Assessing the Effectiveness of Individual Learning in a Realistic Engineering Design Class

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Abstract

Real-world engineering design involves multiple collaborating teams, with each team responsible for one component; components are integrated to achieve the final system. While some researchers believe that project-based learning (PBL) results in different students learning different content, others showed that collaborative approaches reduce compartmentalization of knowledge. In addition, there is little research on student development of knowledge of integration of components. We hypothesize that PBL can result in effective learning about all topics the class covers, within a realistic engineering design environment where components are assigned to teams and ultimately integrated, and that students will be able to learn about integration. Quantitative and qualitative analysis showed a high level of learning in other groups' content, and significantly higher learning in own-group content. Students' reflections point to future directions: incorporating more instructor lectures (i.e., a hybrid PBL model), incorporating hands-on work on other groups' components, and improving presentations by groups.

Keywords

project-based learning, knowledge gain, graduate education

Introduction

Real-world engineering design work usually involves the collaboration of multiple teams, with each team responsible for one component, and with components being integrated to achieve the final designed system. Yet in a traditional university engineering design course, students do not get a chance to work on a project that involves integration of components created by various teams. An engineering class with a project-based learning (PBL) approach, in which multiple teams work on different components that must be integrated, would better prepare students for real-world engineering. However, a potential pitfall is that students might learn only, or mainly, about their own component. Some authors have posited that PBL involves "a shift from all students learning the same thing to different students learning different things[1]. In contrast, we hypothesize that PBL can and should result in effective learning about all topics the class is designed to cover, even if teams are each responsible for one component, with components ultimately integrated. This study provides empirical data to address the common concern about PBL that learners do not learn about topics or components other than their own.

The research questions guiding this study are: 1) How does the extent of learning vary by student between their component and other teams' components, in a realistic PBL engineering design course? and 2) How well do students learn about the integration between their component and other teams' components, in a realistic PBL engineering design course?

Theoretical Framework

Engineering Design. Most engineering programs have engineering design courses to promote teamwork and mimic professional engineering experience. Research on engineering design courses have not addressed our research question concerning levels of student knowledge.

Project-Based Learning. PBL is a pedagogical approach developed originally in the context of pre-university science classes in which “Students engage in real-world activities that are similar to the activities that adult professionals engage in.”[2] PBL is based on constructivism, and places students in the role of constructing their own understanding by engaging in relevant, important, realistic problems. Key features of PBL include a driving question to link important academic content to students’ lives, inquiry and problem solving, collaboration, use of learning technologies, and the creation of tangible products[2]. Research has demonstrated the effectiveness of PBL in secondary science classrooms[3]. PBL has been increasingly adopted in engineering education over the last two decades.

Project-Based Learning in University Engineering Courses. Most literature on PBL in engineering courses at the university level has focused on affective and cognitive outcomes, and broadly reports positive outcomes by implementation of PBL in engineering classes at the university level. There is in contrast very little research on work readiness. Jollands, Jolly, & Molyneaux[4] compared the work readiness of engineering graduates from two groups, one that participated in a traditional curriculum and one that participated in a project based curriculum. Graduates from the traditional curriculum wished they had taken more PBL courses. Both groups agreed that PBL courses assisted with work transition with regard to project management. The PBL group felt that communication was also supported by the PBL curriculum.

Methodology

Setting and Participants. This study is set in a graduate-level PBL engineering design course in the College of Engineering in a public research university in the southeastern USA. The class met once a week for 3 hours. The course was organized around the driving question, “How can we design an integrated robotics system that can autonomously navigate in an unstructured environment?”. See Figure 1. Following practices from professional engineering settings, each team teaches other teams about their work, and teams need to coordinate their work so that their components work together seamlessly to achieve the desired outcome - in this case, an integrated robotics system that can autonomously navigate in an unstructured environment. Two teams worked on monocular machine vision, one team on stereo machine vision, two on context awareness (working on two sub-components), one team on motion planning and control, and one on hardware. The seven teams also came together to integrate the systems into a working vehicle. Each team collaborated in person inside and outside the classroom, and made use of various virtual collaboration tools. In order to share expertise and facilitate the coordination and integration of the systems, each team presented briefly during each class meeting and the other teams and instructors provided feedback. All 26 students in the class agreed to participate in the research study. There were 22 masters and 4 Ph.D. students, from the following majors: Electrical Engineering, Mechanical Engineering, and Civil Engineering. The course was designed and taught by a team of three engineering professors. This paper reports on the first time the course was offered.

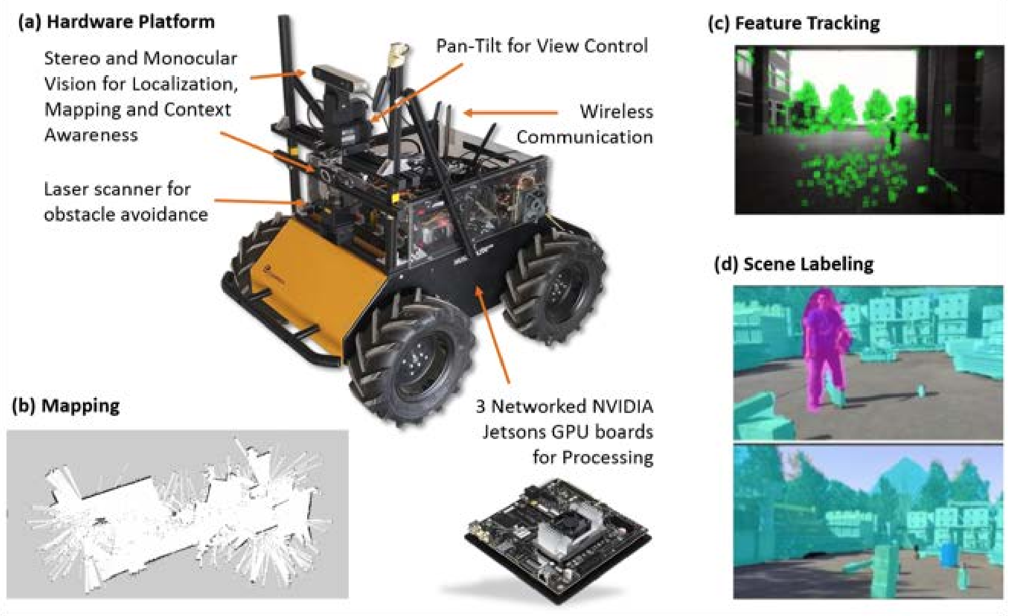

Figure 1. Autonomous robotic platform: (a) the main hardware components involved in the design; (b) an example of a map constructed using the platform; (c) illustration of features detected in an image during mapping; and (d) samples of scene labels detected from the visual data with different colors indicating different object classes.

Data Sources. The course professors developed a test to measure knowledge of the desired outcomes for each component, as well as the integrated robotic system. This test functioned as the final exam for the course. A science education professor assisted in test development, using Bloom's revised taxonomy[5] to ensure that a variety of relevant knowledge dimensions (factual, procedural, conceptual) and cognitive processes (remember, understand, apply, analyze, evaluate, and create) were covered. The final instrument consisted of 20 open-response items, with a total possible score of 200. The test had the following five sections to assess students' understanding of the overall integration and each robotics component: System Overview, Machine Vision, Context Awareness, Planning and Control, and Hardware. By including sections corresponding to each team's specializations, the test allows for formal assessment of student performance on the topics learnt by interacting with other teams, student performance on their own topic, and the system integration. The instructors of the course scored the tests. While the test did not undergo psychometric validation or pilot testing, it is an authentic and ecologically valid assessment of student knowledge deemed important by the instructors of the class.

A second part of the evaluation examined student views on the format of their class. Each of two prompts was used for both a Likert question and an open-response question. The prompts were: 1) In this course, you have specialized in one topic and learnt many other topics (that other teams have worked on) indirectly. How effective this course structure was in teaching those OTHER topics? (Likert scale) And why? (Open-response) and 2) In this course, you had a unique opportunity to work on components that were integrated as a larger system. How valuable was this experience to your engineering training? And why? For the Likert questions, students could circle a value from 1-5: 1) extremely valuable, 2) very valuable, 3) moderately valuable, 4) slightly valuable, 5) not at all valuable.

Data Analysis. Preliminary analysis established that the variable for the difference in performance between own group knowledge and other group knowledge was not normally distributed (Shapiro Wilk, n = 26, W = 0.88, p = .005). Therefore, we used a Wilcoxon signed ranks test to assess the statistical significance of the difference own-team and other-team knowledge. Descriptive statistics were used for the Likert scale questions. A grounded theory analysis[6] was employed on the open-response questions to determine how students may have experienced or learned differently on their own component as compared to other groups' components, and how well they felt they learned about the integration of components. In this qualitative analysis, themes were allowed to emerge from the data, as there is little prior research that could allow us to approach analysis with a pre-existing coding scheme. For the open-response questions, our study adhered to the constant comparative method[6]. The data from the evaluations were analyzed in stages - see Figure 2. First, we engaged in open coding. Two doctoral students in science education individually read and examined all evaluations, and broke sections down into discrete parts. They examined terms and phrases that students used when answering the questions. In open coding, "data are broken down into discrete parts, closely examined, and compared for similarities and differences" (p. 102)[6], with similar parts being combined into an emergent theme. This process was followed separately for each of the two questions. After each doctoral student examined and coded all 26 evaluations, they compared their themes and agreed on twelve categories for question 1 and six categories for question 2. In another round of coding, we combined categories into classes of closely related categories using axial coding. Inter-rater agreement reached 100% after two rounds of coding and discussion.

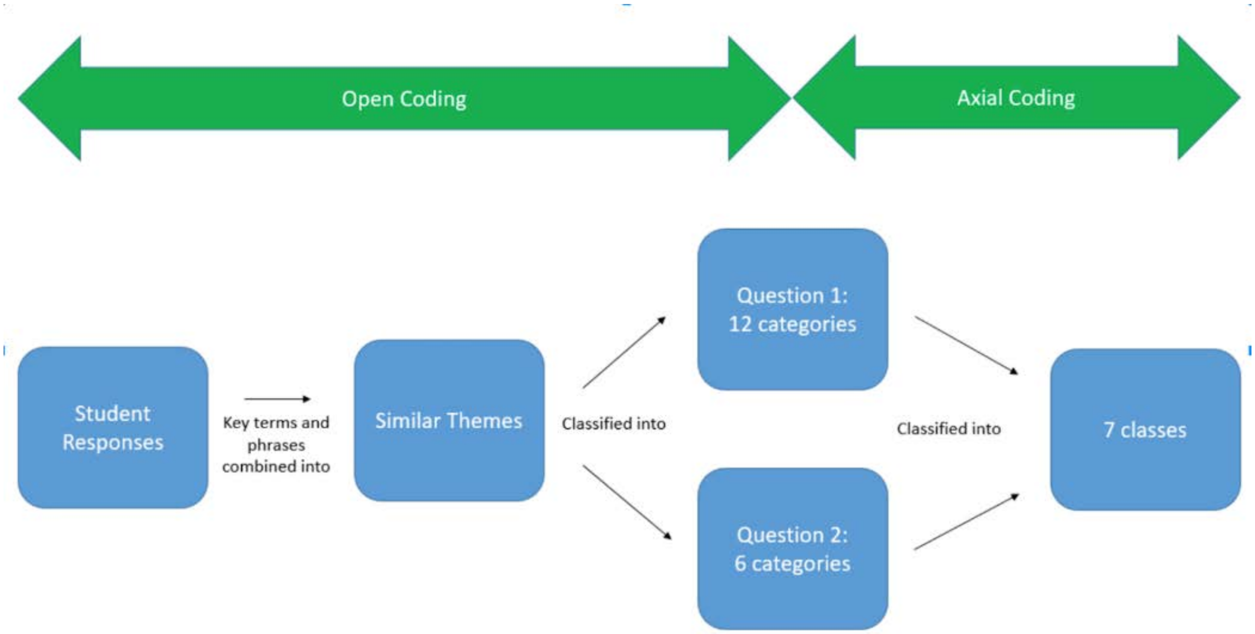

Figure 2. Methods using open coding and axial coding

Results

The Wilcoxon test showed that students performed significantly better on their own group's section than on other groups' section, n = 26, W = 250.5, p < .0001. The students' average on own group's section was 98.8%, and for other group's section was 93.8%. The effect size for the difference was very large, 2.6, calculated using the pooled standard deviation (the square root of the average of the squares of the own and other group standard deviations). For the Likert questions, 85% of students felt that the course was moderately to extremely effective in teaching the content related to other teams' topics, and 100% of students felt that the course was moderately to extremely effective in helping them learn about integration, and that the experience was valuable to their engineering training.

Open-Response Questions

Table 1 shows the categories generated from the themes that emerged, and the classes of closely related categories. Next, we illustrate our findings, organized by class.

Class 1: Teamwork was valuable, but also had limitations. Importance of teamwork and learning teamwork skills. Many students thought that teamwork was an important asset to the course that was rewarding and allowed them to learn about other groups' work. Student #4 stated that the course was "effective because student [sic] who specialized in other topics were able to give first hand information on the challenges they face while implementing their respective modules." Student #22 said, "Assisting the other teams with code analysis, method overviews, and constant integration over the semester was a rewarding experience".

Hard to focus on other topics. Some students felt that it was difficult to focus on the other teams' topics. Student #9 said, "The structure of the course required that everyone to have an understanding of the working being done by the other teams so as to facilitate smooth integration. While it was difficult to understand everything that the other teams are doing." Student #14 stated, "With the specialized topic at hand and uni[versity] workload, it's difficult to focus on OTHER topics". Student #18 said, "since each team was focused on refining their own topics and a lot of material was to be covered in each topic, the focus on other team's topics was inhibited and confined to areas of integration".

No opportunity for hands-on work in other groups. Students felt that there was no opportunity for hands-on work in other groups. Student #26 said that, "the knowledge of what happens in the implementation was only presented over four presentations."

Working in teams was valuable; learned a lot from peers. The class's focus on the larger system was seen as unique, and opened the opportunity for students to work in teams and learn from their peers. They learned both hard and soft skills. Student #7 said that the course was "very, very helpful in terms of developing team-work skills and communication skills. Helped me learn a lot about how to manage to think both within the boundaries of what was defined as my specialization -- but to also how think outside my own box and see the bigger picture, and integration with others." Student #8 said, "Integration with other teams is something which we don't experience in other courses".

Class 2: Real-world relevant, and practical experience. Class emulated the workforce environment. Students in the course felt that this course offered opportunities that they do not receive in other courses and that it simulated the workforce environment. Student #17 specifically stated that, "this class emulated very accurately the workforce environment". Student #25 said, "It was effective as we got to understand the practical difficulties failed by the project teams in their weekly presentations”. Hands-on experience helpful. Student also saw how powerful hands-on experience was to build their engineering skills. Student #1 said the course “taught important skills adhering to project management team-work, timelines, and their critical importance. It also taught the integration of various [engineering] hardware/software and the potential pitfalls and things to look out for during the building of any large-scale [engineering] project”.

Real-world, relevant, and practical. Many students expressed the benefits of the course simulating real-world experiences that were relevant and practical. Student #3 said, "From a practical point of view the course was extremely valuable. There are so many resources nowadays [sic] for one person to really understand which work best and how to use them is really difficult”. Student #15 said, "Moreover, along with the robotics aspect, even the communication, embedded systems and other aspects get introduced and this helps a lot in engineering experience terms”.

Class 3: High level of content understanding. Gaining high level of understanding of their own content. Students had the opportunity to learn in depth from their own module. Student #16 stated, “Directly working on components and concepts personally gives a much better understanding of knowledge of the topic.” Student #24 stated that, “I got a very high level information about them individually.” in speaking about their module.

Class 4: Big picture of system pipeline. Understanding the system pipeline. Students received weekly updates from each team. Learning beyond the scope of their own module allowed students to gain a better understanding of the system pipeline and how all of the components fit together. Student #10 said, “The weekly updates and discussions really helped in understanding the pipeline of the project- especially what other teams were working on and the issues they faced.” Student #24 said, “The good part is that I learnt how exactly they fit into each other and how they can be combined to make a project work”. Knowledge of how parts of pipeline were integrated was useful. Students appreciated the unique opportunity to learn how components were integrated into a working autonomous robot. Student #22 said, “The numbers of papers read, approaches tested, state-of-the-art methods integrated and understood for higher than a single course could have given.” Student 12 said, “Integration is needed to make the final demo. So communications among all the teams makes me learn a lot from other teams”. Experience working on larger systems helpful. Student expressed the value of working in a larger system and understanding the engineering system pipeline. Student #14 said, "the experience of working on larger systems which consist of parts that you understand and not fully understand". Student #20 said "understanding architecture of system helps mitigate integration issues, which we face”.

Class 5: Need other experts’ knowledge. Some of the presentations were not good. Students expressed that they were not able to gain a full understanding of what other teams were doing, in part because some of the presentations given were not good. Student #6 said, “Other teams many not provide a good brief introduction. Sometimes it is hard to understand their topic.” Needed lectures about all topics each week. Many students requested more instructor-led lectures to address their lack of understanding of what other teams were doing. Student #11 said, “I would have liked an in-depth understanding of other topics as well. I have very limited knowledge of other teams’ topics and it’s working”.

Class 6: Application of theories. Helpful to learn how theory applied to concepts and implementation. Students were given the opportunity to apply theory to implementation and students discovered the benefits of this approach. Student #4 said, “This experience is very valuable because it helped me learn [that] concepts in theory and concepts in implementation vary a lot”. Student #19 said, "Theory does not provide explanations for all errors, mistakes, or malfunctions that may occur during implementation. And this was a wonderful opportunity to learn and improve on that”. Student #25 stated, "It was valuable experience to understand the practical important implementation of theoretical concepts”.

Class 7: High-tech, expensive components. Opportunity to work with new high-tech expensive components. Students enjoyed and appreciated the opportunity to work with new and expensive components related to their field. Student #21 stated, "This was the most valuable component of this course. We were able to work with high-end components, and get hands-on experience on how to use them and program them”. Student #11 said that he or she "got to work with a lot of new and relatively expensive components related to my research field and I am extremely happy for this opportunity”.

Discussion

Students performed at a high level on all three sections of the knowledge test: 98.8% on own group’s section, 93.8% for other group’s section, and 99.7% on the integration section. Relative to RQ1, How does the extent of learning vary by student between their component and other teams’ components, in a realistic engineering design course? we can affirm that, while there was a statistically significant, very large effect size of 2.6 favoring own group section over other group’s section, the actual performance on other group’s section was high. While the difference was statistically significant, it could be argued that it was not educationally significant; the 93.8% average score on other teams’ components showed that students were able to learn effectively about all topics. In relation to RQ2, How well do students learn about the integration between their component and other teams’ components, in a realistic engineering design course?, the 99.7% average score indicates that they learned very effectively.

Students’ perception of their own learning, as expressed in the open-response questions, mirrored the results on the knowledge test. Students felt that they learned a lot about other groups’ components, as indicated by the categories “learned a lot from others”, “working in teams was valuable; learned a lot from peers” and “team presentations were helpful”. On the other hand, the students felt that they had learned more about their own group than other groups, as shown by the categories “gaining high level of understanding of their own content” and “had general but not extensive knowledge about other teams’ modules”.

Students also indicated some reasons for their relatively lower level of knowledge of other teams’ content, summarized in the categories “hard to focus on other topics”, “no opportunity for hands-on work in other groups”, and “some of the presentations were not useful”. These results align with a substantial body of research showing that active learning strategies are superior to lecture-based approaches[7]. Students identified potential solutions to the issues they raised regarding the less in-depth knowledge they gained about other groups’ components, as reflected in the category “needed lectures about all topics each week” and comments suggesting the incorporation of hands-on work on the other groups’ components, improved presentations, and perhaps more scaffolding of the design and development process to make it easier to focus on the other groups' topics. Students' perceived need for more lectures from instructors points to a hybrid PBL model, as other researchers have implemented or recommended[8,9].

In general, students found the course very useful. All students found the course moderately to extremely effective in helping them learn about integration; this was reflected in the very high average score on this component of the test (99.7%). All students also found the course moderately to extremely valuable to their engineering training. Student evaluations about the component of teaching the content related to other teams were also high, with 85% considering it moderately to extremely useful. The findings from the knowledge section and the course evaluation section are well aligned. This triangulation[6] attest to the robustness and trustworthiness of the study's findings.

Implications and Conclusion

A well-planned design course in which different teams each address different components can still result in having students learn a common body of content; PBL does not necessarily result in different students learning different content, as Holubova[1] proposed. A collaborative model of PBL that supports knowledge sharing led to high levels of knowledge of other teams' components, in line with previous findings[10]. A realistic design course can provide a window into, and preparation for, professional engineering practice, with students coming away with deep knowledge of process management and integration across components. Continued experimentation with variants of PBL - hybrid, incorporating instructor lectures, or pure, without lectures - is called for to continue to determine the most effective pedagogical approach for university engineering design courses.

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