collection and analysis in MATLAB as well as 3D solid modeling and analysis in SolidWorks were successful at supporting the student teams as they worked to design a Kaplan turbine—approximately 16 unique turbine designs resulted and 5 were successfully fabricated with a rapid-prototyper. Additional modifications may be necessary to further support the students in their ability to model and analyze their designs as they struggled to understand and communicate the expected performance and resultant unloaded mechanical power output of the turbines based on their designs.

The faculty designed transmission system was successful at creating a plant that allowed for convenient and repeated changes to the turbine “under test”. Only five of the approximately 16 turbine designs were fabricated due to naïve expectations of the faculty team that a MakerBot Replicator 2 would be able to successfully produce 16 turbine prototypes. Contingency plans including access to two additional MakerBots, an additional in-house 3-D printer based on another technology, an ABS-based rapid-prototyping facility at a local fabricator, and access to an ABS-based 3D-printer at a neighboring university were all exercised and necessary in order to produce the five turbine designs that were realized. In the future, better fabrication tools and processes will need to be in place. A higher quality ABS-based machine is now available at Norwich University and expected to be used in future iterations of the project after some initial experimentation and validation.

Fabrication proved to be an exceptional challenge when it came to the stator component as well. To achieve the maximum performance from the rotor/stator permanent magnet generator, the stator coils needed to be precisely located and supported by a non metallic material in such a way that the amount of support material between the rotor and stator was minimized. Two opportunities for fabricating the stators were in place early on in the project: production on a rapid-prototyper or CNC milling of an acrylic material. Both processes failed. The stators were ultimately assembled by the electrical engineering students by manually locating the stator coils on a template and encasing them in a filled polyester resin (Bondo brand automotive filler).

Both the mechanical engineering turbine design teams and the electrical engineering teams struggled significantly with cross-team interaction. While it seemed opportune to force the groups to interact and negotiate acceptable torque and speed parameters for their respective components, the level of understanding by both constituencies was not to a point where they could effectively predict what was achievable based on either the project constraints or their overall designs. As such, the designs eventually evolved to the point where they occurred independently. Through the initial communications, students from each discipline seemed to grow in awareness of the needs and limiting factors that affected the other domain; they simply did not have the perspective or understanding to be able to negotiate operating conditions that were realistically achievable. The narrowing of the project scope for the disciplinary sub-teams while increasing the number of design variations that were pursued appeared to decrease the number of student team members disinterested in the activity and seemingly uninvolved.

Once fully implemented, the mechanical impeller combined with the electrical generator proved to be excellent tools at helping the students visualize work and power. In retooling the project for future executions, it would be helpful to allow some of this visualization to occur in advance of the project. While the students may not be in a place to mathematically or numerically predict the performance resultant from their design choices, opportunities exist to have the students conduct parametric tests with respect to machine / system design parameters. Such a test could serve as the basis for one (or more) of the laboratory exercises used to introduce discipline specific tools and could increase the students’ understanding of the relationships among the design attributes and the design performance. With this increased understanding through intermediate experimentation, the students may be better suited to communicate the range of performance that their designs could likely achieve.

A devastating challenge to the endeavor was the unexpected passing of Dr. Radu Florea, a dear colleague and friend integral to the project team, heavily involved in the design and fabrication of some of the faculty-team required deliverables, and instructor of four mechanical engineering student teams.

Course Outcomes

The School of Engineering at Norwich University indicates that a student's participation in the introductory freshman engineering sequence should contribute to that student's achievement of ABET student outcomes b-d, f-k, and a program specific outcome referred to as 1. For clarity and brevity, the aforementioned outcomes[5] can be referred to as efficacious: experimentation (b), design (c), teaming (d), ethical awareness (f), communication (g), broad contextual awareness (h), life-long learning (i), contemporary issue awareness (j), application of modern tools (k), and leadership (l). The program specific student outcome (1) is more fully designed as "an ability to demonstrate initiative and perform in leadership roles." Through the execution of the project, the instructors feel that a number of students showed improvement in their stage of development with respect to outcomes c, d, h, i, k and l. The authors also feel that the project can and should be further modified in such a way that the same observation can be made with respect to outcomes b and g. More effort is needed to devise an effective method to quantify and report on these observations. A method was devised to use data that is currently tracked with respect to the student outcomes mapped to the course, but the time scale on which it is collected made it difficult to be useful. An improved process of survey and analysis designed specifically for the project is needed.

Conclusions

The authors' belief that structuring a project such that the student participants are a part of something bigger than the individual project would result in a positive effect on the interest and effort of some students (LL-e) was validated in the first iteration of the hydroelectric generator project. As a result, the project was modified in an attempt to incorporate the lessons learned from the previous iteration (LL-a-d). Modifications were made to narrow the project scope for the various design teams in an attempt to increase the number of students who would perceive the project as a mastery experience while keeping the general problem formulation as a large, interdisciplinary project requiring coordinated problem solving from various perspectives. Many of the modifications were well received by the students and faculty involved in the endeavor.

It remains a goal and challenge to introduce the design project earlier in the semester while balancing the need to provide the students with discipline-specific content that is both general enough to serve the stated purpose of the course and specific enough to support an increased understanding of the science and engineering principles related to the project. Additionally, it remains a challenge to achieve universal "buy-in" by the faculty responsible for teaching the discipline-specific introductory courses due to the frequent changes that occur in the coverage of said courses.

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