Development of a Low-cost Automotive Communications Network Course for EE and ME Students

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Abstract

In today's modern automobiles, safety, comfort and performance requirements have been constantly increasing. Automotive communication networks are evolving rapidly to assist the increase in bandwidth requirements necessary to support new functionality, interaction between modules and the growing demand for information accessibility. Despite the fact that these communication networks are broadly applied in the automotive industry, the offering of engineering courses in this area is very limited. To address this gap in the curriculum, a new automotive communications network course was developed to educate students in Electrical Engineering (EE) and Mechanical Engineering (ME) programs. This paper provides details on the course content, textbook and reference selection, lab experiments, student feedback and other lessons learned.

Keywords: automotive communications network, intra-vehicle communications, controller area network (CAN).

1. Introduction

The automotive industry is one of the largest economies in the world, producing millions of units a year, and employing a large number of engineers as well as graduates in a wide variety of fields. Significant improvements in vehicles functionality, safety, performance, and comfort were made in the past decades. As a result, modern automotive electronic systems contain a complex network of electronic control units (ECU), sensors and actuators distributed and embedded in almost any vehicle. Intra-vehicle communication describes the exchange of data within the ECUs involved in specific vehicular applications. The increase in the number of ECU (8-10 ECUs in early 90's through around 100 in today's vehicles) and communication signals with complex interrelation between them, requires more robust and time efficient intra-vehicle communication. This is especially important in automotive manufacturing as vehicles become increasingly reliant on robust electronic networks and systems for improved reliability, anti-lock brake systems, steering, on-board navigation systems, and much more. Automotive networks eliminate unwieldy wiring harnesses, and increase vehicle safety and reliability, in addition to fast and efficient communication. Therefore, the education of engineers to work on these systems is critical.

Despite the fact that automotive networks such as Controller Area Networks (CAN), Local Interconnect Network (LIN), FlexRay, and Media Oriented Systems Transport (MOST) are broadly applied in the automotive industry, the offering of courses in this area is very limited.

There was no similar course offering in the author's institution in either the Electrical Engineering (EE) or Mechanical Engineering (ME) programs. To address this gap in the curriculum, a new automotive networks course was developed to educate students from both EE and ME programs. The course was designed to be accessible to students of either discipline. Students learn about very different interdisciplinary aspects that characterize vehicle embedded systems and vehicle communication. EE students gain insight of topics including automotive instrumentation and vehicle functional domain, while ME students gain insight of digital communication, serial communication, and their interplay in automotive bus systems. The course also has a lab component developed to strengthen content understanding of students from both majors. The lab experiments are based on low cost hardware and software in Arduino environment. This paper provides details on an automotive networks course content, textbook and reference selection, lab experiments, student feedback and other lessons learned.

2. Summary of communication buses[13]:

The CAN network (or CAN bus) is a form of serial communication to transfer data between nodes or controllers. It uses differential digital communication and therefore requires two signal lines. It caters to real-time requirements due to its ability to establish fast communication between microcontrollers. It is an Asynchronous multi-master communication protocol serial bus having a data rate of up to 1 Mbps. Nowadays, CAN has gained popularity in industry automation as well as other applications. CAN uses in non-automotive applications range from railways and aerospace, to medical. Some of CAN bus automotive application examples are:

- Safety power train: electronic parking brake, vacuum leak detection automotive black box.
- Chassis: watchdog, motor control, electronic throttle control, body control: bow-end body controller (lighting, network communication) power door, power sunroof, power lift gate.

The Local Interconnect Network (LIN) is a serial communication protocol suited for networking sensors, actuators, and other nodes in real-time systems. It is a single-master, multiple-slave (up to 16 nodes), with up to 20 Kbps data rate automotive network protocol. LIN is used to interconnect low performance devices that do not need much bandwidth for their operation. LIN provides cost-efficient communication in applications where the bandwidth and versatility of CAN are not required. LIN can be implemented relatively inexpensively using the standard serial universal asynchronous receiver/transmitter (UART) embedded into most modern low-cost 8-bit microcontrollers. LIN bus application examples:

- Steering wheel: cruise control, wiper, turning light, climate control
- Seat: seat position motors, occupant sensors, seat control switch
- Door: mirror switch, central ECU, power window lift, door lock
- Safety and investigation: automotive black box.

FlexRay is a high speed communication protocol used to communicate among different devices in an automobile system. It is a multi-master network and was created to increase reliability, quantity and speed of data being communicated among the vehicle's ECU. FlexRay networking standards work on the principle of TDMA and have dual-channel architecture. It has a host processor which controls the communication process via communication controller and bus driver. Each FlexRay node has two physical channels A and B facilitating data rate of up to

10Mbps per channel. It can be employed as a network backbone with CAN and LIN. FlexRay network bus application examples:

- Data backbone: for other buses (LIN, CAN, and MOST)
- Safety-critical applications: X- by- wire, automotive black box
- Distributed control system applications: power train applications
- Chassis applications requiring computations across various ECUs.

Media oriented system transport (MOST) is a high-speed multimedia network technology that can typically handle up to 64 nodes. MOST has a very high data rate of up to 25 Mbps in synchronous and 14.4 Mbps in asynchronous mode. It can operate up to 15 uncompressed stereo audio channels or up to 15 MPEG1 channels for audio-video communication. MOST is a timing-master network with very good error management along with high transmission data rates. MOST applications includes the communication between devices that handle navigation, car audio, cell networks, video, and user input. [13]

3. Challenges

One of the main challenges the author encountered to develop this course was the lack of reference material in lecture or laboratory experiment formats. In the author's online search, no similar course offering was found in other institutions. In addition, no textbook was found. The author explored a large number of documents and books [1 – 5] in the subject that served as reference for this course. Offering an undergraduate course in intra-vehicle communication with a supplemental hardware laboratory for engineering students is not straightforward due to the complexity and cost of equipment that can emulate automotive buses. The author had to be creative, using low cost hardware and free software to equip the lab and develop laboratory experience that students could easily follow and relate to the material covered in the lecture sessions. In addition, the course design had to be accessible to students with backgrounds in electrical engineering and mechanical engineering, which made attention to pre-requisites particular important. For instance, some background information had to be covered to bring ME students to speed in data communication and EE students in vehicle domains. The author spent the first module of the course (about two weeks) to bring EE and ME students up to speed in digital and serial communication, and provide an introduction to automotive instrumentation and bus systems. The other topic necessary for the course was basics of the Arduino program, which was done concurrently with the lab experiments as pre-lab assignments.

4. Automotive communications network course description

The course focuses on in-vehicle system domains and their requirements, and intra-vehicle communication bus Controller Area Network (CAN) and its related physical layers standards. It also covers Local Interconnect Network (LIN), FlexRay, and Media Oriented Systems Transport (MOST). In-vehicle network examples, components and tools are presented. The course content is divided into seven modules and is described in Table 1. We also describe the student learning outcomes and the recommended text for this course below.

4.1 Student Learning Outcomes (SLO)

Upon successful completion of this course students will demonstrate familiarity with the major vehicle communications concepts and technologies, system components, and industry terminology. In addition, students will be able to apply concepts and technologies toward practical applications, including design and data analysis of nodes emulating vehicle system components.

1. Introduction a. Digital communication review b. Serial communication review c. Introduction to automotive instrumentation d. Introduction to automotive bus systems	5. CAN with the Arduino environment a. Introduction to the Arduino software environment b. Arduino board and additional hardware c. Introduction to CAN with Arduino
2. CAN bus introduction a. ISO/OSI reference model b. CAN history and introduction c. CAN physical layer	6. On Board diagnostics a. OBD I and OBD II b. OBD Port c. Accessing data d. OBD scanners e. OBD-II modes of operation f. OBD-II PIDs
3. CAN bus communication a. CAN broadcasting b. CAN arbitration c. CAN error conditions d. CAN bus controllers e. CAN data exchanging f. CAN bus timing	7. Introduction to other vehicular buses a. CAN open b. CAN FD c. LIN d. FlexRay e. MOST
4. CAN bus development tools a. Hardware development tools b. Software development tools	

Table 1. Course schedule divided in 7 modules.

Recommended text for this course includes:

1. D. Ibrahim, Controller Area Network Projects, Elektor Electronics Publishing.
2. W. Voss, A comprehensive Guide to Controller Area Network, Copperhill Media Corporation, 2nd Ed.
3. Pfeiffer, Ayre, Keydel, Embedded Networking with CAN and CANopen, Copperhill Technology Corp.
4. Automotive Handbook, Bosch, 9th Ed., Wiley.
5. D. Paret, Multiplexed Networks for Embedded Systems: CAN, LIN, FlexRay, Safe-by-Wire, Wiley.
6. P. Bajaj and M. Khanapurkar, Automotive Networks Based Intra-Vehicular Communication Applications, Chapter 8, book: New Advances in Vehicular Technology and Automotive Engineering, InTech, 2012.

5. Laboratory experiments and simulations

It is a common understanding that the laboratory must serve as a learning resource center in which the students not only perform formal lab assignments, but also have the opportunity to use the equipment and computers to strengthen their understanding of the concepts presented in the lecture section [14, 15]. We can't stress enough the value of hands-on learning. The laboratory adds realism and solidity to the topics covered in the course. Students usually enjoy laboratory work, especially as it can be related to some of their own major interests. Therefore, it is imperative to choose experiments that provide students with real life applications that are challenging but achievable, and most importantly that the lab experiments are tightly coupled with the lecture. We also receive input from our External Advisory Committee for experiments that would be beneficial for our students in their professional careers. Therefore, undergraduate laboratories require constant updating and development of new and innovative experiments each semester, which requires a fairly large amount of time on the instructors' side. In addition to well-chosen experiments, students' data should be checked before they leave the lab to make sure that the data is at least acceptable to complete the lab assignment.

The lab experiments for this course were developed with low cost and user friendly requirements in mind. It is important to mention the fact that since this course was newly developed, it required time and creativity from the instructor. The instructor did not have a reference lab manual to start with. Hence, the instructor's experience played a role on the time estimation and level of difficulty of the experiments for both EE and ME students. The instructor selected multidisciplinary teams for each lab experiments. In addition to the multidisciplinary nature of the teams, the instructor also rotated partners from one experiment to another. The laboratory experiments were based on Seeed Studio CAN Shield,[6] Arduino Mega board 2560,[7] sensors and actuators. The boards programming was done via Arduino's Integrated Development Environment (IDE), which is a free software.[8] The IDE is a text editor like program that allows one to write computer code for an Arduino board. The IDE has a serial monitor screen, showing the serial port activity. Students of both majors who were not familiar with the Arduino program had access to tutorials, pre-lab assignments, and mentoring to learn about basic Arduino program before working on the lab experiments. Samples of Arduino code were also provided to students. All the necessary material for the class was available on the Institution's learning management system (Canvas®).

5.1 Main hardware description

a. Seeed Studio CAN Shield

- Uses the MCP2515 CAN Bus Controller
- Implements CAN 2.0B specification up to 1 Mbps
- 3 Transfer buffers, 2 Receive buffers, 2 Masks and 6 filters.
- Easy Connectivity to MCU

b. Arduino Mega 2560

- A MCU board based on Atmel: ATmega2560.
- 54 Digital I/O Pins
- 16 Analog I/O Pins
- USB interface for easy uploading
- Great documentation and support

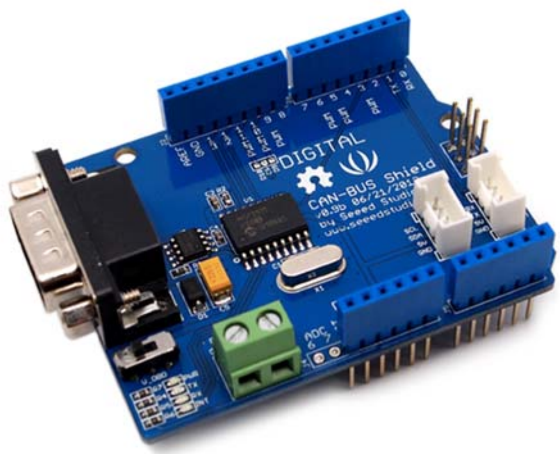

Fig.1 Seeed studio CAN shield board. [6]

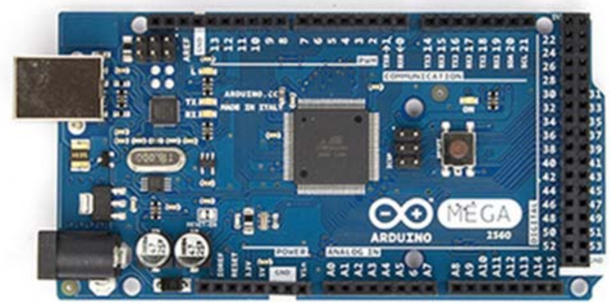

Fig. 2 Arduino Mega 2560. [7]

c. Arduino IDE serial monitor screen

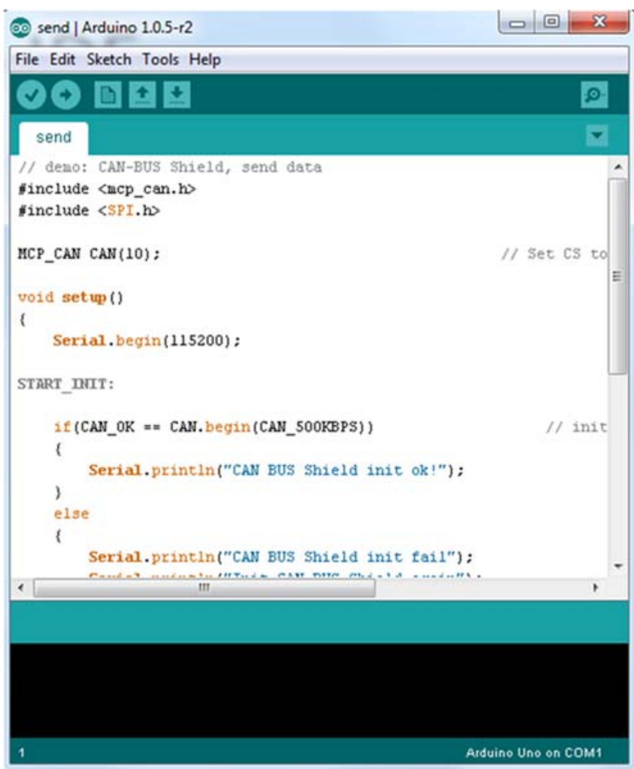

Fig. 3 Arduino IDE.[8]

5.2 List of lab experiments includes:

Experiment #1: Introduction to the Arduino Programming

Objectives: Students are introduced to the Arduino Mega 2560 board, download and installation of Arduino IDE, serial port setup, drive installation, and basic programming. Students also become familiar with the Arduino website and technical literature available.[8]

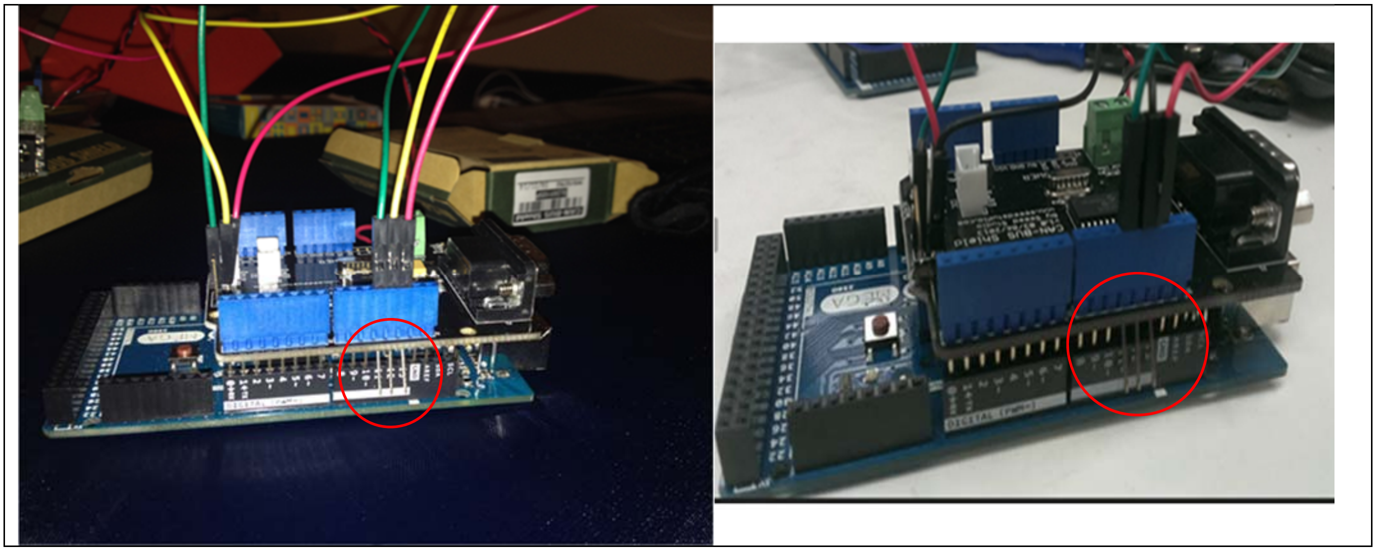

Fig. 1: Arduino board pins modification.

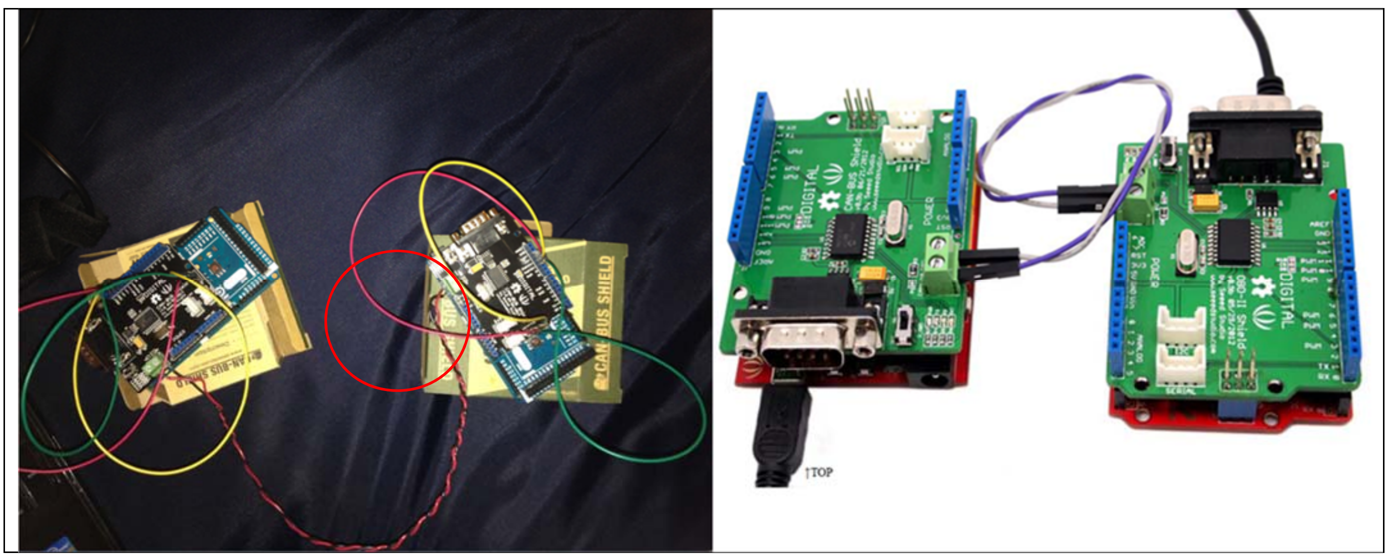

Fig. 2: Two connected CAN nodes. Figure on the left is the author’s prototype nodes and figure on the right is from wiki.org.

Experiment #2: Introduction to CAN with the Arduino Environment

Objectives: Students learn how to setup the Arduino Mega 2560 board and a CAN bus shield to create a CAN node. The CAN bus shield employs the MCP2515 CAN bus controller with SPI interface and MCP2551 CAN transceiver to give Arduino the CAN-BUS capability. This setup can implement a CAN V2.0B (both standard and extended frame) up to 1 Mbps. Note that a board modification is required. To make the CAN Bus Shield compatible with the Arduino Mega the connections in pins D11, D12, and D13 must be removed, which is demonstrated in Fig.1. In Fig.2 we show the connection of two CAN nodes.

Experiment #3: DC Motor Control via CAN using Arduino

Objectives: Students emulate the functionality of a vehicle's power windows by using a CAN node, 2 pushbuttons as inputs (corresponding to either window in upward or downward directions) and a step motor to emulate the actuator moving the window. Students learn how to program the sender and the receiver nodes in order to control the DC motor using CAN communication.

Students perform conditional checks on the input buttons. Depending on the state of the buttons, a message corresponding to the state is created and it is sent to the bus. The system is setup to perform a delay of about 100ms before each message is sent. Three different CAN messages are sent in the bus, one for window up, one for window down, and another for no action. The CAN messages are printed in the serial monitor and labeled accordingly.

Experiment #4: Obstacle detector using CAN bus

Objectives: Students use an ultrasonic sensor to detect an object and send the distance information across the CAN bus. The ultrasonic distance sensor is connected to the transmitting node. This node will send the distance of the obstacle from the sensor across the CAN bus to a receiving node, which will print the distance (in cm) on the serial monitor. Ultrasonic sensors consist of a transducer which is used to transmit the sound pulse and also to receive the echo that is reflected. Ultrasonic sensors are used to detect the presence or absence of a target component by using reflected and transmitted ultrasonic waves.

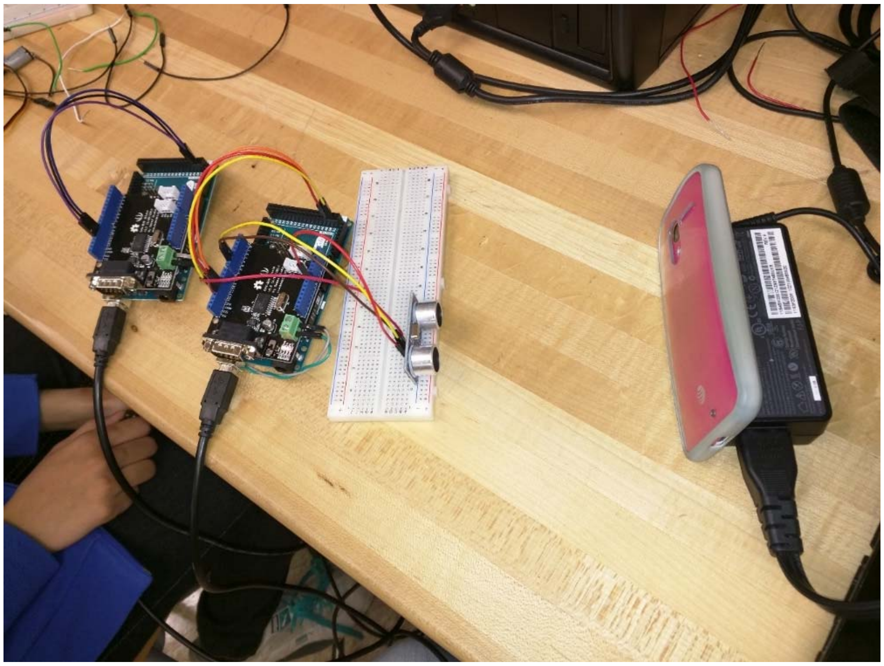

Fig. 3: Simple configuration setup with the two nodes and the sensor.

Experiment #5: Multi-node CAN network and message filtering

Objectives: Students setup a CAN network with more than two CAN nodes. Many CAN networks operate with numerous nodes, sometimes up to 30 nodes on a network, each one supplying multiple messages. The CAN-BUS is easily modified, allowing for additional functionality to a CAN network. This lab expands the two-node network into a three-node network. One node is programmed as the sender and the other 2 nodes are programmed as receiver 1 and receiver 2. The receiver 1 can be programmed to have a CAN filter and, in this way, only allowing messages with specific ID to be received.

A modification must be performed in the Seeed studio CAN bus shield in order to accommodate multi-node configuration. The intermediary node must have its CAN terminator resistor removed. With two CAN nodes with terminator resistors and one CAN node without terminator resistors, the network connection of the 3 nodes may take place.

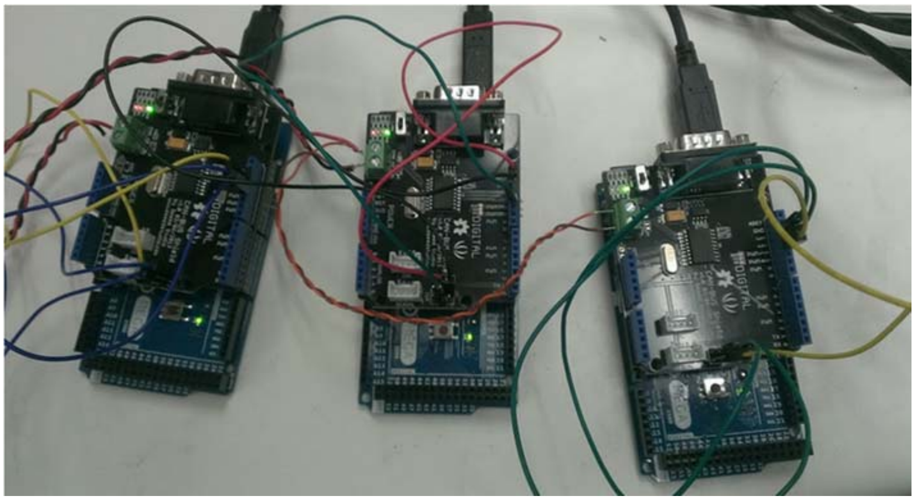

Fig. 4: Three CAN nodes connections.

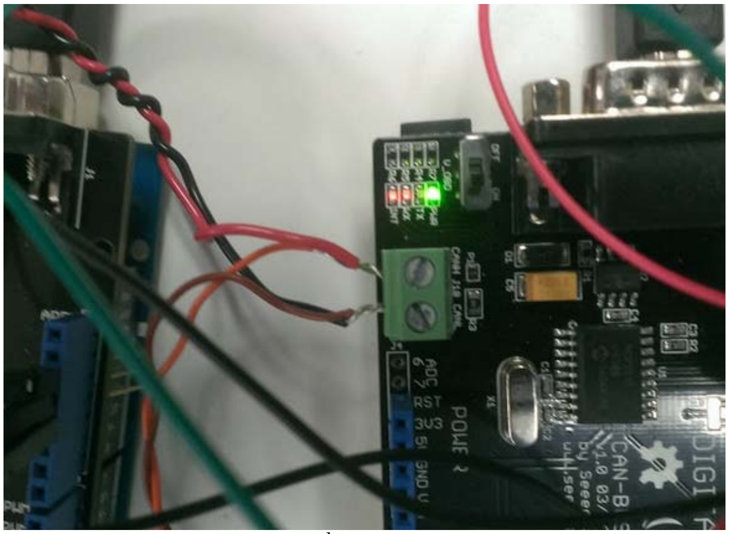

Fig. 5: Connecting the 3rd node to the bus.

6. Active learning methods used

Active teaching and learning is the introduction of student activities into the traditional lecture. One example of how that can be accomplished is for the lecturer to pause two or three times during an hour-long lecture and have students clarify their notes with a partner. Studies have shown significant results in student retention by using this approach. [9, 10, 11] Numerous studies suggest that student attention span during a lecture is roughly 15 minutes.[11] Breaking up the lecture might work because students' minds begin to wander and activities provide the opportunity to start fresh again, keeping students engaged.[12] It is important to highlight that the activities to engage students must be designed in line with the course learning outcomes. Students should be encouraged to think about what they are learning. Adopting instructional practices that engage students in the learning process is the key feature of active learning.[5] Some active learning approaches the author used this courses include:

a) Think-Pair-Share

The instructor poses a problem and has the students think about it individually for a short time. The thinking time can also be used to write the response. The students then form pairs and share their solutions. The lecture time required depends on the type of problem, but the author usually selects problems that can be solved in five minutes or topics for discussion with a duration of five minutes. Students have demonstrated to like this approach as well. It doesn't require any use of technology, so it is "easy and cheap." Sometimes the author decides to give a problem or topic for discussion on the fly during the lecture depending on the student level of engagement or learning of the material.

b) Clickers

The author also uses i-Clickers® for classroom short quizzes based on multiple choice problems to review material taught on previous lectures. Any question/material with less than 70% of correct answers is covered in class again for at least a few minutes.

c) Collaborative learning and Problem-based learning (PBL)

The course collaborative learning was based on laboratory team work. The instructor selects all the partners for the entire semester. Students work with a different partner for each lab section forcing them to change their role instead of constantly doing the same type of task, such as only taking notes or only taking measurements. This is a practical way to train students for the workplace since they usually will not be able to choose the co-workers they will be working with on different projects.

The author frequently applies PBL final class projects. Examples of final class projects are the investigation of in-vehicle network applications, hands-on projects with CAN nodes, and paper on subjects such as: MOST, LIN, FrameRelay, CAN-FD, CAN Open, and development tools.[13]

d) Use of Learning Management System (LMS)

The author extensively uses LMS in every single course. Most of the instructors in U.S. colleges and universities are familiar with LMS and use some sort of this system. I cannot stress enough the importance of pairing active learning techniques with LMS. The use of LMS has proven efficient in course teaching and a time saver.

7. Assessment and student feedback

The assessment results have indicated that the course was successful in meeting the student learning outcomes. The success indicators were based on direct and indirect quantitative measures such as homework, short quizzes, exams, written lab reports, class participation, hands-on-projects, final project research paper, and student surveys. Table 2 has a summary of assignments and student average per assignment. The assignments served as direct assessment for the course content described in Table 1. The author did not observe any significant differences in learning behaviors when comparing EE and ME students. Both groups had a similar level of difficulties, however, EE students were faster in concluding their lab experiments. This is not a surprise considering EE students' background and familiarity with the type of lab environment. Due to the fact that this is a newly developed course, additional course offering will be required for meaningful statistics and comparison results. The student feedback for this first course offering, however, were encouraging and includes:

"The course, in-vehicle communications was a new topic for most of us. Since it was an introductory course and didn't have any prerequisites, the instructor knew where to start and covered all the basics we needed for the class in a single week. The instructor worked perfectly with the time she had. Thanks to her, now I expanded my knowledge in automotive domain."

"*This is the first time in-vehicle communication was offered so I had apprehensions before taking up the class. But, the experience was really great. The lectures, labs were very crisp and clear and even though Professor did not have a regular textbook she gathered all the required material for us.***"**

Assignment	Students' average
Quizzes	83%
Midterm	84%
Lab experiments	85%
Final Project	83%
Final Grade	84%

Table 2: Summary of direct assessment averages.

8. Final remarks

Offering an undergraduate course in intra-vehicle communication, with a supplemental hardware laboratory, has some challenges. In this paper, the author outlined the course content and a few examples of laboratory experiments based on Seed studio CAN shield with MCP2515 CAN Bus Controller board and Arduino Mega 2560. The teaching methods used have proven to be efficient tools in responding successfully to the challenge of teaching an automotive communication course to both Electrical and Mechanical Engineering students. Additional enhancements and improvements are planned for the laboratory experiments. This course can serve as a basis for other advance course in automotive communication and automotive cybersecurity.

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