A Model for Incorporating Undergraduate Research into an Engineering Curriculum

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Abstract

A model is described for incorporating undergraduate research into an engineering curriculum through a vertically integrated design sequence. The sequence is composed of five courses: one each during the spring semester of the freshmen through junior years and two courses during the senior year. Each course offers skills that provide scaffolding for students to contribute to a team performing an engineering design project or research project. Teams are composed of freshmen through seniors (i.e., vertically integrated) and led by seniors. A strength of the model for undergraduate research is that upper level students can mentor lower level students, which allows for students to build on the accomplishments of previous years and create continuity in the research program. A current project on thermosiphon research will be used to illustrate how the model works. The thermosiphon project is in its seventh continuous year, has averaged 12 students per year, and has students working on both research and applications aspects of the project. Students on the teams are members for approximately two years on average, which gives them time to learn the details of the project and then mentor new members in critical areas of the project such as data acquisition and testing procedures. After an initial period of development in the collective knowledge of the research group lasting two years, team members have now written proposals successfully receiving funding from internal university groups and presented their results at regional and national undergraduate research conferences over the past four years.

Keywords: Undergraduate research model, Integrated design sequence, Vertical integration

Introduction

Project-based learning is an effective means to help students learn professional skills, such as teaming, leadership, mentoring, communications, and project management, that are critical to engineering research and design [1]. Students that experience project-based learning have better development of professional skills compared to students that don’t have the experience [2], [3], [4]. The senior capstone course often uses project-based learning as an experiential learning technique to impart these professional skills to students. Some programs use the senior capstone course to offer undergraduate research experiences to their students [5], [6] but these programs are restricted to seniors performing the research.

Cain and Cocco [1] and Savage, Chen, and Vanasupa [7] argue that students need multiple project-based learning opportunities throughout the curriculum to perfect their professional skills. There are a limited number of programs that offer such a research opportunity throughout the entire curriculum. One program that comes very close to achieving this is the Vertically

Integrated Projects (VIP) program centered at the Georgia Institute of Technology [8], [9]. The VIP program integrates sophomore through senior undergraduate students with graduate students to work on a variety of multidisciplinary research and product innovation projects with many partner institutions. However, this program is not a required course so that it does not impact all students within a major and it does not include freshmen. Ideally, a program would offer courses at all grade levels as a degree requirement so that all students, freshmen through seniors, could master their skills through multiple experiential learning opportunities.

Integrated Design Sequence Model

The Integrated Design Sequence is a series of five required courses in the mechanical engineering program that teach engineering design through lectures and project-based learning. One course is offered each spring semester from the freshmen through junior year that provide scaffolding for non-seniors to develop essential skill sets for projects as well as two courses during the senior year. Teams that work on the projects are vertically integrated, that is, freshmen through juniors work on senior-led teams.

Integrated Design I is a two credit-hour course that teaches freshmen the design process through one-hour lectures on Tuesday afternoons and fabrication skills during two-hour workshops on Thursday afternoons. The course lectures introduce the design process featuring the NASA Systems Engineering Engine approach, documentation generation, metrology, design decision making using nominal group technique and Failure Modes and Effects Analysis (FMEA). The workshops teach basic manual machining methods in support of a course fabrication project and are foundational skills for other courses in the sequence. The students use Siemans NX8 solid modeling software for 3D modeling, generation of engineering drawings, generation of metrology drawings, and generation of *.sls files for input to the 3D printer.

Integrated Design II is a two credit-hour course that teaches sophomores the principles of computer-aided manufacturing through two-hour labs and/or lectures on Thursday afternoons. Students build on their NX 3D modeling skills and learn CNC programming to develop rapid prototyping models and develop G-code for numerically controlled milling and lathing.

Integrated Design III is a three credit-hour course that teaches juniors experimental measurement techniques and the design of experiments through two-hour labs and/or lectures on Thursday afternoons. Students learn how to use sensors and other instruments to measure physical quantities, such as temperature, flow rate, pressure, and strain, through a series of lab assignments and must also complete out-of-class project-based learning assignments. Students learn LabVIEW, a data acquisition software developed by National Instruments, to acquire data automatically. Students also learn uncertainty analysis to interpret data and to design experiments through the proper selection of instrumentation.

The remaining two courses in the Integrated Design Sequence consist of the traditional senior capstone courses. Professional Practice I is a three credit-hour course in the fall that teaches seniors professional skills, such as project management, teaming, time management, leadership, professional ethics, and negotiations, to help them lead and manage the vertically integrated teams working on the projects. Course material is delivered through traditional lectures and workshops. Seniors develop a proposal for a two-semester project, perform research or engineering design throughout the semester, and then document their work through an interim report at the end of the semester. Students propose and subsequently defend their work through two presentations to their peers and faculty during the semester. Professional Practice II is a three credit-hour course in the spring where seniors continue the research or engineering design and fabrication to complete the work proposed in the previous course. Students write a final report and defend their work in a presentation at the end of the semester to peers, faculty, and working professionals who are members of a program advisory board.

Projects are typically competition-type projects (e.g., SAE Formula Car or SAE Baja), service learning projects, industrial projects, or research projects. Students select projects in one of two ways. For continuing projects, rising seniors that worked on the project as a junior recruit and interview prospective team members. The rising seniors determine who will be on the team the following year. Sometimes, rising seniors are interested in a new project. The project is proposed to the course instructor and, if approved, the seniors originating the project then recruit and interview prospective team members.

The focus of this paper is on the benefits of applying the vertical integration of teams in the Integrated Design Sequence to undergraduate research but similar benefits can be derived for any project that continues from year to year. For example, the SAE Formula Car and SAE Baja projects are ongoing projects that benefit from continuity in team membership. Typically, seniors will mentor juniors by showing them what models were applied to component designs and how to use the models. Seniors are often co-located with underclassmen teammates in fabrication areas to provide help even if it isn’t work directly related to their component. Another benefit is that teams on continuing projects have students who have previously attended the competitions and are already familiar with the competition environment.

While there are many benefits to the Integrated Design Sequence, there are some limitations to the implementation of such a program. Experiential learning projects like those in the Integrated Design Sequence require more faculty involvement than other forms of learning. Faculty project advisors are typically selected from the Integrated Design Sequence course instructors. From a practical point of view, section enrollments need to be around 20 students to keep faculty from advising more than one or two teams. With students from all four grade levels working on senior-led projects, demand can strain program resources, such as fabrication equipment and workspace. Likewise, there can be greater demand for staff technician time, especially for operating more complex equipment like the 5-axis CNC mill or the CNC lathe.

While there is some integration of course material throughout the Integrated Design Sequence, a major focus of the sequence is the vertical integration of the teams. There are no formally written learning outcomes for the sequence per se but, since all teams are senior-led, consistency in the learning experience across teams is established through course instruction offered to the seniors in the fall-semester Professional Practice I course. Many important aspects of teaming, such as learning to work with people having different social styles and different cultures, interpersonal communications and non-verbal communications, attributes of successful teams to emulate, establishing team expectations and consequences, strategies to manage various team problems, how to hire and fire teammates, mentoring, and leadership, are covered through lectures and practiced in workshops.

A unique feature of the Integrated Design Sequence is the use of vertically integrated teams composed of all four grade levels in the mechanical engineering program. Freshmen through juniors have the opportunity to work on senior-led teams. While the Integrated Design Sequence is required for all mechanical engineering students, it is not a requirement for other engineering disciplines even though different majors have participated on the projects. Projects are largely completed by teams of mechanical engineering students although students in other majors, such as electrical engineering, civil engineering, business, physical therapy, and even theatre, have collaborated in multidisciplinary projects. Non-mechanical engineering students sometimes volunteer their time on a project but typically collaborate through a course in their own major.

Teams are not required to have a predetermined size or a fixed number of students at any particular grade level. Team size and composition are determined by the project scope of work and functional requirements. Over the past 7 years, there have been as few as four teams in the Integrated Design Sequence and as many as nine in any given year. Some teams may have more juniors, for example, if there are significant data acquisition requirements. Earlier in the program, there was a failed attempt to require all freshmen through juniors to work on senior-led projects. Because there are typically more freshmen and sophomores than seniors due to attrition in the program, seniors were often overwhelmed trying to manage a large number of underclassmen. Furthermore, some students lack sufficient motivation and create problems within teams. Currently teams have full autonomy over the composition of the team. Students not selected for a senior-led team in any particular year participate in a course-specific project.

Teams have much autonomy over who is hired and potentially fired. Teams may choose the method for selecting members but, once a method is chosen, it must be applied equally to all who seek membership on the team. Most teams conduct personal interviews but some may also require prospective members to submit a resume. Once teams are formed, teams are asked to develop expectations for team members and consequences if they fail to meet expectations. If a team member habitually fails to meet expectations, the team may fire the offending member. Before this can happen, however, teams must document the offenses, meet with the course instructor and work out a plan to ameliorate the problems, and then work with the offending member to correct the behavior. If significant progress is not made, the team may then fire the offending team member. The instructor of the senior-level Professional Practice course mentors seniors on techniques to address team problems. As problems arise throughout the semester, the instructor will work with the team leader or the seniors on the team to develop a plan to correct the problem.

Students have a minimum number of hours required for each course in the Integrated Design Sequence. Freshmen through juniors are expected to put in a minimum of 60 hours for their spring course while seniors are expected to put in 250 hours over the academic year. Freshmen through juniors are encouraged to participate in team activities at the beginning of projects in the fall even though their course does not begin until the spring semester. Any hours that they contribute to the project in the fall are recorded in weekly reports and a task breakdown that eventually count towards their spring course requirements.

Seniors are encouraged to establish mentor-protégé relationships with freshmen through juniors. Mentoring relationships are not required to ensure that the mentor is properly motivated to help. The mentoring relationships may be formal or informal and help the protégé be more productive and have better feelings about the project. Many times the mentor will work alongside their protégé to train them to take over their position the following year. This is a foundation of one strength of the Integrated Design Sequence model for undergraduate research; students mentoring students to establish continuity in the research methods and a collective knowledge of the research program. A case study will be described to illustrate the application of the Integrated Design Sequence model to undergraduate research.

Thermosiphon Research-An Undergraduate Research Case Study

Thermosiphon Description

A thermosiphon is a device that collects solar energy that can be stored as thermal energy or dissipated immediately as a heating source. The most common application is the storage of thermal energy as domestic hot water heaters. Thermosiphons may also be used as a heating source but, since the solar input is intermittent, they work best as supplemental sources of heat. The thermosiphons studied in the current undergraduate research program are passive systems, that is, there is no pump or any other moving components. Because they require no electrical input, passive thermosiphon systems are ideal for locations with no electrical power or intermittent power. Likewise, because they have no moving parts and are not prone to failure, they are well suited in remote regions with little technical support.

The basic features of a passive thermosiphon are the collector, storage tank (or heat exchanger, depending on the application), and interconnecting tubing, as shown in Figure 1. The collector is composed of parallel vertical pipes connected to manifolds at the top and bottom of the vertical piping. The piping system is attached to an absorber and placed in an insulated container covered with one or more layers of glazing (usually glass) on the top. The pipes and absorber are blackened for maximum absorption of sunlight and made of a material with high thermal conductivity, such as copper, to facilitate the transfer of heat. The collector is placed at an angle that varies with latitude to optimize the collection of solar energy. For domestic hot water heating applications, an insulated horizontal storage tank is used. For supplemental heating applications, a heat exchanger, typically finned copper tubing, would be used in place of the storage tank. A tube, called the hot leg, connects the outlet of the collector manifold to the top of the storage tank and another tube, called the cold leg, connects the bottom of the storage tank to the inlet manifold at the bottom of the collector. The thermosiphon contains a working fluid, typically water, although other fluids may be used if freezing is possible.

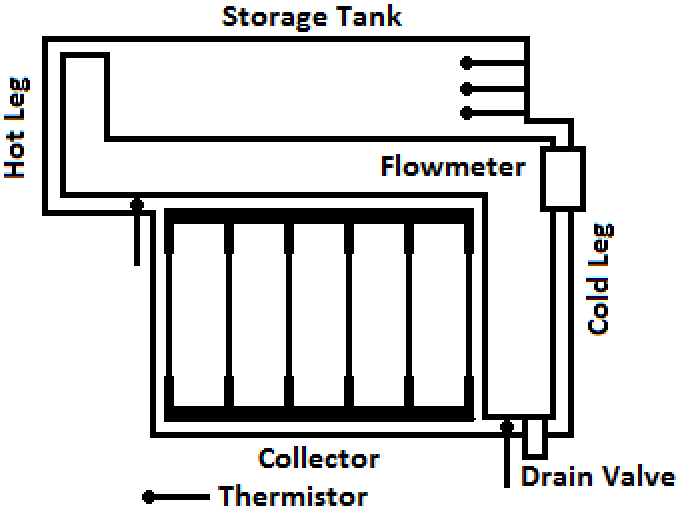

Figure 1. Basic components of a passive thermosiphon.

Instrumentation may also be included to study the performance of the thermosiphon. In the current project, thermistors are inserted into the working fluid at the inlet and exit of the collector to measure collector efficiency. A vertical array of thermistors is inserted into the storage tank to measure the stratification of the working fluid. A flow meter is placed on the cold leg to provide the flow rate for the collector efficiency calculations. The flow meter is an open-bore type flow meter that employs the principle of heat loss from a heated temperature sensor by the fluid to measure the flow rate.

The thermosiphon works on the principle of buoyancy to create the flow. Fluid heated in the collector rises through the hot leg into the upper part of the storage tank while cold fluid is simultaneously drawn from the bottom of tank through the cold leg to replace the fluid in the collector. The density difference between the hot fluid in the hot leg and the colder denser fluid in the cold leg drives the flow. The temperature and velocity of the fluid are interdependent. The fluid velocity is determined largely by the height and temperature difference between the cold and hot regions of the working fluid. The fluid velocity is also determined to a lesser extent by the hydraulic resistance to flow.

Description of the Project Research

The purpose of the current undergraduate research is (1) to improve the collector efficiency through the manipulation of component parameters and (2) to optimize the application of the thermosiphon as a secondary heating source.

One area of research is to improve collector efficiency by reducing heat loss from the collector to increase the heat imparted to the working fluid. System parameters were varied to determine their effect on the collector's efficiency. These parameters included variations in hot leg height, collector angle, storage tank orientation (both vertical and horizontal), and system hydraulic resistance. Additionally, the impact of input power level and ambient temperature on collector efficiency was also studied.

Because of the variability in solar power levels and environmental temperature with outdoor testing, testing was conducted indoors in the facility shown in Figure 2. Electrical resistive tape was wrapped around the collector tubes to simulate solar heating and supplied controlled constant power input.

Figure 2(a) Storage tank for the indoor thermosiphon test facility.


Figure 2(b) Collector for the indoor thermosiphon test facility

A second area of research is to optimize the thermosiphon as a secondary heating source. This work is conducted in an outdoor facility as shown in Figure 3. Ideally, testing is conducted using solar power but resistive heating tapes may also be used to simulate the sun during extended times of cloudy conditions, such as during winter. One aspect of this applications research is focused on optimizing heat exchangers to remove the maximum possible energy from the fluid before it leaves the facility. Another aspect is to develop passive means of mixing the air within the facility. This is necessary since the heat exchanger must be above the collector, which promotes stratified temperatures within the facility or any room, in general.


Figure 3 Solar collector with glazing connected to a heat exchanger contained in the outdoor facility

Description of Thermosiphon Teams

The thermosiphon research project is in its seventh continuous year using vertically integrated teams. Details of the 50 members that have participated in the research project are given in Table 1. The table provides information on the students' gender, race according to the US Census Bureau's classifications (black, white, or Asian), grade level (freshmen through senior), the degree that the student ultimately obtained from the university (ME-mechanical engineering, CE-civil engineering, BUS-business) or if they transferred (T), and mechanical engineering students that eventually enrolled in graduate school. Students who have not yet graduated have "not applicable" (N/A) shown in the "Degree Completed" column. Students who have not yet graduated or who transferred from the university have "not applicable" listed under the "Graduate School" column.

Table 1 Team member description

Student	Gender	Race	Grade Level				Degree Completed	Graduate School
			F	So	J	S		
1	M	B				X	ME	Y
2	M	W			X	X	ME	Y
3	M	B			X	X	ME	Y
4	M	B			X	X	ME	N
5	M	W			X		ME	N
6	M	W		X		X	ME	Y
7	M	A		X			CE	N
8	M	W		X	X	X	ME	Y
9	M	W		X	X		ME	N
10	M	W			X		ME	N
11	M	W			X	X	ME	N
12	M	W				X	ME	N
13	M	W			X	X	ME	N
14	M	W			X		ME	N
15	F	W			X	X	ME	N
16	F	W			X		ME	N
17	M	W			X	X	ME	N
18	F	W			X	X	ME	N
19	M	W		X	X		ME	N
20	M	W		X	X	X	ME	Y
21	M	W	X				ME	N
22	M	W	X	X	X	X	ME	Y
23	M	W	X				T	N/A

24	F	W				X	ME	N
25	M	B				X	ME	Y
26	M	W			X	X	ME	N
27	M	W			X		ME	N
28	M	W			X	X	ME	Y
29	M	B		X			N/A	N/A
30	M	B	X	X	X	X	ME	N
31	M	W	X	X	X	X	ME	N
32	M	W	X	X	X		ME	N/A
33	M	W				X	ME	N
34	M	W			X	X	ME	N
35	F	W			X	X	ME	N
36	F	W	X				BUS	N/A
37	M	W	X				BUS	N/A
38	F	B	X	X			N/A	N/A
39	M	B	X				N/A	N/A
40	M	W	X	X	X		N/A	N/A
41	M	W	X				N/A	N/A
42	M	W				X	ME	N
43	M	W			X	X	N/A	N/A
44	M	W			X		N/A	N/A
45	M	W	X	X			N/A	N/A
46	M	W				X	N/A	N/A
47	M	W				X	N/A	N/A
48	M	A			X		N/A	N/A
49	M	A			X		N/A	N/A
50	F	W	X				N/A	N/A

Table 1 provides a description of the students who have participated in the research and can be used to describe the teams. On average, team members spend 1.7 years on the team, 16% are female and 84% male, with 78% of the members white, 16% black, and 6% Asian. From a retention perspective, 89.2% of the students who participated in the research project (excluding those who have not yet graduated) graduated with a mechanical engineering degree. It is expected that the percentage of students graduating with a mechanical engineering degree would be large since teams are composed of declared mechanical engineering majors registered in the program's required Integrated Design Sequence. Furthermore, 97.3% of the students who participated in the research project eventually graduated from the university. Finally, 27.3% of the students who received their undergraduate degree in mechanical engineering went on to graduate school in mechanical engineering.

Table 2 shows a breakdown of the team composition by grade level and academic year. The table also includes two columns showing the percentage of team members and seniors with prior thermosiphon research experience returning to the team for another year of research. Several observations can be made from the data. The size of the average team is 12 undergraduate students of which 16.7% are freshmen, 16.7% are sophomores, 34.1% juniors, and 32.5% are seniors, on average. One reason that the team composition is weighted more towards juniors and seniors is that the project is focused on data acquisition and analysis, skills that the upperclassmen have already obtained from the Integrated Design sequence. There is also anecdotal evidence that the upperclassmen have greater representation because they are more likely to consider the possibility of graduate school compared to the underclassmen.

Data from Table 2 shows that nearly half (46.6%) of the team on average returns to a new team each academic year. Furthermore, over 70% on average of the seniors bring one to three years of experience to each new team. This level of experience is critical to mentoring newer members on experimental procedures and the use of experimental equipment.

Table 2 Breakdown of team composition by grade level and academic year

Year	Team Composition by Grade Level					Percent Team Returning	Percent Seniors with Prior Experience
	F	So	J	S	Total		
2012-13	0	4	4	1	9	N/A	N/A
2013-14	0	0	4	3	7	71.4%	100.0%
2014-15	3	2	6	3	14	21.4%	66.7%
2015-16	3	4	5	7	19	42.1%	71.4%
2016-17	6	1	4	5	16	43.8%	80.0%
2017-18	1	2	3	5	11	63.6%	80.0%
2018-19	1	1	3	3	8	37.5%	33.3%
Average	2.0	2.0	4.1	3.9	12.0	46.6%	71.9%

Benefits of the Model’s Application to the Thermosiphon Research Project

One strength of using the Integrated Design Sequence model for undergraduate research is in the continuity of knowledge of the research project. One issue with conducting undergraduate research using a traditional capstone course composed of seniors alone is that much of the knowledge gained throughout the year is lost after graduation. Some of the knowledge can be transferred through the faculty adviser or final reports but many of the details related to experimental methods or operation of equipment is lost. Examples of this with the thermosiphon research project include returning team members mentoring new members on how to operate the thermosiphon system, how to run and modify the data acquisition system, how to calibrate new measurement equipment, and how to avoid common pitfalls.

Another strength of the model is that returning members are already familiar with the research project and can be productive at the beginning of the academic year. Undergraduate research conducted through the traditional capstone course requires time for the seniors to climb the steep learning curve that wastes valuable time that could be spent advancing the research. For example, at the facility location fall is a perfect time for testing as the skies are generally clear and sunny. Early teams were unable to get system components designed and fabricated in time to take advantage of this testing period and would typically be ready when the skies would often turn cloudy throughout most of the winter. This would offer only a short testing period in the late spring before reports were due. For the past several years, teams were able to set up equipment in the fall to take advantage of the sunny conditions and be more productive. Another example is that many of the internal university funding opportunity deadlines are early in the fall semester. Over the past few years, returning seniors have been able to write successful proposals to fund the acquisition of hardware, equipment, and instruments because they bring with them extensive knowledge of the project at the beginning of the semester.

Finally, another strength with the model is that the collective knowledge and experience from returning members allow the team to work on more complex aspects of the project in each subsequent year. For example, early in the project, students analyzed data using spreadsheets with a lot of manual manipulation of the data. As the project progressed, a MATLAB program was written to automate data analysis and uncertainty analysis. The following year, the MATLAB program was improved using a better numerical integration scheme to analyze the data. As the complexity level increased, students were able to compare results to the earlier methods to build confidence in the more complex methods. Another example is with the dissemination of the experimental findings. During the first two years, many of the results were preliminary as the teams were developing the facility. Results were either not presented or presented at a local conference held at the university. However, as their collective knowledge grew and the quality of their work matured, teams have now presented results at a regional conference (Butler Undergraduate Research Conference) and three times at the National Conference for Undergraduate Research (NCUR).

Conclusions

The Integrated Design Sequence is a required series of courses at each grade level that teach engineering design through traditional lectures, labs, and project-based learning. Vertically integrated teams composed of students at all grades levels work on senior-led projects. The first three courses of the sequence offer scaffolding for skill sets that freshmen through juniors can use on the integrated projects. The last two courses offer seniors the opportunity to learn and practice professional skills to lead teams, mentor protégés, and manage projects. The Integrated Design Sequence offers every student five opportunities to work on teams while learning and practicing techniques on both successful and low-performance teams alike. The sequence also offers five opportunities for students to practice and improve their communications skills through formal oral presentations to defend their work and written proposals and reports to document it.

The Integrated Design Sequence is an excellent model for conducting undergraduate research as it offers many benefits over the traditional two-semester senior capstone course. Because the model offers students the opportunity to work on the same project for up to four years, one benefit is that returning members can mentor new members and maintain continuity in knowledge of the research project. Another benefit is that returning team members can be productive at the beginning of a new school year and not waste time on a steep learning curve that a new and inexperienced team must overcome. Finally, the model allows teams to work on more complex aspects each new year of the research using the collective knowledge obtained from previous teams.

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