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Research & Development of a Decentralized Battery Management System for Modern Automobiles

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Wireless Battery Management System (Design, Build & Test)

Abstract

As part of the Electrical & Computer Engineering (ECE), and Engineering Technology (ET) Curriculum, Applied Design Projects for senior students in their final year augments their education and training in research and research methods. It represents the centerpiece of the ECE-ET curriculum's professional component and follows ABET-IEEE guidelines as provided in their formats. Without exception, all applied projects are team efforts. Teams must consist of between three (3) to five (5) members and the selection of a Team-Lead, and Project presentations before the class, faculty and at a college-organized Design Expo before Industrial Advisory Board Members. Modern Lithium Battery systems require the use of a Battery Management System (BMS) to keep batteries in parallel connections, safe. These BMS sense Temperature (T), Battery Voltage (V), and State of Charge (SoC) for the user, then balances the cells to an equal voltage. Research and Development were conducted to modify the current standard of centralized BMS into a decentralized wireless D-BMS system to successfully meet industry requirement. In modern Electric Vehicle (EV) automotive applications, a BMS is a critical component in the design of modern battery systems. It usually requires the BMS to monitor Voltage, State of Charge (SoC), Temperature, charge, and discharge rates. Most BMS used today are centralized, which means all connections lead to a single location. This type of BMS has the advantage of being simple, inexpensive, and easy to source. However, with the race to create the most efficient electric vehicles, manufacturers are looking for new types of BMS Instrumentation topology termed 'Decentralized Battery Management System D-BMS'. These D-BMS cut wiring down by not stringing wires all throughout the battery system, saving weight, complexity, and reducing points of failure. In this project, this was achieved by breaking up the BMS into several separate 'child-units' created by Infineon-device monitoring, one module at a time. An ESP-32, a Low-cost, Low-Power system-on-a-chip L-PSoC microcontroller with integrated Wi-Fi and dual-mode Bluetooth, was used to turn the ISO-UART connection to the master board into a Wi-Fi connection. This conversion of connection type is the basis of what is now a wireless D-BMS, and all data was then transferred to a MATLAB script for data to be visualized and analyzed. As an instructional project, the D-BMS system incorporates knowledge of battery management, distributed computing, and wireless communication.

Introduction

Battery Management Systems (BMS) play a critical role in the design of modern battery systems. It usually requires the BMS to monitor Voltage, state of Charge (SoC), and Temperature. Most BMS used today are centralized, which means all connections lead to one single location. This type of BMs has the advantage of being simple, inexpensive, and easy to source. However, with the race to create the most efficient electric vehicles, many manufacturers are looking toward a new type of BMS topology called Decentralized Battery Management System (DBMS). These DBMS cut wiring down by not stringing wires all throughout the battery system saving weight, complexity, and reducing points of failure.

Background and Related Work

The literature reveals that numerous efforts are ongoing to create BMS systems. However not every kit provides a good base for expansion or adaptation as are described in the following selected works.

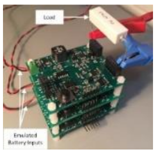

Figure 1: *Smart Cell PCBs. Cell Connection on Left. Output on Right* [1]

“Completely Decentralized Active Balancing Battery Management System”, examines some of the drawbacks associated with centralized battery management systems and the strengths of individual cell monitoring [1]. The battery packs used in current all-electric vehicles are typically retired when the nominal capacity of the pack is reduced to around 70-80 percent of its value. Switched capacitor topologies are usually used in an active balancing system and are only able to cope with minor differences in cell capacities. If cells have degraded enough, the current market battery management systems fail to restore them. This paper proposes that a decentralized BMS can mitigate these losses and increase the longevity of the battery pack’s service life. These researchers were able to design a stable battery pack using these individually monitored “smart” cells.

The article “Scalable, Decentralized Battery Management System (DBMS) Based on Self-organizing Nodes” provides an overview and evaluated comparison between the existing BMS topologies in terms of reliability, scalability, and flexibility [2]. A decentralized, distributed BMS based on self-organized and locally operating nodes was proposed. Existing BMS topologies discussed were centralized, modularized, distributed, and decentralized. The proposed flexible BMS topology consists of three types of modules: renewable energy producers, batteries, and consumers; connected with a common power line and at least one global communication bus. It allows optimized system configurations for a wide range of applications collaborating in a holistic ecosystem, from electric vehicles and houses to stationary energy storage/battery systems, to renewable energy sources, especially Solar and Wind. Each battery, producer and consumer are equipped with its own Local Control Unit (LCU) which includes battery monitored data, communication interface, microcontroller, DC/DC converter, and protective relay for safety.

The paper, “Towards a Smarter Battery Management System for Electric Vehicle Applications: A Critical Review of Lithium-Ion Battery State of Charge Estimation”, examines the challenges of monitoring Lithium-ion (Li-ion) battery cells and reviews the four main categories of estimating Li-ion state of charge (SOC) [3]. The four main methods highlighted were: direct measurement, book-keeping, model-based, and computer intelligence. Direct measurement was further broken down into electromotive force, impedance spectroscopy, internal resistance, and open circuit. These all require direct and physical connections to each cell. Book-keeping is based purely on battery charging or discharging current. Model-based Methods use Li-ion parameters to deploy the battery model and estimate its charge using advanced algorithms. Computer intelligence-based methods covers different programming methods of SOC estimation such as: genetic algorithms, bacterial foraging, particle swarm optimization, fuzzy logic, neural network, adaptive neuro Fuzzy inference system, support vector machine, multivariate adaptive regression splines, and many more.

“An Internet of Things (IoT)-Based Network for Dispersed and Decentralized Wireless Battery Management Systems” explores the effects of implementing an Internet of Things based network on a Decentralized BMS [5]. The implementation of an IoT- based network on a decentralized BMS eliminates issues caused by wires such as physical connection failure due to a vibratory environment and reduces complex battery pack design due to concerns about isolation. It influences the architecture of battery Modules by minimizing the communication wire-harness issues and improves battery health monitoring and management through the IoT-Cloud platform. In this system, each BMS unit acts as a node and a leader node, which is selected by an algorithm, monitors the state of charge (SoC), available capacity and power of the battery Modules. This function is not disrupted because a leader node is selected whenever the current one fails. The data stored on the nodes are sent to a cloud database with assured security using an IoT Gateway. The results show that the system selects a new leader and aggregates data to the cloud database in a reasonable time.

The paper “Wireless Battery Management System of Electric Transport” provides avenues for exploration and represents the type of project this Project Team has in its purview to accomplish [7]. This team used an older and simpler kit from Texas Instrument TI that communicated data on State of Charge, Voltage, Temperature, and Charging rate. It communicates through Zigbee protocol and uses two master-slave and four slave units.

“Design And Analysis of a Wireless Battery Management System for An Advanced Electrical Storage System” goes in depth into the problems a central BMS can experience [8]. Wired communication on BMS is prone to interface from EMF interference and using a strong wireless signal can help with how small of an area a car is. Connectors for BMS are prone to breaking and the cost of connectors of a BMS usually estimate to about 8 percent of the total cost. The hope is to use this information to help influence others on the potential that a wireless can help achieve. This paper, “Wired vs. Wireless Communications in EV Battery Management”, examines the design considerations of TI’s wireless battery management system and compares it with traditional wired systems [9]. Some of the advantages of wired systems include reliability, redundancy, and security. Disadvantages of wired systems include increased weight, difficulty of service, time-synchronization issues due to propagation delay, and overall complexity. The advantages of a wireless system include decreased weight, smaller foot- print, serviceability, and time synchronous. Disadvantages of wireless systems include signal reliability, cost, and security.

“Efficient decentralized active balancing strategy for smart battery cells” explores a method to maximize the usable capacity of a battery pack through Active Balancing [12]. Active Balancing is the process of transferring charges of cells with a higher State of Charge (SoC) to cells with lower SoC. Although this method is expensive, it provides a more efficient way to keep losses during charge transfer low. The Researchers utilized the decentralized BMS architecture, where each cell has a local controller that controls, monitors, and communicates with neighbor cells called Cell Management Unit (CMU), to develop an active balancing strategy called Boundary Cell based Active Balancing (BCAB). The key concept of BCAB strategy is to identify boundary cells, cells that do not require any charge transfer to or from cells above or below it, thus decomposing the global balancing problem into several independent local subproblems. And as the balancing operation continues, more boundary cells form, causing more cells to be balanced. By using a decentralized BMS simulator to evaluate the BCAB strategy, researchers concluded that the BCAB strategy outperformed existing strategies in terms of losses as well as communication overhead without impacting balancing time.

“Review of Battery Management Systems (BMS) Development and Industrial Standards.” described details of BMS for electrical transportation and large scale (stationary) Energy Storage System (ESS) applications [13]. It provides recommendations on BMS safety aspects, battery technology, current market, and regulation needs. Also, it provides a framework for building new BMS standards, especially for BMS safety and operational risk. Advantages of using BMS are as follows: - Prevent damage from over/under voltage and cell balancing with limited charge current. Operational benefits include safety, reliability, and dual-purpose. Minimizes the occurrence of a thermal runaway for high-voltage batteries. Identifies the faulty cells connected in series and parallel (dual-purpose). Economic advantages are extensions of battery lifetime and lowering cost. For example, BMS shares only 8 percent of the total battery pack cost for a 22kWh mid-sized EV battery pack. Drawbacks of current BMS are as follows: - Limited data logging functions. Potential solution: cloud BMS and digital twin technology which im- proves data storage capabilities and computational power by cloud computing. Commercialized BMSs lack state of charge (SOC) and state of life (SOL) estimations.

This paper, “Wired vs. Wireless Communications in EV Battery Management”, examines the different types of wireless battery management systems typically used in electric vehicles [15]. This includes Cloud-based battery monitoring utilizes an internet of things (IoT) device and cloud computing to manage large scale battery systems. This cloud component contains analytic tools, storage, and visualization. IoT based systems utilize a microprocessor and sensor package which sends the data to a computer to detect performance and send alerts on battery health and location. Bluetooth wireless systems use low power Bluetooth communications. This output can be sent to phones or computers for real-time, short-range monitoring. Zigbee wireless systems use a low power, low cost, high reliability chipset. The hardware contains sensor packages to monitor voltage, current, and temperature. This data is sent to a master controller which calculates SOC.

The paper “Wireless battery management system” introduces a wireless battery management system (WBMS) that enables the manufacturing of smaller, lighter, low cost, and more reliable battery packs [16]. The system’s topology consists of a master BMS which wirelessly communicates with a slave BMS. So, no wire-harness is involved. The slave BMSs monitor the state of charge (SoC), the state of health (SoH), current, voltage, and temperature of the cells. This data is then reported to the master BMS, which stores. Wireless communication is done through a Wireless Battery Area Network (WiBaAN). WiBaAN is a platform optimized for low-power, high- security, and high data-rate. The WBMS has many advantages such as low cost, high productivity, high reliability, built-in diagnosis, low redundancy or Fault-Tolerance, and adequate Intelligibility. Tests conducted proves that the WBMS is a feasible device with reliable and secure wireless communication. This paper, “Towards a Wireless Battery Management System: Evaluation of Antennas and Radio Channel Measurements Inside a Battery Emulator”, examines the antenna design considerations necessary for the use of wireless transmission inside a battery pack [17]. Three different types of antennae were tested for different frequency ranges. Double helix 100 MHz - 600 MHz Planar helix 800 MHz - 1200 MHz Planar Inverted-F-Antenna (PIFA) 2200 MHz - 2600 MHz. A simulated battery pack enclosure was constructed. The antennas were tested, and results analyzed. Some of the results from the study included low frequency fidelity, and high frequency viability with special design consideration to overcome notching and reflection.

The paper “Implementation of a wireless battery management system (WBMS)” introduces a strategy to implement a wireless system in a BMS; thereby eliminating failure points, reducing wire weight, and enabling a flexible architecture of the system [18]. This system has two main hardware components. The primary main hardware system is a National Instruments myRIO integrated with a Bluegiga BLEl12 Bluetooth System-on-a-Chip (SoC) which controls, collects, and transmits data to the second main hardware system. The second main hardware system is the battery pack fitted with a Linear LTC6803 IC which measures the voltage of the cells in the battery pack. This data is used to balance and monitor the health of the cells. The implementation of Bluetooth enables an easy replacement of the entire system and minimizes the need for wires.

The paper “A Comparative Study of Wireless Proto- cols: Bluetooth, UWB, ZigBee, and Wi-Fi” goes over all the major wireless protocols used in most devices [19]. Bluetooth is great for short range communication and moderate bandwidth. UWB is a unique but unpopular wireless communication used mainly in the home environment. It is used mainly for media relaying and can be a replacement for USB 2.0 communication with its 110 Mbps bandwidth. Zigbee is a low-speed protocol very popular for its low power use but does not have the range of WIFI but is great for mesh networking. WIFI is the most common wireless protocol with moderate power usage. Its main strong point is its potential for great range and high bandwidth communication. The article “Li-ion batteries: basics, progress, and challenges” goes over all the different advantages and dangers involved with Li-ion batteries [20]. Technology for LI-ion is getting better every year with larger companies and governments seeing the need to use alternative power sources. The dangers of Li-ion are if the batteries are to be punctured hydrogen gas and other toxic fumes will leak out causing a fire. Thermal runaway can happen when a cell is shorted causing it to heat up to the point of causing a fire. Toxic elements such as cobalt and lithium are used in the production of these batteries and researchers are making great strides to find less toxic and abundant elements to use.

Proposed Solution (Method of Approach)

One of the main hurdles of any design is to select a method and hardware that fits both the means and scope of the project. Many BMS systems already exist within the current technological landscape, however not every kit provides a good base for expansion or adaptation. The method proposed here will be to utilize a pre-existing BMS on the market and adapt it to communicate wirelessly from pack to pack. Although simply put, this proposed method offers a wide range of options, selecting an adequate base design is vital to the scalability and modularity of the final design. The design parameters for this method require a BMS that is decentralized, allowing operation of each pack to be independent of a main control unit. This allows for better scalability as packs can be added or removed as needed in each application. The next step of the proposed method is to integrate wireless communications. The elimination of many wired connections can result in a more modular design, as well as a lighter overall weight and smaller footprint in many settings. By selecting a decentralized BMS and integrating wireless communication protocols, the design can be both simplified yet optimized for use in many applications and environments.

The final presentation includes multiple battery packs managed by a BMS that operates in a wireless environment. These battery packs will be housed inside a travel pack offering user friendly outputs, as well as acting as a load for the packs. The packs will be able to be connected in parallel in a modular fashion, allowing between one and three packs to power the external outputs.

Selecting proper components is an important step in the implementation of the proposed method. At the core must be a decentralized BMS. After reviewing and comparing many of the systems available on the market, the Infineon Technologies Development Kit began to emerge as the best choice. When comparing price, design, and particularly availability the Infineon BMS kit became a comprehensive solution. The Infineon kit offers a decentralized BMS that utilizes a wired iso UART communication system. As designed, the BMS kit utilizes an AURIX microcontroller coupled with the TLE9015QU board as the MCU. Each pack will operate as a Supervisory Control Unit (SCU), utilizing the TLE9012AQU board that will provide both BMS balancing as well as generating and receiving the UART communication. Once the base BMS kit had been selected, the next step is to select components to integrate wireless communication. Initial Designs include a plan to establish a wireless network. To do this an ESP32 board was chosen to both translate the UART signal from the BMS as well as establish a wireless mesh network for communication. Each BMS pack coupled the TLE9012AQU BMS board with its own ESP32. The BMS boards can power themselves through the pack directly, however the ESP32 will not work as well with such a large range of voltage. In this case, a buck converter will be connected to power each ESP32 with a stable voltage despite any changes in pack voltage. Each battery pack will then be composed of twelve series batteries, one TLE9012AQU BMS board, one buck converter, and an ESP32 wireless communication board.

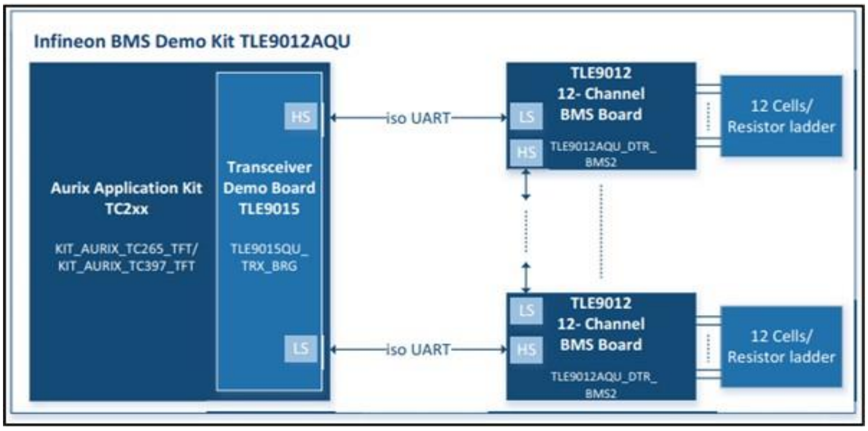

Figure 2: *Infineon Technologies Demo Kit - TLE9015QU and TLE9012AQU*

During construction, programming, and testing, it was determined that the output signals from the BMS boards were encrypted, likely due to security measures taken by the developer, Infineon. At this time, reversion to the wired isoUART connections was considered. A raspberry Pi Zero board will now be utilized to generate wireless signals from the MCU to an end user. The components for the final pack will also be chosen to fit both the needs of the user as well as the design parameters of the battery packs. The battery packs will utilize Xt-90 connectors and appropriately sized wiring to connect to positive and negative distribution blocks within the final pack. The main power lead would run to a cut-off switch which would in turn power a forty-eight volt to twelve-volt DC buck converter. This twenty-amp max buck converter will power a fuse block that can then power several accessories and outputs such as USB ports, AC inverter, lights, or even a cigarette lighter style port. The outputs will be the usable interface between the battery packs as a power source and the end user.

Design Steps

For a baseline BMS design, the Infineon Technologies Demo Kit TLE9012AQU and TLE9015QU will be utilized. This kit utilizes the Infineon Aurix micro-controller coupled with a TLE9015QU transceiver board in a shield configuration to operates as the MCU. This MCU is then couple to the TLE9012AQU 12-channel BMS board through a wired UART connection. The TLE9012AQU board can connect to twelve series batteries and support between five- and sixty-volts DC. Twelve Panasonic NCR18605GA batteries will be used to create the battery packs, offering a maximum of forty-eight volts DC and ten amps max current. Each set of twelve batteries and the TLE9012AQU BMS board will make up each SCU. The overall BMS design can support either a single SCU or as many as are specified by the application, in this case four units. These battery packs or SCU can be connected in series utilizing the iso UART wired connections on each board as shown in Figure 2.

Initial plans to further the design of the Infineon kit have wireless communication replacing the wired ISO UART connections.

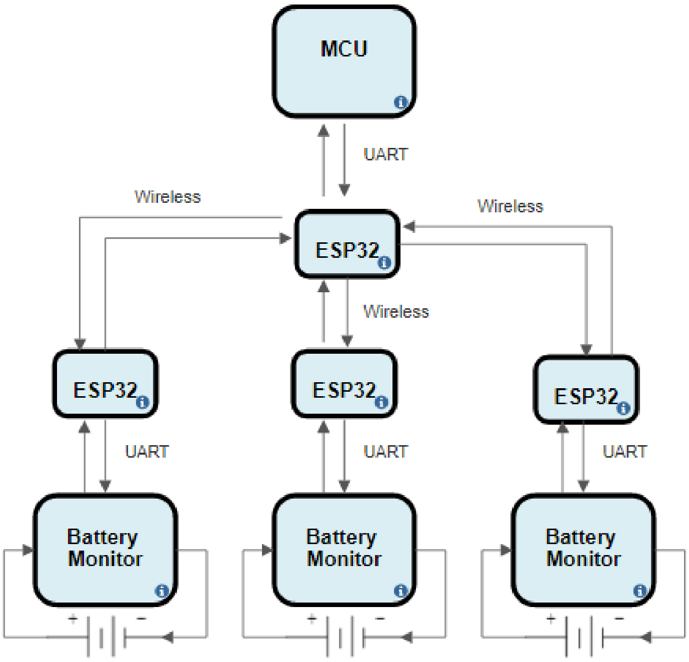

Figure 3: *Initial BMS Design Flow Diagram*

ESP32 boards will replace each wired isoUART connection, creating a wireless mesh for the boards to communicate. The iso UART wired connections will be used for communication between each TLE9012 BMS or TLE9015 transceiver boards and the corresponding ESP32. Each ESP32 is programmed to translate between the iso UART signal sent over wired connections to or from the board and the wireless signals sent between the newly established ESP32 mesh network. The ESP32s will utilize the ESP-NOW protocol, one developed specifically for these types of boards, to communicate wirelessly within the network.

Experimental Results

The wired BMS system was tested with a 12-cell pack. MATLAB was used to connect to the Parent BMS Module and preform various read and write operations. The BMS was initialized to preform voltage measurements on each individual cell and the voltage of the block. Testing was performed on all four packs simultaneously. All voltages were confirmed by multi-meter. Balancing was tested and confirmed working with the packs. The Wireless BMS uses a parent child architecture. First a request for cell information is made from the parent to the child pack. The parent now waits for a response. The child communicates with the BMS chip and relays the data requests back to the parent. This keeps wireless activity at a minimum since the children only talk when asked. This design can be easily scaled up and replicated. It does not require any complicated setup, making it implementable quickly with little to no overhead.

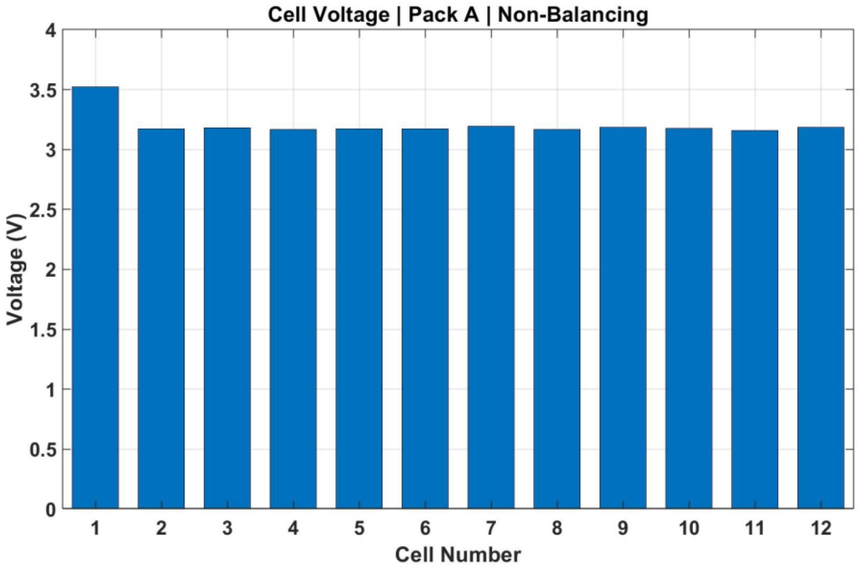

Figure 4: *Cell Voltage Graph*

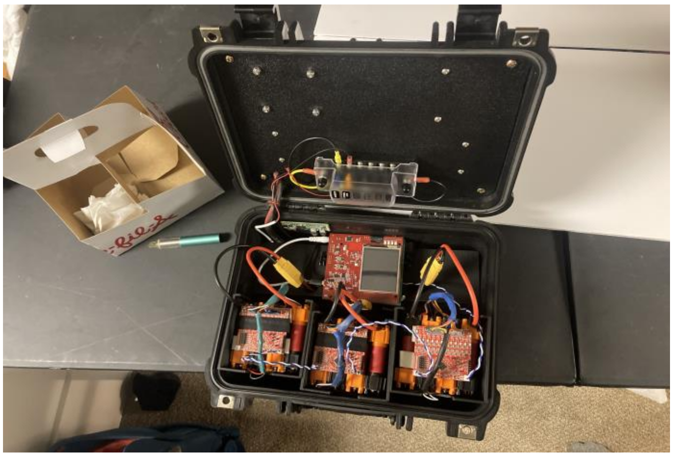

Figure 5: *Final Project Prototype*

Conclusions

The results of the project were a successful wireless BMS that measured all required values and communicated properly with the user. This project provides the baseline and proof-of-concept for what a wireless BMS needs for bringing it into the consumer market. The results show that with unbalanced cells it is possible to balance them through the Infineon BMS board using wireless communication technology. All data was successfully transmitted to a PC where a MATLAB script made it possible to visualize all data.

The most important consequence of the exercises reported in this paper are the benefits from a deliberate application of the ABET-IEEE Capstone Assessment Rubrics; the mandatory Presentation of all Design Projects by Teams in front of the class, faculty and Industry Experts; and finally, a college organized Design Expo on the last day of the semester in the College Auditorium.

Project Assessment Rubrics

Every effort is made in this entire process, to measure the students against the ABET-IEEE outcomes in multiple ways. We also have artifacts to show what has been done (ABET evaluation criterion in parentheses):

Each Team writes a project plan where they provide the Statement of Work (SoW), the requirements, the work breakdown structure, and schedule.

About mid-semester, each Team writes a Preliminary Design Report where they are required to:

- Present their preliminary design.
- Write research report
- Identify the challenges they think they will encounter.
- Identify the risks and what mitigation strategies they have planned.
- Prepare a PowerPoint presentation and present it to the class orally.

At the end of the semester, each Team writes a Final Report containing following key elements:

- The final design and test results.
- Requirements traceability matrix.
- Lessons learned (challenges they did not expect)
- Then the Teams give an oral presentation with PowerPoint Slides.

Each student completes a Peer Evaluation on their team members and Team Leads.

A regularly planned Design Expo serves as a Poster presentation and demonstration activity.

The supporting artifacts are:

- Statement of Work document.
- Research Report
- Requirements document
- Project Plan document
- Preliminary Design Review document
- Preliminary Design Review PowerPoint Presentation
- Final Report document
- Final Report PowerPoint Presentation
- Poster presentation and project demonstration
- Video archive of the final oral presentations
- Demonstration video
- Peer Evaluations

Credits:
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