Project-based Learning within a Large-scale Interdisciplinary Research Effort

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ABSTRACT

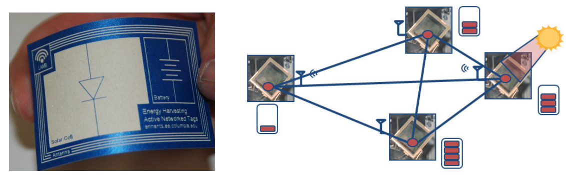
The modern computing landscape increasingly requires a range of skills to successfully integrate complex systems. Project-based learning is used to help students build professional skills. However, it is typically applied to small teams and small efforts. In this paper, we describe our experience in engaging a large number of students in research projects within a multi-year interdisciplinary research effort. The projects expose the students to various disciplines in Electrical Engineering (circuit design, wireless communications, hardware prototyping), Computer Science (embedded systems, algorithm design, networking) and Applied Physics (thin-film battery design, solar cell fabrication). While a student project is usually focused on one discipline area, it requires interaction with at least two other areas. Over 4 years, 115 semester-long projects have been completed. The students were a diverse group of high school, undergraduate, and M.S. Computer Science, Computer Engineering, and Electrical Engineering students. Some of the approaches we have taken to facilitate student learning are real-world system development constraints, regular cross-group meetings, and extensive involvement of Ph.D. students in student mentorship and knowledge transfer. To assess our approaches, we conducted a survey among the participating students. The results demonstrate the effectiveness of our methods. For example, 70% of the students surveyed indicated that working on their research project improved their ability to function on multidisciplinary teams more than coursework, internships, or any other activity.

Categories and Subject Descriptors: K.3.2 [Computers and Education]: Computer and Information Science Education – *Computer Science Education*; C.2.1 [Computer Communication Networks]: Network Architecture and Design — *Wireless Communication*.
General Terms: Design, Experimentation, Management.
Keywords: Project-based learning, interdisciplinary learning, wireless networking, embedded systems, Internet of Things.

1. INTRODUCTION

The modern computing landscape requires system engineering skills and interdisciplinary knowledge that are best acquired through participation in large-scale projects. While the need to engage students in large-scale "system perspective" projects has been recognized [13, 16], such projects are rarely attempted in academic settings. Project-based learning [8, 9] is actively used to help students build professional skills, such as teamwork and communication skills. However, project-based learning is typically only applied to small teams and small efforts.

ITiCSE'13, July 1–3, 2013, Canterbury, England, UK.



(a) (b)

Figure 1: The intended EnHANT form factor (a), and an envisioned energy harvesting-adaptive EnHANT network (b).

In this paper we describe our experience in engaging a large and diverse group of students in project-based learning within a large-scale interdisciplinary research effort. While many project-based learning approaches have been attempted and many frameworks have been proposed [2, 3, 12, 15], to the best of our knowledge, our experience with organizing multiple student projects to contribute to a large-scale effort is unique. This paper describes our approaches and describes some of the lessons we learned.

Our ongoing project-based learning activities are related to the *"Internet of Things"* – digital networking of everyday objects. Since 2009 a team of five faculty members from the Department of Computer Science and the Department of Electrical Engineering at Columbia University have participated in the *Energy Harvesting Active Networked Tags (EnHANTs)* project [1]. The goal of the project is to develop a new type of a networked wireless device. These small, flexible tags (the envisioned form factor for a future EnHANT is shown in Fig. 1(a)) will be attached to commonplace objects to allow them to communicate and network. EnHANTs will enable futuristic applications envisioned for the Internet of Things, such as finding lost objects (i.e., lost keys, sunglasses, or toys will be accessible via wireless links) and detecting object configurations.

Recent advances in ultra-low-power wireless communications, energy harvesting (deriving energy from ambient sources such as light and motion), and energy harvesting adaptive networking will enable the realization of EnHANTs in the near future [5]. Designing adaptive networks of EnHANTs, shown schematically in Fig. 1(b), requires reconsideration of protocols on all levels of the networking stack. Additionally, designing the EnHANTs to achieve the desired form factor requires tight integration of the networking and communications protocols with the enabling hardware technologies, which necessitates close and continuous interactions of students and faculty members with expertise in the associated technology areas. Working on the EnHANTs project exposes the students to various disciplines in Electrical Engineering (circuit design, wireless communications), Computer Science (embedded systems, algorithm design, networking), and Applied Physics (battery and solar cell design).

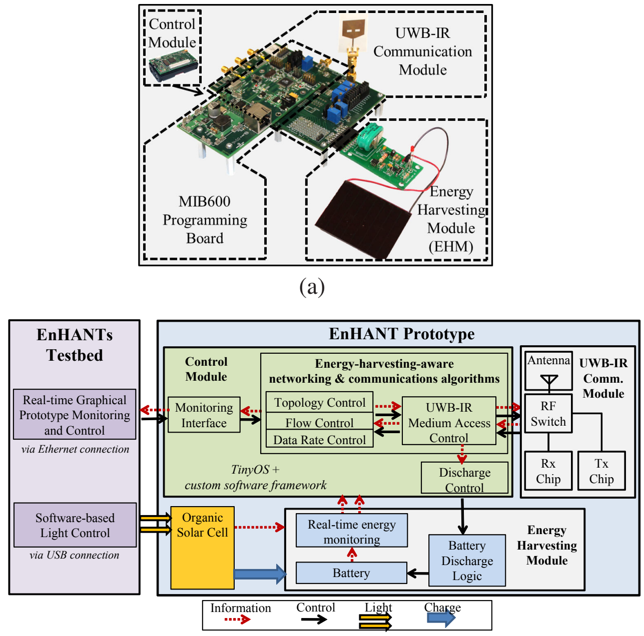
Throughout 11 semesters, we have involved a diverse population of 52 high school, undergraduate, Masters, and Ph.D. students in 115 semester-long research projects related to the design and development of the EnHANT prototypes and the prototype testbed. The student projects are multidisciplinary. A project typically focuses on one disciplinary area, but requires interaction with at least two other areas. The projects necessitate collaboration, provide students with in-depth fundamental understanding of networking concepts, and require students to improve their communication skills. We use "real-world" system integration deadlines and frequent system demonstrations to motivate students and to encourage cross-disciplinary collaboration. Students demonstrated prototypes and the testbed in several conference demonstration sessions (e.g., [14, 17]), and in over three dozen additional live on-site and off-site demonstrations. To evaluate our project-based learning activities, we conducted a survey among the students. Of the students who completed the survey, over 90% indicated that the project was rewarding and enriching, and 70% indicated that working on this project improved their ability to function on multidisciplinary teams *more than any other activity in their academic career*.

This paper is organized as follows. Section 2 describes the EnHANTs project. Section 3 describes the student projects, and Section 4 describes our approaches to organizing them. Section 5 describes some of the lessons we learned. Section 6 presents the evaluation results. Section 7 briefly summarizes the related work. Section 8 concludes the paper.

2. UMBRELLA PROJECT

The *Energy Harvesting Active Networked Tags (EnHANTs)* project [1] is a large, multi-year, interdisciplinary research project related to the *Internet Of Things*. The main focus of the EnHANTs project is the development of the **EnHANTs prototypes**. The current prototype, designed and developed over the last 4 years, is much larger than the tag shown in Fig. 1, but it already integrates the technologies that will enable its envisioned small and flexible form factor. The current prototype is shown in Fig. 2. The prototypes communicate with each other via custom-developed transceivers and harvest indoor light energy using custom-designed organic solar cells. The prototypes implement custom energy harvesting-adaptive algorithms on several layers of the Open Systems Interconnection stack. We also developed an **EnHANTs prototype testbed** to evaluate communications and networking algorithms and to demonstrate future Internet of Things applications. The testbed, shown in Fig. 4, monitors the prototypes' communications and networking parameters and controls the amount of light supplied to the prototypes' solar cells. Detailed technical descriptions of the prototypes and the testbed are provided in [6].

We developed the prototypes and the testbed in a set of phases over 4 years, shown schematically in Fig. 3. The photos of the testbed in the different phases are shown in Fig. 4. *All hardware, software, and algorithm modifications to the prototype and testbed functionality that are shown in Fig. 3 were designed, developed, integrated, and tested as part of student projects*. Below, we present a brief summary of the prototype functionality development.



(b)

Figure 2: The EnHANT prototype: photo (a), and block diagram (b).

- **Energy harvesting** allows EnHANTs to *self-power* by obtaining energy from ambient sources (light, motion). As part of the umbrella project we have fabricated flexible **solar cells** that efficiently harvest indoor light, and integrated them with the prototypes. Initially, we designed the prototypes to sense, but not harvest, available environmental energy (Phase I). Next, we integrated commercial solar cells and implemented real-time energy harvesting state monitoring (Phases II and III). Finally, we integrated the custom-designed solar cells.
- **Ultra-Wideband Impulse-Radio (UWB-IR) wireless communications** spend significantly less energy than other low-power wireless technologies [4]. Early-phase prototypes communicated with each other via standard (non-UWB) commercial sensor network mote transceivers. Prior to integration of the custom UWB-IR communication modules in Phase III, we substantially modified the mote operating system (which did not support custom transceivers). The integration additionally required the implementation of a custom medium access control module, since the UWB-IR transceiver characteristics differ greatly from the properties of the conventional transceivers.
- **Energy harvesting-adaptive algorithms** were first designed and developed for simple single node scenarios, and were later implemented for network scenarios. Following the integration of the UWB-IR transceivers in Phase III, we re-implemented the algorithms to take the UWB-IR characteristics into account.
- **Testbed functionality** first consisted of a data logger with a simple visualization interface, which we replaced with a custom-designed real-time monitoring and control system. We additionally developed several prototype light energy control systems, from relatively simple manual setups (Phases III and IV) to a software-based system that exposes the prototypes to real-world trace-based light energy conditions (Phase V).

At the end of each phase, a fully functional prototype testbed was demonstrated by students at a conference (e.g., [14, 17]). The

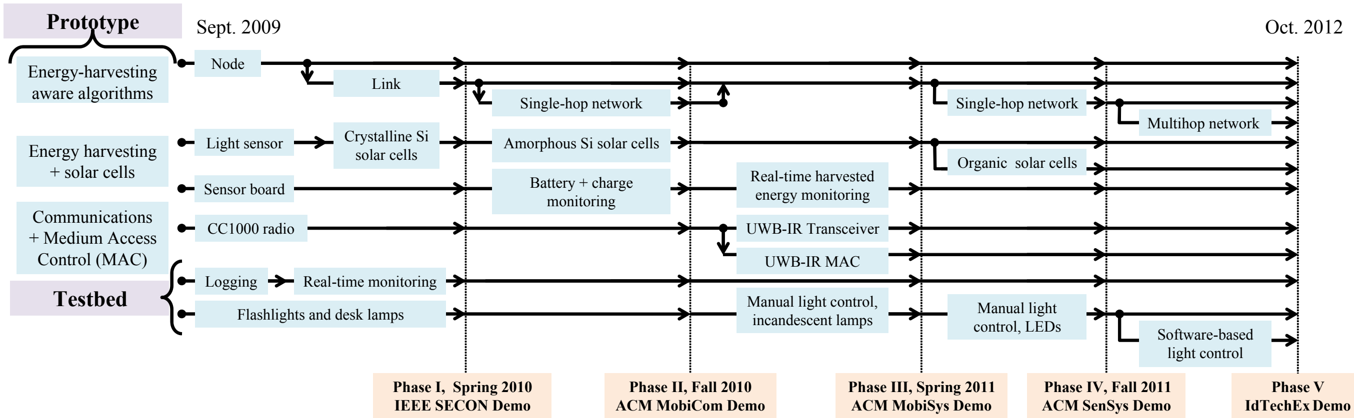
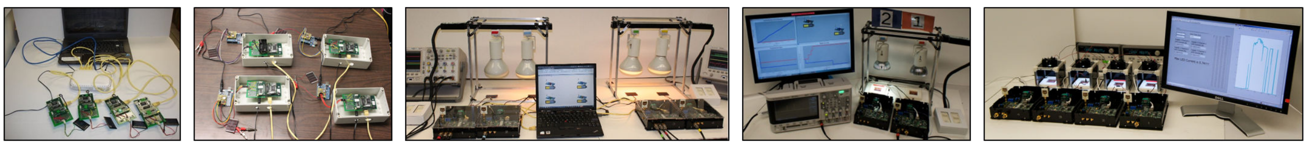


Figure 3: Phase-based EnHANT prototype and testbed development.



(a) Phase I. (b) Phase II. (c) Phase III. (d) Phase IV. (e) Phase V.

Figure 4: EnHANTs prototypes and testbed, Phases I-V.

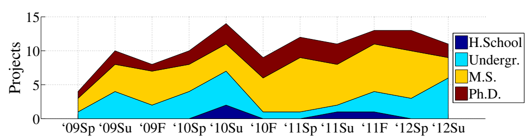
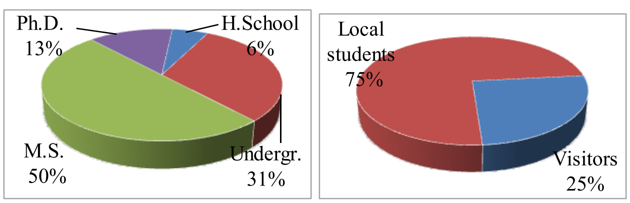
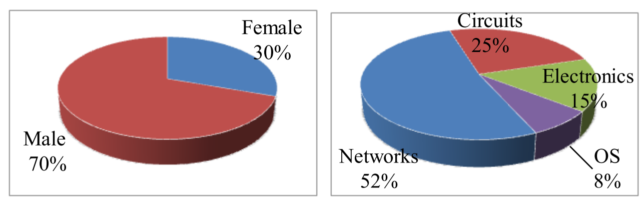


Figure 5: Student projects.



(a) Academic level. (b) Academic affiliation.

Figure 6: Students involved in the EnHANTs project.



(a) Gender. (b) Main focus area.

Figure 7: Student semesters.

Phase IV demonstration [14], co-authored by 10 students, received the conference *Best Student Demonstration Award*.

3. STUDENT PROJECTS

Under the EnHANTs umbrella project, 52 students completed 115 semester-long projects over 11 semesters. The number of student projects completed each semester is shown in Fig. 5, and student demographics are presented in Figures 6 and 7. Out of 52 students, 6% were high school students we engaged via a program that pairs university researchers with students from under-served communities. 31% were undergraduates, 50% were M.S. students (nearly all of which were in non-thesis terminal M.S. programs), and 13% were Ph.D. students. 75% of students were enrolled in academic programs in Columbia University, while the other 25% were visiting students, such as Research Experience for Undergraduate (REU) students, students from local colleges without advanced research facilities, or visiting international students. Out of 115 student projects, 51% were full-time projects (summer research internships, REU projects, M.S. thesis research semesters). The other 49% were semester-long research project courses to which students typically dedicated 8-15 hours per week. 70% of the projects were completed by male students and 30% by female students. The main focus areas for the student projects were networking (52%), circuits and systems (25%), electronics and applied physics (15%), and operating systems (8%).

The student projects within the EnHANTs project are **collaborative and multidisciplinary**. A project typically focuses on one disciplinary area (e.g., algorithm design, operating systems development, solar cell design), but requires interaction with at least two other areas. These projects challenge students by requiring them to gain understanding of concepts outside of their comfort zone. Additionally, the projects require students to independently and proactively seek out relevant expertise throughout the research groups involved in the EnHANTs project. This improves students' communication and teamwork skills. Finally, the projects expose the students to all aspects of networking, from the physical-layer pulses generated by the UWB-IR transceivers to the adaptive flow control and routing protocols. Students thus gain an **in-depth fundamental understanding of networking concepts**. Several representative student projects are described below:

- *Real-time Monitoring and Control System* (Phase I project, completed by an undergraduate Computer Science student): The student developed a Java-based system to monitor and control the EnHANTs prototypes. The project involved designing the necessary data structures to enable communication between the prototypes and the computer running the monitoring system. The student designed the system to support both a text-based interface and a "visual demo" interface that shows the activity of the prototypes in an easy-to-understand way. This project, implemented using TinyOS and Java, required knowledge of sensor networking, wireline communication, and software design. The student extensively interacted with students who were modifying the prototype operating system and developing energy harvesting-adaptive algorithms.

- *Prototype UWB-IR Communication Module* (Phase III project, completed by an M.S. Electrical Engineering student): The student developed and tested the UWB-IR communication module. The student integrated a custom-designed UWB-IR transmitter and receiver chipset onto a single printed circuit board and programmed a complex programmable logic device to perform data serialization and deserialization, preamble detection, and byte synchronization. The student also developed a UWB-IR radio driver using TinyOS. Primarily focused on circuit design, this project required the student to develop expertise in networking, operating systems, and software design.
- *Energy Harvesting-adaptive Network* (Phase V project, completed by an undergraduate Computer Engineering student): The student implemented network layer protocols that handled the EnHANT packet routing. The student first tested the network functionality using the commercial transceivers, and then extensively evaluated its performance with the custom UWB-IR transceivers. The student also implemented energy harvesting adaptive network layer algorithms, which changed packet routing paths based on the environmental energy availability. The student extensively tested these algorithms with the custom energy harvesting modules. While primarily focused on networking, the project required the student to gain an in-depth knowledge of energy harvesting and UWR-IR communications.

4. PROJECT ORGANIZATION

Organizing multiple student projects to contribute to a large-scale effort is challenging. We present some of our approaches to organizing projects, motivating students, and facilitating learning.

Real-world system integration deadlines: EnHANTs prototype and testbed design, development, and integration have proceeded in a series of phases (see Figures 3 and 4). At the end of each phase, the fully integrated prototype and testbed were presented at a major conference. We used the conference timelines as real-world deadlines for the integration of different student projects. The benefits of this approach are multi-fold. First of all, it *motivates students*. Providing short-term deadlines for student projects, rather than abstract long-term goals, energizes and motivates the students. Students are additionally motivated by seeing their work integrated with the work of others, used in a conference presentation, and subsequently extended. It also *encourages cross-disciplinary collaboration*, as under short-term system integration deadlines, the students work, individually and jointly, to quickly solve problems as they arise. Finally, it *reduces the impact of unsuccessful projects*. By constantly updating the software and the hardware components throughout the system integration deadlines, we restrict the negative impact of the projects that are technologically flawed.

Frequent cross-group meetings: We conduct regular (weekly or bi-weekly) meetings where students present their work to the faculty and students from the different research groups. This challenges students to present their work so that it can be understood by people with different backgrounds. Additionally, students reported that observing how faculty members solve problems during these meetings improved their own problem solving skills.

Ph.D. student mentorship: The faculty members involved in the EnHANTs project are heavily engaged in the student projects. However, faculty members delegate many of the day-to-day student supervision tasks to their Ph.D. students. The Ph.D. students provide technical support and guidance to the students, test and verify student projects before integration with EnHANTs prototypes and testbed, and ensure continuity among the different student projects. While somewhat time-consuming, these tasks provide the Ph.D. students with important opportunities to demonstrate and improve their mentorship, leadership, and project management skills.

Frequent system demonstrations: Functional "live" EnHANT prototypes and testbed are frequently demonstrated in different on-site and off-site presentations.[1] Frequent demonstrations, particularly those conducted off-site, encourage students to design and develop robust software, hardware, and algorithms and to extensively verify and test their work. This improves students' technical skills, and provides them with an understanding of the quality standards required from technology in "real-world" applications. Additionally, the testbed demonstrations give students opportunities to present their work to vastly different audiences.

5. LESSONS LEARNED

Throughout the 4-year course of the EnHANTs project we learned many important lessons. Our experiences highlight and reinforce the need to foster opportunities for **close and continuous cross-group interactions**.

The students work in different labs, focus on different disciplines, and have different technical skills, priorities, work styles, and expectations. Early on we discovered that *the gaps between the knowledge of the students with different expertise areas are much wider than anticipated*. For example, Electrical Engineering students are oftentimes unfamiliar with good software development practices, while many Computer Science students may not understand how to properly handle experimental electronics. Additionally, many students that are not majoring in Electrical Engineering do not understand the concepts of frequency-domain signal processing that are essential to the understanding of wireless networking. These knowledge gaps often lead to both technological and interpersonal issues. Cross-group problem solving requires students to trust each other's expertise, but these gaps in knowledge can make the trust difficult to establish. When working with students we highlight that such gaps are normal and should be treated as a learning opportunity. Ultimately these issues can only be addressed by *establishing, maintaining, and nurturing the connections between the groups and between the different students*. Specifically, we have learned the importance of the following:

- *Extensive use of collaborative tools*: As the project has progressed, we have expanded our use of collaborative tools. The EnHANTs project has an internal wiki and an external website that are kept up to date with shared technical information and documentation. We use less formal Google docs to keep the students "on the same page" with regards to project timelines and tasks.
- *Carefully defined interfaces between student projects*: Some of the most challenging problems arise when a student interfaces

[1] Inspired by agile software development practices, we ensure that a version of the prototypes and testbed is always ready to be demonstrated. We do not integrate new software or hardware without extensive testing and design for backward compatibility. This further reduces the impact of unsuccessful student projects.

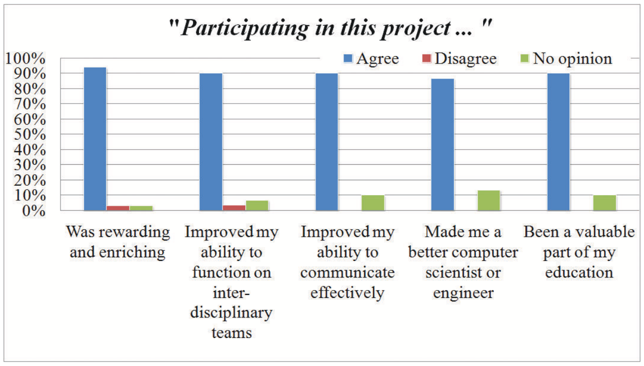


Figure 8: Project survey results.

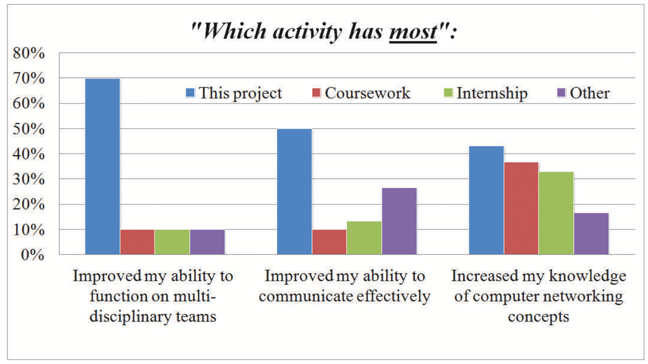


Figure 9: Project survey results: EnHANTs projects compared with other activities.

his or her project with another project. The difficulty of solving these interface problems can in certain cases lead to interpersonal tensions. Designing the interfaces between different technologies (e.g., solar cells and the energy harvesting module, UWB-IR communication module and the control module) has been a challenging task that often required faculty members' involvement.

- *Formalized knowledge transfer process*: A large-scale, long-term project necessitates knowledge transfer between the students. In our experience, while knowledge transfer needs to be carefully monitored and emphasized, most students embrace it when they see first-hand that the documentation they create is used by their peers. Similarly, most students embrace the opportunity to introduce peers to their work and to teach them.
- *Showcase of individual student contributions*: With many student projects integrated into the prototypes, the contributions of some students may not be as visible as the contributions of others. To address this, we conduct workshops where the students present their projects individually. We also separately showcase each student project on the EnHANTs project website.

6. EXPERIENCES AND FEEDBACK

After the completion of Phase V of the EnHANTs project in October 2012 we conducted a survey amongst all 45 high school, undergraduate, and M.S. students that had participated in the project. The survey contained multiple-choice questions and optional open-ended questions. The survey response rate was 75.5%. In the survey's open-ended questions, students shared many observations, comments, and suggestions about the EnHANTs project organization. Figures 8 and 9 show some of the results.

Overall, the students' experiences were overwhelmingly positive. Over 90% of the students believed their project experience to be rewarding and enriching. Over 85% of the students indicated that working on this project improved their ability to function on multidisciplinary teams and to communicate effectively, made them a better computer scientist or a better engineer, and was a valuable part of their education. 70% of the students indicated that working on the project improved their ability to function on multidisciplinary teams *more than any other activity*. Additionally, 50% of the students indicated that working on the project improved their ability to communicate effectively more than any other activity, and over 40% of the students indicated that this project increased their knowledge of computer networking more than any other activity.

The students' impressions of the project organization features provided additional insights into the features' effectiveness:

- **Multidisciplinary projects:** Most students enjoyed the multidisciplinary nature of their projects. When specifying what they liked most about the project, over 50% of the students commented on one of its multidisciplinary aspects. One student enjoyed her project being *"about both hardware and software"*, and said it was *"innovative and challenging to integrate many different aspects in one"*. One student's favorite thing about his project was the *"integration of my work with other parts of the system – felt like a cohesive project that mattered more"*.
- **Ph.D. student mentorship:** The majority of students appreciated the support provided by their Ph.D. student mentors. Over 80% of the students said that their mentor was approachable and accessible, and provided appropriate guidance.
- **Frequent cross-group meetings:** Most students appreciated the opportunities for problem-solving and work presentations provided by the regular cross-group meetings. One student noted that *"the meetings are an excellent way for putting everything in the big picture."* Yet several students also commented that the meetings were unnecessarily long, and suggested that a better meeting structure should be considered for the future projects. To improve the quality of the meeting presentations we encourage students to discuss their presentation with their Ph.D. mentors. We are also considering joint presentations for students from the same research group.
- **Frequent system demonstrations:** *Over 95% of the students* indicated that presenting their work was a rewarding and enriching experience. Several students specifically mentioned the presentation skills amongst the skills they acquired or improved while working on the EnHANTs project. One student noted that *"the opportunity to present to others was invaluable. Plus it was a lot of fun!"*

The majority of the negative feedback focused on insufficient knowledge transfer and the need for further facilitation of cross-group communications. Several students commented on the insufficient technical introduction to their project. One student stated that *"In the beginning I felt I didn't have enough support to ask very basic things"*, and another student noted that *"a lot of work goes to waste if you are unable to successfully pass it on to the next person"*. Students noted that *"getting everyone on same page was difficult at times"*, and said that *"not being able to know exactly what others are doing"* was an impediment to achieving some of their project goals. Based on this feedback, we have increased our efforts to ensure that students create high-quality, up-to-date documentation. We have been additionally encouraging the students to independently collaborate with each other.

As of January 2013, 55% of the students have graduated (the other 45% are continuing their studies). Of the students who have already graduated, 30% continued to higher-level academic programs. Many students have been accepted to Ph.D. programs in leading universities such as University of Illinois at Urbana Champaign (UIUC), Princeton, Harvard, and Carnegie Mellon. The other 70% of the graduates joined different technology companies, including Microsoft, OPNET, and Oracle. Several students have indicated that working on the EnHANTs project prepared them for some of the challenges they face in their careers. For example, one student noted that the *"experience presenting my work has been really helpful in my current job profile"*, and another highlighted that *"being held accountable for deadlines and project completeness helped prepare me for work environment"*.

7. RELATED WORK

This paper describes a method for engaging students in project-based learning within a large-scale multidisciplinary research effort. Previous research has described structuring student research experiences as a course [7, 11], a research-based program aimed at undergraduates [10], and a framework for accommodating undergraduate students in a research group [2,15]. Researchers have also examined methods for providing students with interdisciplinary research opportunities [12] and for increasing student communication and collaborative skills [3]. To the best of our knowledge, our experience with providing many students interdisciplinary project-based research opportunities as part of a single large-scale ongoing research effort is unique.

The EnHANTs research effort is in the embedded systems domain. The applicability of project-based learning to embedded systems has been specifically noted. Additionally, the importance of learning embedded system design from a system perspective has previously been emphasized [16]. Project-based learning approaches for embedded system design have also been embraced in different courseworks [8, 9]. The necessity of engaging students in large system development projects has been recognized as an important educational objective, and some tools for emulating the scale of the development have been proposed [13].

8. CONCLUSIONS

While the modern computing landscape increasingly requires large-scale system engineering skills, such skills are rarely acquired in a typical computing program. To address this, over the last 4 years, we have been engaging a diverse group of students in research projects within a large-scale interdisciplinary *Energy Harvesting Active Networked Tags (EnHANTs)* project. To date, 115 semester-long projects have been completed within the EnHANTs project. The projects challenge students' knowledge and organizational and communication skills. Some of the approaches we have used to facilitate student learning are the real-world system development constraints, regular cross-group meetings, and extensive involvement of Ph.D. students in student mentorship and knowledge transfer. Students find the projects rewarding and gain valuable skills. Our experience demonstrates feasibility of engaging diverse groups of students on large-scale interdisciplinary research efforts. It sheds light on some potential pitfalls of such efforts (e.g., inadequate cross-group communication and knowledge transfer), and suggests best practices to overcome these challenges.

9. ACKNOWLEDGMENTS

We thank the students for their participation in the projects and in the evaluation survey. We thank R. Margolies for contributing to student project organization. This work was supported in part by Vodafone Americas Foundation Wireless Innovation Project, United Microelectronics, a grant from Texas Instruments, and NSF grants CCF-0964497, CNS-0916263, and CNS-10-54856.

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