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Introduction to Embedded Systems Course: An Engineering Design Approach*

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This work is a case study of teaching Embedded Systems course using project based learning method. Instead of delivering lectures coupled with lab demonstration on commercial embedded systems platform, this study takes a blended approach. A group of two or three students are assigned a design project at the start of semester. Theoretical foundation is laid through short lectures and demos; in lab, sessions students perform various activities using a commercial microcontroller board and are introduced to PCB design workflows and while they continue to work on their design project; in the last leg of semester students continue to work on their project in self-directed learning as a team. Projects of applied nature are considered to keep the students motivated. Direct and indirect assessment methods demonstrate that the design project approach not only increases the interest of students but also provides them with necessary confidence and prudence to design and implement functional prototypes. The detailed implementation plan is included to assist others who are teaching this/similar courses.

Keywords: embedded systems; engineering design thinking; micro-controllers; project based learning

1. Introduction

Micro-controller based systems are used in a variety of electronic systems ranging from home appliances, medical equipment, automobiles and drones. In the context of Internet of Things (IOT) and other automation applications such devices have become even more important. The cost of such devices has come down considerably while their processing capability has increased significantly. In this scenario it's very important for engineering graduates to be familiar with the theory and application of micro-controllers (i.e., architecture, peripheries, interfacing techniques and programming), but should also be conversant with tools, techniques and work-flows to design and implement functional prototypes of embedded systems.

According to [1] final year project is not enough to develop competencies such as team work, project management and design skills necessary to work in industry. These authors also suggest that inclusion of design courses early in the program improves the quality of engineering design education. This idea has been gathering traction and gradually more and more design courses have been standardized into curriculum.

ESE-221 has been taught at sophomore level over the past 10 years. This course has evolved considerably over the past decade from purely theoretical module focusing on 8051 micro-controller architecture and assembly language for programming to Proteus and MPlink based simulation. The use of assembly language clearly demonstrates the interconnect and operation of the components of microcontroller. However, excessive focus on assembly programming limits the ability of students to develop projects incorporating complex algorithm and/or multiple peripherals. Recognizing the importance of Engineering Design Thinking skills, ESE-221 was offered as a hands-on course with special emphasis on Design Based Learning (DBL).

In [2], Bolanakis provides an extensive review of microcontroller education over the past 20 years. Through exhaustive review of literature, the authors suggest that *Project Based Learning* (PBL) has been by far the most preferred way of organizing embedded systems course at undergraduate level. In [3] authors demonstrate that application of embedded systems course helps to promote self-directed learning. In literature numerous case studies are available where embedded systems course is executed with PBL methodology, e.g., in [4] authors have proposed an educational model where content is presented through lecture, demo and hands-on practice. Authors in [5–7] have documented cases where teacher spends substantial time on slides and Commercial modules are used to introduce the basic I/O interfacing and programming techniques during lab sessions; the course culminates in a mini-project which builds upon key concepts and techniques learned throughout the module. Although mini projects have been widely adopted, however, in our opinion it does not provide enough rigor to acquire experience, skills and competencies required from a young embedded systems engineer.

The choice of Arduino framework for an intro-

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ductory course on micro-controllers has been debated in literature [8]. On one hand authors in [9] argue that Arduino platform is suitable for teaching embedded systems course to undergraduate engineering students. The author contend that broad community base and widely available support enable students to develop complex projects in short duration and add immensely to their creative abilities and confidence. However, in [10] authors argue that platforms such as Arduino do not provide sufficient exposure of key underlying concepts, virtues of C and assembly programming. Although concerns of [10] are valid, but we have considered this framework in this module because instead of going into the nitty-gritty of embedded programming, we wanted our students to have a comprehensive experience of embedded systems design process.

The course was organized with a student-centric approach. The students working as active participants on different projects learning to design micro-controller based circuits through review of data-sheets and literature available on internet; designing circuitry/systems where necessary from first principles. The instructor and lab. staff facilitated the students through this process.

The proposed module aims to impart embedded systems course through a blend of PBL and DBL approach. Both these approaches are similar, however there are subtle differences, as discussed in [11]. According to these authors PBL consists of three stages i.e., problem analysis, problem solving and project report, with focus of problem solving through analysis, whereas DBL induces skills such as design thinking, innovative competence, project management, product and process report. According to [12] DBL enhances student's ability to review literature and apply knowledge to solve engineering design problems.

In [13], the authors have highlighted the importance of Design Thinking in Engineering, the authors discuss how slowly and gradually this component has been weaved into the fabric of engineering education. The authors also enlist the key skills namely, anticipate unintended consequences, reasoning about uncertainties, making estimates, conducting experiments, making design decisions, design thinking in team environment and the language of engineering design.

We have devised an inverse course where students are provided very little direct lecturing, replacing class lectures with mentoring at the lab level; Every group of two-three students is assigned a sizeable project at the start of semester. These students embark on design journey with no clear roadmap or expected outcome. The students as a team need to understand project requirements, finalize the design specifications, bill of materials, materialize hardware/software implementation and user interface.

The semester is divided into three parts, the first part is used to develop the basic theoretical concepts of micro-controllers, the students traverse the process of electrical schematics design, routing and fabrication to produce a custom add-on board for low-cost readily-available micro-controller and use it for various programming activities (see Sec. 5 for details). In the remaining two parts of the semester the students are provided workspace to continue working on their projects under supervision of teaching staff, while core concepts are covered through short lectures.

To the best of our knowledge, such application of DBL to micro-controller based course has not been published in literature. This activity qualifies as a design thinking project because students not only design the electronic circuit and the software to go along with it, they also spend a lot of time designing the product while taking into consideration issues such as form-factor, ergonomics, cost and possible value addition.

As highlighted in the literature, design based learning is far more demanding for students and teachers; but when executed with due deliberation, this mode of education can be a valuable experience for students and teachers alike.

It is apparent that the objectives of this module are broad spectrum; Clearly, more emphasis is placed on skills and competencies to work with embedded systems instead of just a particular platform.

2. Motivation

In the presence of regulatory guidelines and requirement of accrediting bodies there is a very little space left to experiment with out of the box solutions to instill the critical skills and competencies required of next generations engineers. The students need to be creative and must be laced with theoretical as well as technical skills.

The idea has become widely accepted that instead of self-contained/isolated lab sessions it makes more sense to make students implement a semester long project. As in the case of courses offered at various reputable universities same project may be offered to all the participants. Although this approach is practical and pragmatic, different projects were offered to a group of students. Our opinion is that through formal and informal interactions the students can gain from each other experiences.

The motivation for development of this module is manifold. First and foremost, this module is a valuable tool for instruction and assessment under OBE framework. The module reinforces key skills such as engineering design, familiarity with tool chains/processes, prototyping, troubleshooting and competencies such as creative thinking, working as a team to complete project and authoring a comprehensive report. Program steering committee takes this as an opportunity to inculcate the skills of 21st century [14] namely, creative thinking, critical analysis, collaboration and communication. The module has been designed with special emphasis on design skills and competencies; engineering programs everywhere are struggling to incorporate these attributes into traditional teaching-learning process.

Second, in the age of tech-entrepreneurship, the door is ajar for aspiring engineers to develop solutions through crowd and venture capital funding, business incubators & accelerators, Govt. initiatives and even by winning a business plan competitions. It has become ever more important for our students to have a thorough experience of design, prototype and implementation.

Third, we take this course as an opportunity to drive home the idea of engineering design thinking. Students are exposed to top/bottom vs bottom/up and inside/out vs outside/in approaches of design [15]. Students were encouraged to develop internal and external design of the product in tandem. For example the selection of I/O interfaces must be finalized even before the start of electrical circuit design. Electrical/PCB layout will ultimately affect the user interface and form-factor of the product and the other way around.

Although the implementation of the projects using through-hole components would have been more time and cost effective, surface-mount components were preferred to let students appreciate the importance of design tolerances and challenges of design and fabrication of compact circuits.

3. Objectives

From the OBE stand point of view, the following PLOs were considered. The specific statements for course learning outcomes are presented in Table 1.

3.1 Design and Development

This module also provides a very good opportunity to reinforce skills already taught at different stages of the program. For example the design of the assembly and enclosure of the product requires students to apply the skills learned in Computer Aided Design course, the students also revisit the application of different semi-conductor devices such as, voltage regulators, MOSFETs, motor drivers, operational amplifiers and various digital logic components.

3.2 Modern Tools and Techniques

This is one of the key components of this module; exposing students to the design and fabrication process of micro-controller based embedded systems. Through carefully designed lab modules students develop understanding of design considerations and competence in placement and routing of electronic components, verification and validation of electrical layout, tolerances of fabrication facility, selecting appropriate component packages. Eagle 7.5 is used for the said assignment as this is an entry level software which provides all functionalities required for implementation of projects at this level.

3.3 Team Work

Teamwork is another important tenet of OBE framework under Washington Accord; this is a key skill required of undergraduate students, the students are required to delegate responsibilities; simultaneously working on different facets of the project to deliver within deadline.

3.4 Communication

Through implementation of OBE framework it was apparent that students lack in both written and oral communication skills, students lack the ability to write a medium sized (20–25 page) structured document. The authored reports lack structure, clarity, conciseness and accuracy. They have no experience of citing literature. To address this deficiency the students were asked to compile their report in the form of web page. The use of webpages was pre-

Table 1. Course learning outcomes of ESE-221

CLO	Description
1	To **design** a micro-controller based system and demonstrate ability to **integrate** various electronic components into embedded system design.
2	To **use** computer aided design software (e.g., Eagle) to prototype micro-controller based circuit.
3	To **execute** a complex engineering task though application of good practices of teamwork.
4	To **produce** an structured document, demonstrating ability to prepare a clear, concise and coherent document.
5	To **implement** a complex engineering task though application of good practices of project management.
6	To **demonstrate** ability to implement a design project by delving deeper into available literature and learning concept outside of syllabus.

ferred for three reasons, firstly this mode of documentation is interactive, as images, videos and source files can all be easily incorporated in the report, secondly students can refer to useful references such as datasheets, referred websites and other online resources through hyperlinks and last but not the least, these reports may be published on the homepage of this course to help other students learn from the shared resources.

3.5 Project Management

This is also an important skill essential for engineers to work as a part of a team accepting and delegating responsibilities, learning to work under deadlines. The students are asked to document the project management processes they have applied to plan and execute their project as a team.

3.6 Life Long Learning

Life long learning is promoted through design experience, review of data sheets, application notes of various electronic components, reviewing relevant material on the internet, design circuits through application of first principles and trouble-shooting circuits.

By selecting appropriate type of projects this module can also be used to achieve other graduate attributes of Washington Accord framework such as engineering knowledge, problem analysis and investigation.

4. Implementation

A list of projects was developed with the following attributes (i) the project must have a practical application (ii) the project must require design and implementation of electronic circuit/system (iii) the students must develop user interface and enclosure assembly of the product. Although use of readily-available development boards would make the implementation of projects much more straightforward, the students were encouraged to come up with their own customized circuit boards. This stimulated students to delve deeper into the design and development of embedded systems, paying attention to system design consideration ranging from formulation of design requirements, selection of components, hardware/software integration, developing user interface and enclosure. The projects offered to the students are presented in Table 2.

To facilitate the sophomore students and to not burden them to develop the entire project from scratch the students were allowed to adopt any of the open-source design solutions available in the literature, giving due credit to the source. Two interim presentations were organized to let students share their experiences with the rest of the class, specific templates are provided for these presentations.

Table 2. List of Projects allocated to students of ESE-221

1	Maze Solving Robot
2	MPPT Charge Controller
3	PWM Charge Controller
4	FM & MP3 Player
5	LED Strip Digital Clock
6	IoT/GSM Based Automation
7	2D Servo Gimbal
8	Persistence of Vision
9	Cricket Score Board
10	Blood Pressure Monitor
11	Ambu-bag based Ventilator
12	IoT based Energy Meter

Efforts were made to document the team work part of the project. Students were asked to delegate different assignments among themselves and document it. The teaching and lab staff observed the progress of groups throughout the activity and observed the attribute of teamwork and graded every student through a standard rubric.

4.1 Development Platform

Low cost commercially available module was a clear choice as a development platform. ATmega328p and ATmega32u4 are entry level micro-controllers with descent clock rate, number of I/O pins, memory and other peripherals. Extensive user base and readily available libraries let students start experimenting within a few hours.

4.2 Design Software

AutoDesk Eagle is a preferred choice for CAD software as it meets our design requirements. For design of enclosure students used Solidworks. The circuit boards were fabricated using in-house fabrication facility.

4.3 Fabrication Facilities

There exist abundant options for PCB design and fabrication solutions ranging from DIY to high-end capabilities. At the department of Electrical Engineering, we utilize Roland monofab SRM-20 with Fab Foundation Platform [16], which is a freely available platform and more than adequate for our applications. For 3D printing and woodwork activities Prusa i3 printers and Denford 2600 CNC router were used.

5. Course Design

ESE-221 is the only course in the schema of electrical engineering program introducing sophomore students to generic architecture of micro-controller, peripherals/special features, interfacing with sensors and actuators and most importantly the programming techniques to develop a robust embedded system. This is a 4(3+1) credit hours course which means 3 contact hours of theory sessions and 3 contact hours of lab sessions every week.

A semester spans 18 weeks split into three terms. Two term exams take place during the 7th and 13th week, while final exam takes place in the 18th week.

For the fall semester of 2019, it was decided that ESE-221 will be offered as a design project course and understanding was developed that for this particular group of 45 students other courses with lab will not offer a semester/term project. The course learning outcomes of the module were developed in alignment with the program learning outcomes under Washing Accord. The students were divided into groups of two-three students.

The projects were assigned to groups in the second week of the academic session. The instructors provided the students with useful references, as the documentation on these projects is widely available on the internet, students were encouraged to perform a comprehensive review of literature and understand various requirements of project such as bill of materials, and come up with implementation plan and timeline etc.

The projects have some primary requirements e.g., every team must (i) develop a micro-controller based circuit board, (ii) implement embedded software using off-the-shelf code where available and developing code where necessary (iii) develop a user interface for the product; while there exist secondary requirements which are applicable to different projects, these requirements include (i) the design and implement electrical/electronic circuits (ii) integrate sensors/actuators into the system (iii) design and fabricate enclosure for assembly of the project.

5.1 Teaching Methodology

A blend of teaching techniques was applied to improve the efficacy of teaching-learning process (i) short lectures & demos (ii) Lab activities (iii) self-directed learning as a team.

5.2 Module Execution

To streamline the execution of the module the supervision of various projects was distributed among teaching staff. The students worked under close supervision, following the process from higher level system design to electrical schematic, PCB component placement and routing to design of suitable user interface and enclosure.

The students were introduced to the constructs of design (in particular top-bottom/bottom-top approach), the students were provided counseling on design attributes, the intended and un-intended consequences of design decisions at various stages of the project.

5.3 Course Description

The semester was divided into three segments from the start of the semester the students start to develop comprehension of theoretical topics such as, architecture of the micro-controller, review of functional block diagram of generic micro-controllers e.g., 8051, instruction sets and cycle, special registers, IO ports and memory map, Basic IO operations in assembly through memory map; micro-controller programming constructs such as, bit-wise operations, logical operators; For the lab session in first term students are introduced to Eagle software and its design flow and with the help of staff, students fabricate an add-on board for the micro-controller module. The module includes six monochrome Leds, one RGB Led, one Pot and tactile button. The PCB layout and fabricated output is illustrated in Fig. 1. This exercise provides a first-hand experience to design electrical schematic and PCB layout using CAD software and follow the process to fabricate and solder the add-on board. This add-on board was then used to perform several data manipulation and I/O exercises. By the end of first term students were able to use software development framework to perform basic data flow and I/O operations and use various peripheral devices.

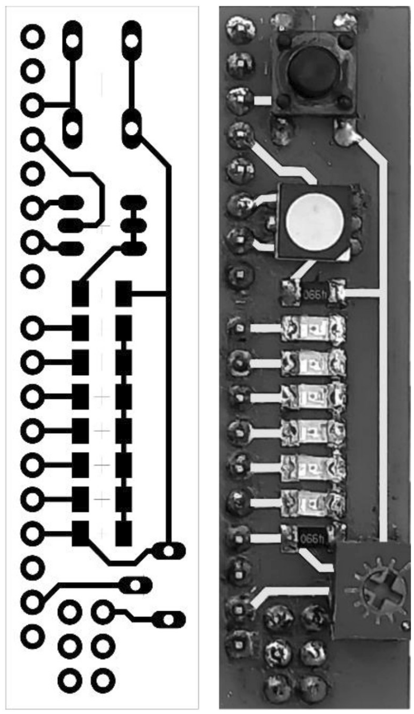

Fig. 1. PCB Layout and Prototype of Arduino add-on board for first usage of micro-controller.

Table 3. The week-wise break up theory, lab and project activities at ESE-221

Week	Lecture/Demos	Lab Activities	Project Activity
1	Introduction/Applications of micro-controller	Introduction to Eagle CAD	Initial Discussion
2	Architecture of generic micro-controller	Electrical Schematic & PCB Design	Assignment of Project
3	Assembly Mnemonics		
4	Assembly Workflow/examples		
5	Introduction to Arduino Platform	Basic I/O, PWM	
6	Data types/Bitwise Operations	Logical Operations/ Flow Control	
7	1st term Examination		1st Presentation
8	Interrupts/Timers		Continue working on the project
9	I2C, SPI and UART Protocols		
10	Keypad/LCD Interface		
11	DC Motor Control		
12	Sensors & Transducers		
13	2nd term Examination		2nd Presentation
14	Design Approaches/Case Studies		Continue working on the project
15	Rotary Linear Actuators/Solenoid Valves		
16	Power Supplies & HV Control		
17			Project Demonstration
18	Final Examination		Project Report Submission

Table 4. Weightage of assessment activities in ESE-221

Lab Component					
1st Review	**2nd Review**	**Final Viva**	**Project Report**		
10	10	10	20		
Theoretical Component					
1st term	**2nd term**	**Quiz**	**Final Exam**	**Project Demo**	**Project Work**
10	10	10	20	10	40

In the second leg of semester topics such as interrupts, timers, communication protocols and interfacing with peripheral devices were imparted through short lectures and demos. The students continued to work on their design project. In the last leg of semester students were provided more time to complete their project and compile report. The week-wise breakup of semester plan is presented in Table 3.

6. Assessment

The contribution of different activities towards final grades is presented in Table 4.

6.1 Assessment Methodology

The assessment of interim and final oral presentations was performed through standardized rubrics, while the project report and execution of the project was assessed through separate rubrics covering all learning outcomes of the module. The students were provided with detailed feedback on their project report (in writing) to help them improve.

6.2 Results

The cohort level attainment results are presented in Fig. 2. The students showed extra-ordinary interest in the design project; almost all the students realized flaws with their design, most of the students wanted to have a second go at the layout of components on PCB to improve their design. After going through the design activity, the students developed a clearer perspective about the design process; students came to appreciate that instead of implementing every stage of the project in isolation the development team has to consider the larger scheme of things, contemplating how each design decision will fit with

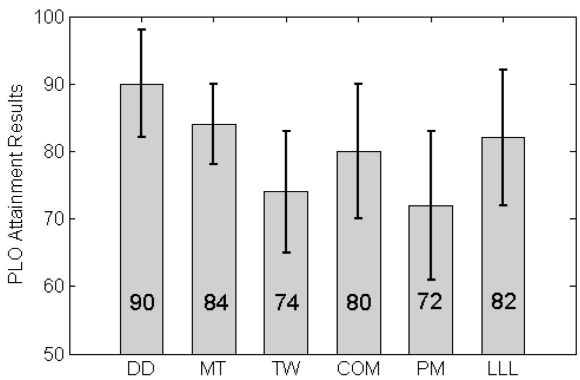

Fig. 2. PLO-wise attainment results of ESE-221.

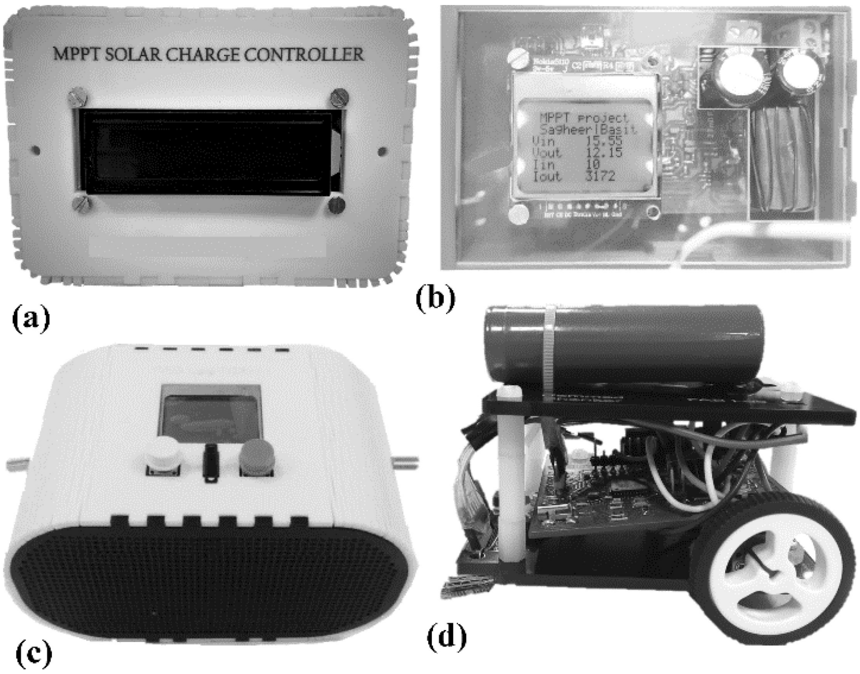

Fig. 3. Final prototypes of semester design projects (a) MPPT Charge controller (b) Another implementation of MPPT Charge controller (c) FM Radio (d) Maze solving robot.

the rest, translating into a prototype with fewer flaws and fewer design iterations.

6.3 Feedback

At the end of semester student feedback was obtained through feedback survey forms. The concise report of the responses is presented in Table 5. It is apparent from results that the overall interest of students and their confidence to design embedded systems did increase substantially.

According to student feedback some of the students suggested that theoretical content should be enhanced, some students complained about excessive rigor. Most of the students approved the new hands on approach and suggested that design courses should be offered at various stages of the program.

7. Report Requirements

In the absence of clear guidelines about the structure of the report document, the reports tend to be inconsistent and irregular. To address this issue, students were provided general guidelines to help them write a comprehensive and structured report. The requirement to project report are presented in Table 6.

The report was developed in webpage format with special emphasis on (i) documentation of design considerations and decisions (ii) use of multimedia to document various stages of the project execution (iii) prepare the cost of the project (iv) documentation of successes, failures and the lessons learned.

8. Discussion

During the implementation of this module several factors came to light e.g., composition of groups, nature of projects and traits such as team work, time management, attitude and aptitude.

The groups were put together to blend students of different academic abilities, also taking into consideration the gender and ethnicities. This deliberate attempt allowed students of diverse

Table 5. Survey questions and feedback results

#	Survey Question	SA	A	N	D	SD
1	Your interest in the module before start of the semester	10	20	8	3	–
2	Your interest in the module at the end of semester	21	11	8	1	–
3	You feel confident in your embedded programming skills	10	20	7	4	–
4	You Feel confident in your PCB designing Skills	12	22	7	–	–
5	Your fell confident in your Sensor/Actuator interfacing skills	13	19	8	1	–
6	At the end of semester you will resourceful to carry out the design and implementation of embedded systems	14	18	7	2	–

Table 6. The list of requirements to the project report

#	Activity	#	Activity
1	Introduction to your Project	20	Challenges you face in Bootup and how you got around them
2	Design Requirements	21	Picture of successfully operating circuit
3	Sample image of final design	22	Picture and Video of assembled system
4	Mechanical Drawing	23	Demonstration of operational circuit
5	Project Execution Plan	24	Flow code of your software Design
6	Distribution of Tasks	25	Diagram outlining main constructs of program (functions/ libraries used)
7	Higher Level System Diagram	26	Challenges you faced and how you got around them
8	Description of Principle of Operation	27	CAD Design of Enclosure (your design considerations)
9	Choice of Components/Power Considerations	28	CAD Design with Dimensions
10	Brief Description of Major Components	29	Procedure followed to fabricate and design 3D printing/Laser cutting
11	Connectivity of Components (Protocols)	30	Picture of final Design with/without assembly
12	Electrical Schematic	31	Business model you make with this product
13	Brief Description of Schematic	32	References you have used to implement the project
14	PCB Layout	33	Paragraph explaining your understanding of intellectual property
15	Challenges you faced and how you got around them	34	Table outlining the cost of project
16	Bill of Material tapped on a paper	35	Zip file containing the source code
17	Picture of clean Printed Circuit Board	36	Zip file containing the sch and brd files
18	Picture of populated Printed Circuit Board	37	Zip file containing cad files
19	Procedure adopted to burn the bootloader	38	Reflections

backgrounds to gel and work together as a team to achieve their objectives. From this experience the students could be classified into three categories (i) active participants who genuinely strived to complete the project then (ii) Compliant students, not as enthusiastic as active participants, but they supported the team to complete their project (iii) non-compliant students were of little help to their team mates. It must be emphasized that as the semester progressed, instructors saw upward shift in the behavior of students. The students who could delegate tasks amongst themselves and collaborated as equals achieved better results.

Not all the projects posed same level of challenges, some projects were more hardware intensive requiring integration of hardware, design of enclosure and user interface, while others required students to delve deeper into processing and translating data in various formats and using peripherals of microcontroller to perform various tasks simultaneously. From this perspective the learning experience of each group was slightly different.

9. Conclusion

Engineering Design Thinking is a must have skill for every engineering student; if executed with due diligence, the proposed activity can add significantly to the skills and competencies of graduates.

ESE-221 was a tremendous experiment, it provided the program steering committee and the instructors with first hand opportunity to assess a wide spectrum of program learning outcomes. The module was instrumental in imparting technical skills such as work flows for design of circuit boards, enclosure assembly, and competencies such as development of embedded system with foresight of design decisions; this course also proved as a valuable tool to infuse the importance of project management, collaborating as a team, technical report writing and finding solution to practical problems through first principles. The authors are aware that proposed activity does not help/push students develop solutions from ground up, and use of readily available resources may not provide students with deeper insight that is expected of them as engineers but having a thorough exposure to design processes and system integration challenges at sophomore level open up these students to many opportunities up the road.

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