Effect on Compliance with Required Learning Outcomes Through the Introduction of State-of-the-Art Technologies and Industry-Standard EDA Tools into the Digital Logic Design Laboratory Sequence

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Abstract **- As part of a concerted effort to bring greater relevancy to an existing first year digital circuit design lecture and lab course on a campus comprised primarily of Aerospace and Mechanical Engineering (AE/ME) undergraduates, student learning and material retention were studied when current state-of-the-art technologies used in industry replaced previous teaching strategies involving a "cookbook lab" approach and manual wiring. This is in response to low motivation and overall outlook on the digital circuits course from students in non-Electrical or Computer Engineering majors. Four digital circuit design laboratory sections were targeted as part of this project (two control sections), all with similar academic major breakdowns. A total of 171 students served as subjects for the study.**

Data show that students attained a greater understanding of digital logic design concepts and were more comfortable using industry-standard tools compared to students who learned via "cookbook labs". There was a significant increase in relevance of topics studied in digital circuits, subjectively perceived by the students, as a direct result of the redesign of the laboratory sequence, which may provide a positive impact on future capstone design courses for students in the AE/ME disciplines.

Index Terms - Industry-standard tools, electrical engineering for non-majors, first-year engineering, motivation.

INTRODUCTION

We designed a new digital circuit design laboratory sequence for first-year engineering students and non-majors and piloted it across two test sections at Embry-Riddle Aeronautical University—a small, teaching university in the Southwest, which primarily serves the aerospace and mechanical engineering (AE/ME) disciplines. The modified Digital Logic Design, CEC222, laboratory sequence was created to meet the needs of students majoring in AE/ME. The exit survey results from the students in the test sections of the course were compared with students in two control sections where the modified laboratory approach was not implemented. Both the test and control groups had approximately identical breakdowns by student academic major.

I. Background and Motivation

In the preceding semesters, the CEC222 laboratory focused primarily on electrical and computer engineering (EE/CE) concepts, had little integration with industry-standard tools and equipment, and consisted mainly of "cookbook labs", which required students to wire large circuits with discrete components using step-by-step instructions. An overwhelming number of students taking the traditional laboratory sequence could not connect the covered concepts to real-world applications, could not understand the relevance of digital circuits toward their curriculum, and had an overall negative outlook on the course (based on student ability to troubleshoot faulty circuits and course evaluations).

The modified laboratory sequence departed from traditional "cookbook" labs and required the use of Field-Programmable Gate Array (FPGA) development boards. Students were aggressively introduced to the VHSIC Hardware Description Language (VHDL) and industry-standard FPGA design, simulation, and synthesis tools, such as Xilinx Vivado. Using electronic design automation (EDA) tools and powerful FPGA hardware allowed the students to implement and test more advanced devices, which were relatable to their majors (*e.g.*, servo motors, accelerometers, analog-to-digital converters, encoders, potentiometers). Besides bringing relevance to the laboratory, this approach removed a level of abstraction associated with using discrete components and manual wiring.

II. Course Content

It is well-known that applying concepts to real-world scenarios increases student interest and motivation for learning [1], hence we evaluated whether such a change made to the laboratory sequence of the course yielded similar results, while still achieving the required learning outcomes. Since Embry-Riddle has two residential campuses, both campuses must agree on a "Master Course Outline" (MCO), which provides a blueprint of all concepts to be covered in a course and learning outcomes that students should achieve at the conclusion of the course. To maintain consistency of the material taught between sections, each instructor should cover at least 75% of the MCO topics and outcomes.

A concise version of the MCO for CEC222 [2] is given below. All of the learning objectives relate, with various degrees of intersection, to ABET Criterion 3 [3], student learning outcomes A-K (with particular emphasis on B-G and K, which get introduced in this course). At the conclusion of the laboratory sequence, students should be able to:

- Design, analyze, troubleshoot digital circuits (*B, C, E*).
- Perform behavioral and timing circuit simulations (*B, K*).
- Explain operation of prog. logic devices (PLD), (*G, K*).
- Interface digital circuitry with external devices (*B, C*).
- Develop combinational/sequential logic circuits, construct truth tables, minimize Boolean expressions (*B, C, E, K*).
- Use standard lab equipment (*e.g.*, oscilloscope), (*B, K*).
- Interpret manufacturer device data sheets (*G*).

The main question we wish to address is what effect does the introduction of industry-standard tools (ABET Criterion 3, outcome K) into the curriculum have on student perceptions of the course and material retention between students in traditional laboratory vs. the modified sequence. In addition, we wanted to examine and document an approach that would allow us to stay within the 75% MCO coverage requirement, while making the laboratory sequence meaningful to the students.

III. Overview of Similar Pedagogies

A similar project-based learning (PBL) method was implemented at the University of South Australia (UniSA), in which, similarly to Embry-Riddle, the courses taken during the first year are mostly identical for all engineering disciplines [4]. UniSA researchers proved the increase in student motivation within an EE first-year service course, when PBL was used. The authors in [5] implemented a *floating facilitator* model (similar to the one used in CEC222), where 3–5 students were grouped together, with the instructor acting as a facilitator for student understanding of the material. This allowed the students to curb their overconfidence in the material and prepare them for solving real problems based on the material presented in lecture.

Research also shows that computer-based tools allow for greater learning, as real-life scenarios can be examined that otherwise would not be possible in a traditional classroom or laboratory setting [6, 7] and allow the course enrollment to be scaled without significant impact to student learning [8]. In addition, the early introduction of computer-aided design (which includes EDA) tools stimulates the students to produce more involved projects, when they enter their capstone design courses [9].

IMPLEMENTATION OVERVIEW

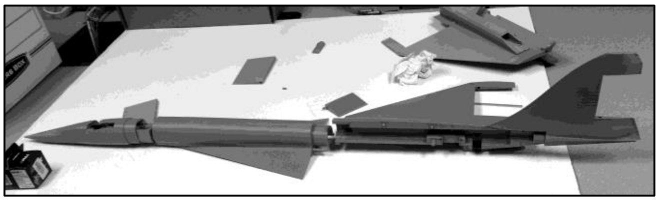
Scaffolding was used to create a series of labs with the goal of meeting the MCO student learning outcomes. The revamped laboratories covered most of the existing topics, but used FPGA development boards and an industry-standard EDA tool for synthesis and simulation from the beginning. Despite having no formal training in using hardware descriptor languages (HDL) or EDA tools, by the fourth week of the laboratory, the students could independently troubleshoot complex errors generated by the EDA tool with little help from either the instructor or teaching assistants. Prior research has shown that introducing concurrent processing and FPGA devices into the ME curriculum had positive impact on the perceptions of value of the learned material among students taking the course [10].

The sequence of laboratories, given in Table I, covered all basic facets of digital circuits and interfacing to external hardware with an AE/ME flavor, while giving the students valuable experience with industry-standard EDA tools, which can be used during their internships, job opportunities, or used in their capstone design [9] courses.

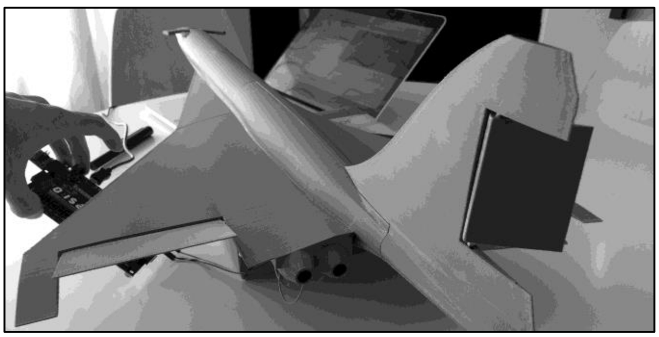
TABLE I
DIGITAL CIRCUITS CONCEPTS COVERED, BY LABORATORY ASSIGNMENT

No.	Description	Concepts covered
01	*Introduction*	Resistors, Breadboards and wiring, Power supplies, Voltmeter, Oscilloscope, Digital-to-analog conversion, FLASH-based FPGA programming.
02	*Logic Gates*	Boolean algebra, Discrete components, Logic gates, Signal generators, Reverse-engineering digital circuits.
03	*Combinational Logic Circuits using Intellectual Property (IP) blocks*	Basic combinational logic circuits, Truth tables, Behavioral simulations, Timing diagrams, Circuit minimization, Reading data sheets, Intellectual Property (IP) blocks, Creation/distribution of IP blocks, Interfacing to external components, FPGA pin assignments.
04	*Combinational Logic Circuits using VHDL*	Circuit minimization using Boolean algebra and Karnaugh maps, Concurrent statements in VHDL.
05	*Multiplexing 7-segment Displays*	Multiplexers, Demultiplexers, Sequential logic in VHDL, Timing simulations.
06	*Accelerometer Interfacing*	Accelerometers, SPI data transmission, Gyros vs. accelerometers, Number system conversions.
07	*Servo Motor Control using Pulse-Width Modulation (PWM)*	PWM, Analog servo motor operation and control, Duty cycle, VHDL arithmetic ops., Clock dividers in VHDL.
08	*Accelerometer-based Servo Motor Control*	Signed and unsigned number representations, Bus widths, IP block re-use.
09	*1:1 Accelerometer-based Servo Motor Control*	Calibration based on system response, Safety mechanisms, Hardware and software-based limit "switches".
10	*Switch De-bouncing*	De-bouncing of mechanical SPDT switches, VHDL-based de-bounce.
11	*Serial Communications Protocols*	Serial communications protocols, Moore and Mealy finite state machines, State machines in VHDL.
12	*Analog-to-Digital Conversion*	AD conversion, Noise and isolation, Crosstalk, Potentiometers, Input calibration, Voltage dividers.
13	*Joystick-based Control of Aircraft Surfaces*	AD converter channel sequencing, Data multiplexing, Design of control surface behavior, Safety mechanisms, Mechanical systems.
14	*Autonomous Aircraft Control System Design*	Feedback, Open/closed loop control systems, Safety systems, External forces on the airframe.

Overall, we structured this laboratory sequence using a bottom-up approach, starting from lower-level concepts, followed by more advanced applications and interfacing to external devices, and ending with implementing a control system responsible for controlling all aircraft control surfaces of a Tupolev TU-144 model aircraft (shown in Fig. 1), containing 4 movable surfaces (left and right elevon, rudder, and retractable forward canards). The two last laboratories within the sequence, given in Table I, would introduce the students to direct control via a joystick and fully/semi-autonomous control, based on accelerometer feedback.



(a) A disassembled view of the aircraft model, showing the internal structure and spaces for the servo motors. Canards have a gearbox that restricts the angle of rotation to 0–90º; elevons are connected to two servomotors through flexible couplings (to prevent damage to servo); rudder is connected to a servomotor within the fuselage by a pulley system.



(b) Demonstration of control surface deflection based on inputs.

FIGURE 1
MODEL OF THE TUPOLEV TU-144 AIRCRAFT USED FOR THE LAB SEQUENCE

In contrast to other pedagogical approaches that provide the student with step-by-step instructions for each laboratory experiment (becoming "cookbook labs"), the modified laboratory experience promotes hands-on learning and critical thinking skills by requiring the students to build up to the final control system step-by-step. In addition, the heavy AE/ME bias of the laboratory experiments provides students with proper multidisciplinary context and serves to increase retention of the material and interest in the subject matter (some control system designs for Lab 13, posted by students, can be seen via Twitter hash tags **`#CEC222`** **`#ERAU`**).

The final course design comprised 14 laboratories, each 2.5 hours long, during which the students were provided a direct lecture on some of the more difficult lab concepts and a hands-on exercise, where they used an industry-standard EDA tool. As the semester progressed, the technical content of the laboratories increased, with greater emphasis being placed on device interfacing and integration. After familiarizing themselves with the software, the students could explore concepts on their own, with little help from either the instructor or the teaching assistants. By experimenting and observing the outcomes of their modifications, the students attained a deeper level of learning than would otherwise be possible with a traditional laboratory.

Contrasting this with traditional labs, which required manual wiring (a sample of one such completed lab is given in Fig. 2), laboratories based on industry-standard EDA tools remove an unnecessary level of abstraction that comes with manual wiring. Some note that in a typical traditional laboratory, about two-thirds of the time is spent either wiring the circuit or troubleshooting wiring issues, which leaves no room for learning, experimentation, or independent experimental design.

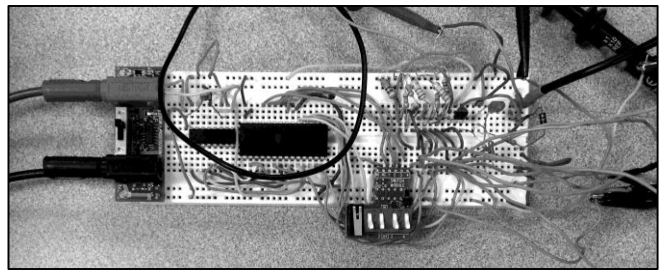


FIGURE 2
EXAMPLE OF A TRADITIONAL LABORATORY, WITH MANUAL WIRING.

Laboratories based on "virtual wiring" achieve the same learning outcomes and leave the students with ample amounts of time for independent experimentation. In debriefing interviews, students who have taken the traditional laboratory in the past reported not feeling as rushed to complete the experiments: more thought could be given to what they were doing, instead of rushing through all the required laboratory steps. Most EDA tools provide schematic capture tools (*e.g.*, the IP Integrator tool in Xilinx Vivado, a screenshot of which is provided in Fig. 3) and by the halfway semester mark, the students can diagram their circuits on paper and independently implement them in hierarchical VHDL files using **`COMPONENT`** definitions and **`PORT MAP`**s. This would enable students to have transferrable knowledge, which can be used with any industry-standard tool and won't lock them in to using specific tools, following the suggestions in [7].

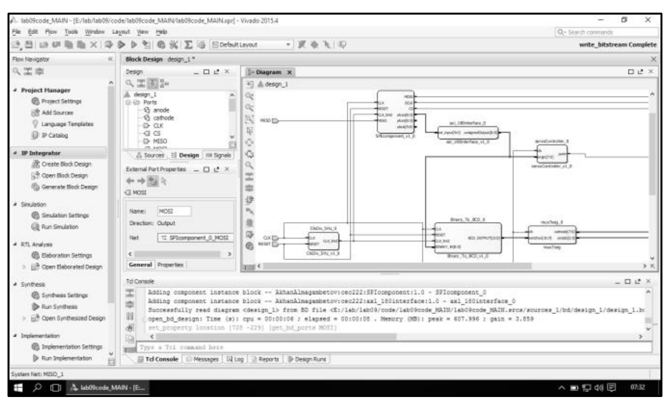


FIGURE 3
SCREENSHOT OF IP INTEGRATOR SCHEMATIC CAPTURE TOOL IN VIVADO.

The authors will note that the students' achieved level of familiarity with the EDA tools and concepts in the laboratory would not be possible without "front-loading" the pre-laboratory portion of the lab, where students read and follow a significant number of written tutorials and complete independent exercises on their own time (often involving independent learning by referring the manufacturer data sheets and reference manuals), prior to attending the laboratory section. This allows for the laboratory period to be used for experimentation and guided inquiry, instead of blindly following explicit instructions given in the lab manual. Based on observation of student performance, the students spent approximately 1/3 less time during the laboratory period, when compared with the control group.

The CEC220 Digital Circuit Design course and CEC222 laboratory placement within the curriculum structure at Embry-Riddle (*i.e.*, a required first-year offering to a multidisciplinary group of engineers) results in high student enrollment numbers, so larger laboratory sections can benefit from using industry-standard software, versus the traditional wiring approaches, as outlined in [8]. Scaling up the laboratory section sizes would not detract from the learning experience, as only the number of teaching assistants would need to be increased, instead of increasing the number of actual lab sections. It has been our experience that undergraduate teaching assistants can become adept at answering the majority of open-ended student questions that may arise during a typical laboratory exercise (either pertaining to higher-level abstract concepts or specific questions regarding the EDA software and errors).

RESULTS

The impact of the modified laboratory sequence was evaluated using a 15-question survey. To gauge the effectiveness of the lab, anonymous student responses were collected from both the control and test groups. This feedback is drawn from four sections of the course, with an average enrollment of 44 students per section. Two of the sections served as the test group and the other two sections served as the control group for this study.

Of the 171 students enrolled across the sections where data were collected (87 in the test group and 84 in the control group), 145 participated in this study (70 and 75 for the test and control groups, respectively), yielding an overall 84.8% return rate. Students were advised that the participation in the study was optional and that their non-participation would not negatively impact their laboratory grade or class standing.

As previously mentioned, the CEC222 laboratory at Embry-Riddle serves as a "service" course to the largest department on campus: Aerospace and Mechanical Engineering. The academic majors in the class were divided into: AE/ME, EE/CE/Software Engineering (SE), Unmanned Aerospace Systems (UAS), Global Security and Intelligence Studies (GSIS), and "Exploring engineering" (Undecided). The breakdown of the students, by academic major, is given in Table II.

TABLE II
BREAKDOWN OF ENROLLED STUDENTS, BY ACADEMIC MAJOR

Academic Major	Test Group	Control Group *
AE/ME	66 (75.9%)	58 (69.1%)
EE/CE/SE	17 (19.5%)	18 (21.4%)
UAS	3 (3.45%)	5 (5.95%)
GSIS	–0–	1 (1.19%)
Undecided	1 (1.15%)	2 (2.38%)

* The total does not add to 100% due to rounding error.

The exit survey questions focused on the following aspects of the course (mainly, the skills required by the MCO and the transferability of these skills to other courses in their academic major), which were evaluated by the students using a Likert-type scale with options ranging from strongly disagree (1) and strongly agree (5).

1. Level of motivation
2. Meaningful toward career goals
3. Relevance of digital circuits toward major
4. Advancement of critical thinking skills
5. Benefit in upper-level AE/ME or CE/EE courses
6. Transferability of material to real-life scenarios
7. Willingness to take similarly structured laboratory
8. Recommendation to your peers

Knowledgeable in:

9. industry standard EDA tools
10. implementing digital circuits using VHDL
11. designing digital electronic circuits
12. constructing digital electronic circuits
13. troubleshooting digital electronic circuits
14. interfacing digital circuits with external devices
15. using common test equipment

To calculate aggregate results for each of the questions on the exit survey, Likert-type responses were recoded as numerical values 1-5.

As seen from Fig. 4, which summarizes the survey responses from both the test and control groups, all dimensions were improved. The error bars represent $\pm 1\sigma$, with significant changes in darker red (test group) and blue (control group), while the less-significant in lighter red/blue, and least-significant results in dark gray (test group) or light gray (control group).

The largest improvements were observed for the relevance of digital circuits lab toward their major (question 3, 42.9% improvement over the control group), whether the students would be willing to take a similarly structured and designed laboratory sequence (Q7, 44.8% increase), and whether the students would recommend the CEC222 laboratory sequence to their peers (Q8, 51.0% increase).

As expected, a significant improvement was observed with the ability of the students to use industry-standard EDA tools (Q9, 33.8%) and the ability to implement complex digital circuits using VHDL (Q10, 29.4%).

Minor improvements were observed in a subjective measure of whether the CEC222 laboratory sequence would be meaningful toward the students' career goals (Q2, 27.2%), the level of motivation in the laboratory (Q1, 26.3%), the ability to apply the learned material to real-life scenarios (Q6, 23.1%), and the ability to interface digital circuits with external hardware, such as servo motors, indicators, sensors. (Q14, 19.7%). The other questions on the exit survey showed only a marginal improvement over the control group.

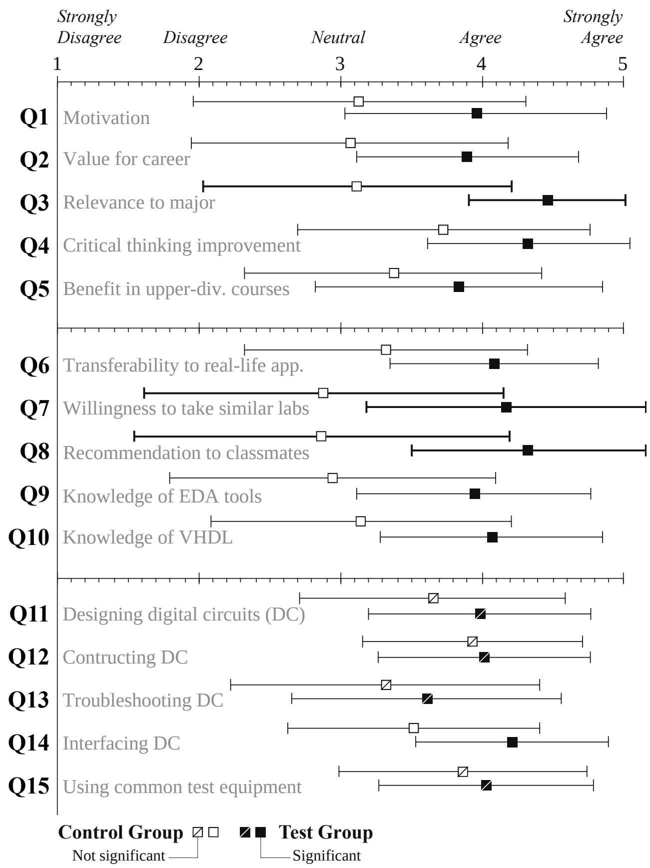


FIGURE 4
AGGREGATE COURSE EXIT SURVEY RESULTS FROM BOTH GROUPS

FUTURE WORK

In the Fall 2016 semester, we would like to address the issues highlighted by questions 11, 12, 13, and 15 of the student survey. All of these questions demonstrated only a marginal improvement in student perception. Our plan of addressing these deficiencies is as follows:

Q11: *"Would you consider yourself knowledgeable in designing digital circuits?"* The results of this question address the transferability of knowledge to other applications. The students are not as comfortable with independently designing arbitrary circuits outside of the laboratory setting. This may be addressed by providing the students with a more rigorous pre-laboratory exercise for each laboratory. The exercise will focus on designing multiple circuits, not just ones used in the laboratory. These circuit designs will cover a wider range of possibilities and will enable students to better understand how the various circuit design changes affect its function.

Q12: *"Would you consider yourself knowledgeable in constructing digital circuits?"* Part of the problem behind the marginal improvement on this question comes from our over-enthusiasm in and extensive use of EDA tools for constructing digital circuits in laboratory. To address this deficiency, we will place a stronger emphasis on physically constructing circuits, instead of directing the students toward performing most of the work with an EDA tool. For example, instead of relying on onboard hardware (*e.g.*, buttons, seven-segment displays, switches), these devices can be implemented on a breadboard using discrete components and connected to the many hardware interface ports available on the Basys3 board.

Question 13: *"Would you consider yourself knowledgeable in troubleshooting digital circuits?"* The results of this question are directly related to Q11. Since the students are not as confident in designing digital circuits with arbitrary functionality, they are also not comfortable with independently troubleshooting them. Besides changes addressed by Q11, we plan on having the students work through several faulty circuits on their own, to correct wiring or implementation errors. As this can be implemented within the EDA environment, we will assign as an independent exercise (*e.g.*, as a post-lab set of problems).

Q15: *"Would you consider yourself knowledgeable in using common laboratory test equipment?"* One challenge we faced during the spring 2016 semester was a large student enrollment in laboratory sections. The enrollment cap on each section was 44 students (or 22 lab station setups). None of the large general-purpose computer laboratories at ERAU have standard lab bench equipment, such as discrete oscilloscopes and digital signal analyzers. This equipment is present in smaller laboratories, which can accommodate up to 30 students. During the spring semester, the students used the portable Digilent Analog Discovery 2 units, which integrate oscilloscope, voltmeter, digital signal analyzer, and power supply functionality. In the fall, we will transition the students to laboratories with individual lab bench test equipment, which should mitigate this problem.

CONCLUSION

In this paper, we have discussed our experience of "overhauling" a first year digital circuit design laboratory on a campus that is comprised primarily of Aerospace and Mechanical Engineering (AE/ME) undergraduate students, where the lecture and lab for this course serve as a service course for several academic majors. The outcome of the modifications was that the students realized the value of the course toward their academic majors, with proposed teaching strategies replacing manual wiring and "cookbook-style" labs with ones that required the students to be independent thinkers and use industry-standard electronic design automation (EDA) tools for completing their designs.

Results show that this approach to digital circuits laboratory increases student interest, allows students to realize the relevance of the course toward their major and future career and attain a greater understanding of the presented concepts, when compared to the control group that used the traditional lab sequence.

It may be worthwhile to explore a digital circuits lecture and lab sequence that is specifically targeted toward AE/ME disciplines, especially at schools where the students from those academic majors comprise the larger part of the course enrollment. Certain material that is not relevant to AE/ME can be de-emphasized in such a lecture/lab sequence, making room for a more hands-on approach that would increase student interest, increase their marketability for defense and commercial aerospace companies, and improve the retention of digital circuits material for future capstone design courses, as shown in [9].

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APPENDIX

Fig. 5 includes a normalized breakdown of individual survey question responses; this may provide the readers with a more accurate representation of the survey data.

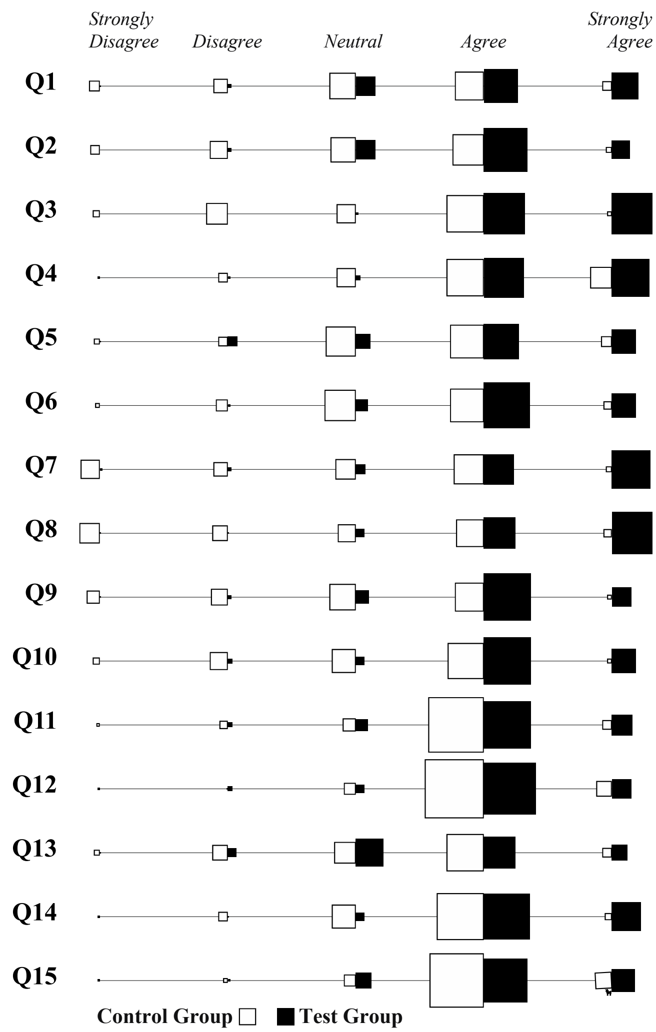

FIGURE 5
INDIVIDUAL SURVEY QUESTION BREAKDOWN FOR BOTH GROUPS