121st ASEE Annual Conference & Exposition
Indianapolis, IN
June 15-18, 2014
Paper ID #10350

Case study of a Multidisciplinary Engineering Capstone Design Project: Electric Drive Control System

Dr. Amit Shashikant Jariwala, Georgia Institute of Technology

Dr. Jariwala is the Director of Design & Innovation for the School of Mechanical Engineering at Georgia Tech. He graduated with a Bachelors Degree in Production Engineering from the University of Mumbai, India with honors in 2005 and received Masters of Technology degree in Mechanical Engineering in 2007 from IIT Bombay, India. He was awarded a Ph.D. in Mechanical Engineering from Georgia Tech in 2013, with minors in Entrepreneurship. Dr. Jariwala has more than nine years of research experience in modeling, simulation, engineering design, and manufacturing process development, with research focus on design of polymer based micro additive manufacturing process. During his Ph.D. studies, he was also a participant of the innovative TI:GER® program (funded by NSF:IGERT), which prepares students to commercialize high impact scientific research results. Dr. Jariwala has participated and led several research projects from funded by NSF, the State of Georgia and Industry sponsors. At Georgia Tech, he is responsible for enhancing corporate support for design courses, managing design and fabrication/prototyping facilities, coordinating the design competitions/expo and teaching design courses, with a strong focus on creating and enabling multidisciplinary educational experiences.

Dr. Feng Zhou, Georgia Institute of Technology

He is currently pursuing PhD in Mechanical Engineering at The George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology. His research interests include engineering and product design, human Factors for Product Design, and human-computer interaction. He also obtained his PhD degree in human factors in 2012 in Nanyang Technological University, Singapore.

Mr. Wen-hao Zeng, Georgia Institute of Technology

Wen-hao Zeng is currently a graduate student at Georgia Institute of Technology. His major is Computer Engineering with a focus on embedded systems and networking. He is expected to graduate in December 2014. The electric drive control system was his graduation design project for his undergraduate studies in 2013.

Shijiao Li, Georgia Institute of Technology
Mr. Charles Drexler
Mr. chong wang
Mr. Hongrui Zhang, Georgia institute of technology
Dr. Roger Jianinx Jiao, Georgia Institute of Technology

http://www.me.gatech.edu/faculty/jiao

Case study of
A Multidisciplinary Engineering Capstone Design Project: Electric Drive Control System

Abstract

This paper presents the design, development, testing, and validation of an electric drive control system for a multi-motor vehicle with independently driven wheels that can be used as a platform to test an electric car's differential drive function. Due to the time and budget constraints, we designed the electric car with four motors and one Servo, in which each motor supplies power to each wheel and the servo uses Ackermann steering. Furthermore, the control system consists of three components: the Zigbee transmitters, the embedded system, and the electric speed controller. The testing prototype showed its potential and feasibility, and it demonstrated that it could simplify the mechanical layout of future electric cars by connecting the motors directly to the wheels and reduce the number of drivetrain components, thus improving the overall reliability and efficiency.

Furthermore, the paper focuses on the systematic design process used by the multidisciplinary team in order to accomplish the project as a Capstone Senior Design project. The design project was adequately partitioned between the students from the two majors (two students from Mechanical Engineering and two from Electrical and Computer Engineering) to ensure that the entire team could contribute effectively while being able to leverage from the expertise of all team members. Based on the team's experience and faculty interaction, future guidance on how a sustainable model for enabling multidisciplinary Capstone Design projects is also suggested.

Keywords

Multidisciplinary, capstone design, senior design, electric drive control system

Introduction

Like many universities in the country, Capstone Design is a culminating course offered to undergraduate students in several disciplines at the Georgia Institute of Technology. Students work in teams to design, build, and test prototypes with real world applications. At the end of each semester students showcase their efforts at the "Capstone Design Expo". Three of the important outcomes of this capstone experience involve learning about professional ethics, teamwork skills, and design methodologies[1]. Traditionally, at the Georgia Institute of Technology, Capstone Design is monodisciplinary with teams averaging five students from the same engineering discipline on a team (e.g., mechanical, electrical, biomedical, industrial, and aerospace, etc.) from problem definition to an adjudicated exposition of design solutions at the course climax: the Capstone Design Expo[2]. This is not the way products are developed and designed in modern factories where a collaborative exchange of expertise, knowledge, and experience happens across domains, and the outcomes of capstone experiences for monodisciplinary teams would not be as rich as those from multidisciplinary teams. There is an increasing need for organizations to form joint design and development teams across departments to quickly locate, evaluate, and make effective use of the best resources available (e.g., tools, facilities, people)[3]. Miller and Olds[4] have shown that multidisciplinary design teams tend to produce better engineering designs. Howe and Willbarger[5] reported that there was an approximate 14% increase in multidisciplinary design teams from 21% in 1994 in a survey of 1724 programs at 350 institutions to 35% by 2005. Furthermore, Hotaling et al.[2] quantitatively showed that multidisciplinary biomedical and mechanical engineering teams developed higher quality projects or were better prepared for the work force than monodisciplinary biomedical or monodisciplinary mechanical among Georgia Tech Capstone Design teams.

In this paper, a multidisciplinary Capstone Design team was assembled between The George W. Woodruff School of Mechanical Engineering (ME) and The School of Electrical and Computer Engineering (ECE) for the very first time to support the students' desire to work in a multidisciplinary work environment. The Capstone Design Expo at Georgia Tech is an opportunity for student teams to present their projects to solve real-world problems to industry, investors and the general public. Industry experts from corporate partners, alumni, entrepreneurs and faculty are invited to judge the student teams and help decide the winners who typically receive cash awards. The award categories include the best project in each monodisciplinary capstone design course, people's choice award and best multidisciplinary (involving more than one school like ME, ECE, etc.) project out of a total of 125 teams. Typically, there are less than 10% of the total number of teams which are multidisciplinary. A higher probability of winning an award at the expo greatly improved the motivation of the team members to explore ways of working on a multidisciplinary team.

A case study of an electric drive control system for a multi-motor vehicle with independently driven wheels was reported. The team had designed and prototyped an electrical control system platform. This platform was used to test differential drive by applying a different speed to each wheel. The system determines what speeds to apply by reading measurements from the motors' speed sensors. This was done without mechanical components, such as mechanical differentials, differential locks, transmission, transfer case, etc. Two embedded processing units were used to monitor the wheels' speeds. Another embedded processing unit was used to retrieve the speed readings from the other two processing units and make decisions based on those readings. A brushless motor and its controller were attached to each wheel in order to supply torque to each wheel independently. The cooperative Capstone Design experience among the student team was discussed in terms of the design process, teamwork skills, and creativity.

Team Formation

Given that there was no formal multidisciplinary Capstone Design courses within the College of Engineering at Georgia Tech, the team had to face several challenges. The major one was that the team members have to satisfy their own departmental/school requirements in the Capstone Design. However, individual Capstone Design courses were offered in their respective departments. Therefore, the students from ECE were invited to attend the first lecture in ME and introduced themselves to find team-members from ME, and vice-versa. Faculty teaching capstone courses orchestrated a common meeting between the students from various schools and industry sponsors of multidisciplinary capstone projects[6]. The teams also use the Institute-wide multidisciplinary Capstone Design portal or a capstone projects' marketplace (http://capstone.design.gatech.edu), which was launched in Fall 2013 as a Beta version. For this case study, two senior students from ME and three senior students from ECE (one majoring in electrical engineering and two majoring in computer engineering) formed the team. Then they identified one advisor from ME and one from ECE for mentoring. For those students, all the academic requirements within departments were provided online, both ME and ECE. This enabled them to know exactly what to do to satisfy all the requirements. However, whenever the ECE requirements and ME requirements conflict, the students would seek help from their advisors. In this process, the advisor from ECE agreed to follow all the requirements specified by the ME school. Therefore, in the end, the project was generally following the ME requirements. Due to fact that both schools are under the College of Engineering, this simple solution was surprisingly effective and saved a lot of potential confusion.

Case Study

There is a current shift in the automobile market toward electric vehicles. However, the currently most popular electric vehicle, the Tesla Model S, still has a structure similar to that of a conventional vehicle. This design cannot fully utilize the potential of an electric vehicle. Instead, it makes the vehicle even more complex by adding electric modules onto a mechanical system while minimally reducing the number of mechanical components. A fully digitized electrical control system could unleash a higher potential of the electric vehicle. It could dramatically simplify the mechanical layout by connecting the motors directly to the wheels. This design would reduce the number of drivetrain components, thus improving the overall reliability and efficiency. This option also reduces the drivetrain weight since the mechanical differentials are not used[7]. Therefore, the team designed an electric drive control system to test its feasibility and reliability.

Design Process

The design process mainly followed the P&B method[8]; including four phases, namely, planning and clarifying the task, conceptual design, embodiment design, and detail design.

Planning and Clarifying the Task

The first phase of the P&B Method involves product planning as well as the clarification of the task. This phase sets the general direction of the following phases by determining what the problem is. By analyzing the market, the team found possible customer needs that can be satisfied and by analyzing the requirements of Capstone Design, the team looked to possibly diversify its product portfolio or change its design strategy. This analysis led to valuable information which the design team could use to find and select product ideas and to formulate a requirements list for conceptual design.

Extensive research has been devoted to the development of the multi-motor drive control system by the MIT Media Lab. They created a full-scale version of the electric multi-motor vehicle named CityCar[9]. It incorporates the concepts of a folding chassis to occupy a small space when parked, drive-by-wire control, front entry and egress, zero turning radius, and “robot wheels” with integrated electric motors, steering servo, suspension, and braking. The CityCar has a range of over 100 kilometers on one charge and is capable of being rapidly charged using the latest lithium-ion battery technologies. Another research is done by Mercedes-Benz, which in 2012 unveiled the SLS AMG Electric Drive[10]. During the selection and development of the SLS AMG components, special emphasis was put on weight, weight distribution, and center of gravity position. Essential weight potentials arise from light material construction and integrated light construction. The e-machines, drives, and high-voltage batteries were packaged very low on the vehicle, using the installation spaces of the previous transaxle drive.

Although the electric vehicle market is growing very fast due to its several advantages, the batteries' low range and high weight and price are preventing electric vehicles from gaining popularity[11]. Hence, one opportunity to advance the current electric vehicle market could be to simply improve the battery energy density, reduce overall weight, and lower price. Based on the trend that the total price for manufacturing electric vehicles is steadily decreasing, the target price for the electric drive control system should be mainly based on the research and development cost[11]. Research on improving energy density in batteries is currently being performed across numerous universities. For the course project, the team focused on identifying methods to reduce the overall weight of the car by designing and testing an electronic drive control system, instead of the conventional mechanical transmission.

Based on the market research and technical requirements, the design specifications were categorized into two sections – one corresponding to the electronics performance of the car and the other related to the mechanical aspects of the prototype. The overall requirements list developed for the prototype is shown in Table 1. We proposed to design a reduced-scale prototype is because of the time and budget constraints, and what matters most in the project is the functionality of the electrical control system, especially the deferential drive function.

Table 1: Requirements list for vehicle prototype

Parameter	**Requirement**
Length	600 mm
Width	575 mm
Ground clearance	70 mm
Track	500 mm
Wheelbase	453.6 mm
Max turning angle	30 degrees
Drive ratio	1:6.92
Top speed	> 20 m/s (45 mph)
Curb Weight	6.6 kg
Controller response time	<0.1s
Motor response time	<1ms

Conceptual Design

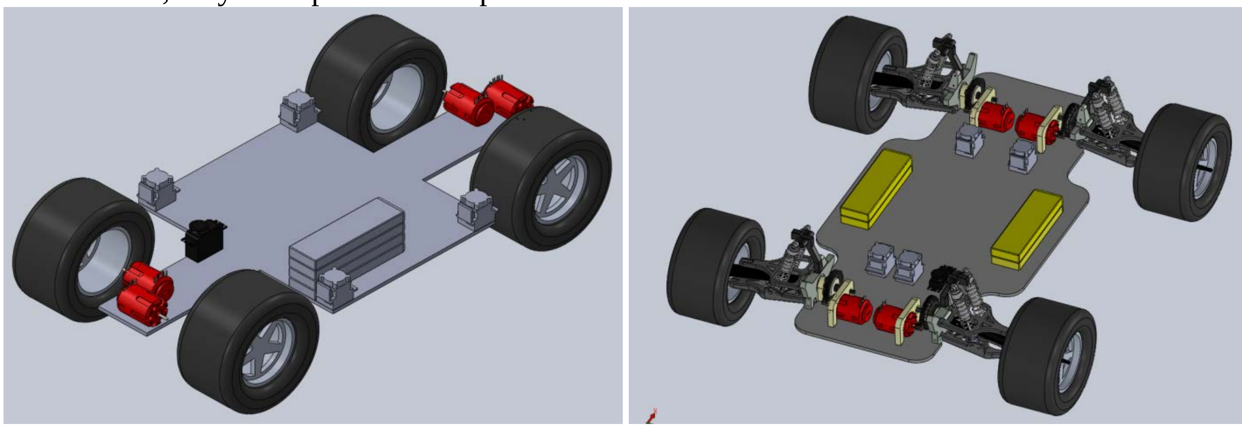
Conceptual design phase helped to determine possible design alternatives based on the requirements list generated in Table 1. The essential problem was identified as design an electric car prototype with wheels controlled by individual motors. Then function structures were established to express different input-output relationships. Working principles were finally proposed and suitable combinations of them are formed and firmed up into principle solution variants. The results were four design alternatives as shown in Table 2. One of the technical challenges with controlling the system is to synchronize multiple motors. Even though the motors and speed controllers have the same manufacturer and model, small but inevitable variations would be introduced during the manufacture process. Thus, even if the motors are all sent the same speed command, their output speeds would be different. Although these errors will be small, they cannot be ignored. Because the behavior of the entire system will be unpredictable, letting these small errors accumulate over a short period of time may lead to failure. Therefore, the balance between the numbers of motors and servos and performance of the vehicle is the key in the concept design.

Table 2: Four design concepts for vehicle prototype

	Concept 1	**Concept 2**	**Concept 3**	**Concept 4**
Specification description	Two motors and one Servo; Two motors would supply power to the two front wheels respectively; The servo would be installed in the front and control the directions of the front wheels.	Four motors and one Servo; Each motor supply power to each wheel; The servo uses Ackermann steering, which has proven to be practical and dependable.	Four motors and two Servos; Two servos could be added to Concept 2.	All-In-One Wheels: Build the suspension and powertrain systems inside the wheel instead of on the side of the chassis.
Advantages	The control system would only need to control two motors; One embedded processor controls the speeds of the front wheels individually to achieve differential drive.	Improve the performance and give better grip; More compatible with autonomous driving vehicles; A simple way to distribute the weight of the vehicle.	Improve the performance further; Greater control of the car; A simple way to distribute the weight of the vehicle.	Greatly improve the quality and ease of maintenance and exchange of engine parts; The body would only be used for control and support.
Disadvantages	Not fully utilize the advantage of an electrical control system.	Need to synchronize four motors instead of two; Requires two processors.	Complicate the design; Time and budget constraints; Additional safety mechanism needed.	The engine is too big to be put inside the wheels; Time and budget constraints.

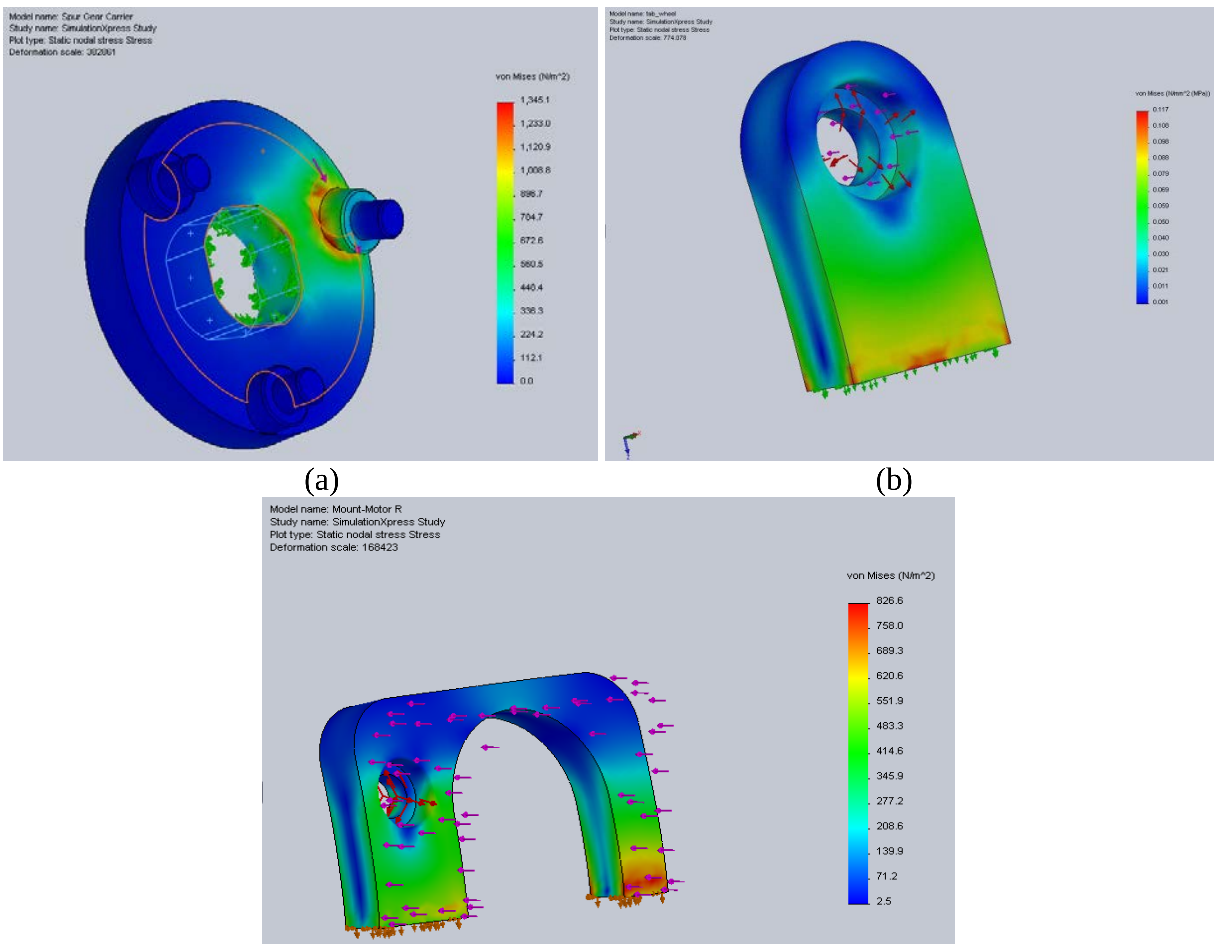
Embodiment Design

Based on the advantages and disadvantages, especially the time and budget requirements, Concept 2 was selected for the capstone project. A preliminary prototype was assembled in Solidworks as shown in Figure 1 (a), based on which, further evaluation checks and optimization of the design were also conducted and the refined prototype was shown in Figure 1 (b). When designing and building the prototype vehicle, many mechanical variables had to be considered to ensure the function as a platform that provides the implementation of the differential systems and the potential for further research. One of the challenges was to make the model run as fast as 45 miles per hour. Both the stress inside the frame and the torque that the motor provides are critical factors to minimize the vibration and meet the speed requirement. Due to limited budget and time, the decision was made to utilize some parts from commercially available remote controlled cars and fabricate the rest of the customized parts, such as the spur gear carrier that connects the spur gear to the output shaft. Mountings and housings that align the motor and output shaft were also 3D printed. The steering arm and shock tower were redesigned to fit the extended track. Then, a stress concentration analysis was conducted to test the design and help select the right material. Stress analyses of the spur gear carrier, wheel side mounting, and motor side mounting were done with SolidWorks as shown in Figure 2. Since these parts are not for structural use but housings and connectors, they were fabricated with ABS plastic and were 3D printed. During various tests, they were proven to be practical.



(a) (b)

Figure 1: (a) Preliminary prototype CAD drawing; (b) Refined prototype CAD drawing



(a) (b)

(c)

Figure 2: (a) Stress analysis of spur gear carrier; (b) Stress analysis of wheel side shaft mounting; (c): Stress analysis of motor side mounting

Figure 3 shows how the pinion gear, motor, spur gear, spur gear carrier and output shaft are connected and how the powertrain system connects the motor to the tire. In this type of design, the whole assembly is treated as one unit, including all the suspension components, powertrain components, and even the power supply. With such a simple configuration, this module can be patterned to every corner of the vehicle. Vehicle maintenance is easy for the whole module to be taken off and replaced.

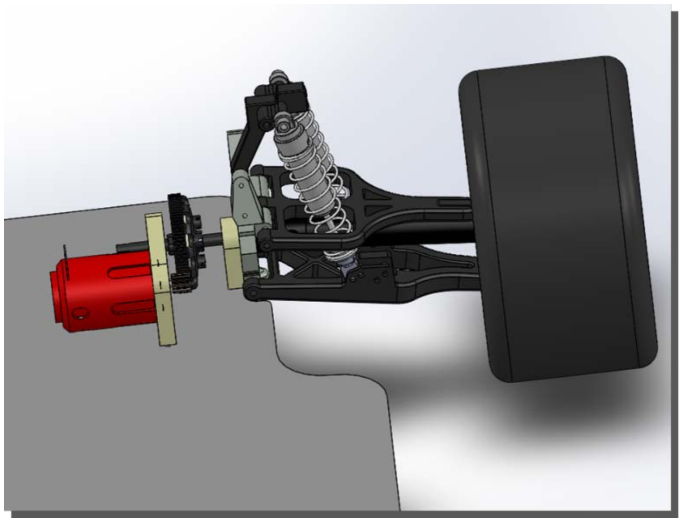


Figure 3: CAD model of powertrain system

Detail Design

During this phase, the details of the design were finalized, and complete detail drawings were drafted. First the *control system design* is shown in Figure 4. It consists of three components: the Zigbee transmitters, the embedded system, and the electric speed controller.

The Zigbee transmitters consist of two parts, with the first part being a laptop with a Zigbee module. Two slider potentiometers are used as the user interface. By sliding the respective potentiometers, speed and heading of the car can be changed. The Zigbee module, which receives raw signals from the potentiometers, automatically transmits the data through 915 MHz radio waves. The signals are formatted according to the Zigbee wireless protocol[12]. The receiver is also a Zigbee module, and it captures the radio waves and reconstructs the raw data from the signals. It is connected to the embedded system through a two-pin connection.

The embedded system consists of three embedded chips: a CPU that acts as a command chip that actively adjusts the speed of each motor, a data collector chip that reads speed data from the two left wheels, and another data collector chip that reads speed data from the two right wheels. To read the data from the speed sensors, each data collector chip has two one-pin connections, both to one of the sensors from which the chip is reading. By recording the voltage spikes generated by the sensors through an analog input, the data collector chip calculates the relative turning speed of the motor. To calculate the turning speed, interrupts are used to measure the period of motor turning. This allows twenty measurements in one second and doubles the sensor's reading rate.

Since the motors are controlled by the output voltages of the speed controllers, four speed controllers are needed to achieve independent speed control for each motor. The speed controllers take in pulse width modulation (PWM) signals from the command chip and adjust their output voltages according to the percentage of high state in the signals. If 8.0% of the PWM signal is in the high state, the output will be 0V, whereas 9.0% of high state in the PWM signal will be translated into the maximum output voltage. The command chip, which actively adjusts the speed of each motor through the controllers, enables electrical control by employing a closed loop control design. By obtaining the turning speed data from the two data chips, the command chip adjusts the voltage supplied by the controller until the turning speed of each wheel is synchronized. The voltages can be changed by linearly increasing or decreasing the high state percentage of the PWM signal.

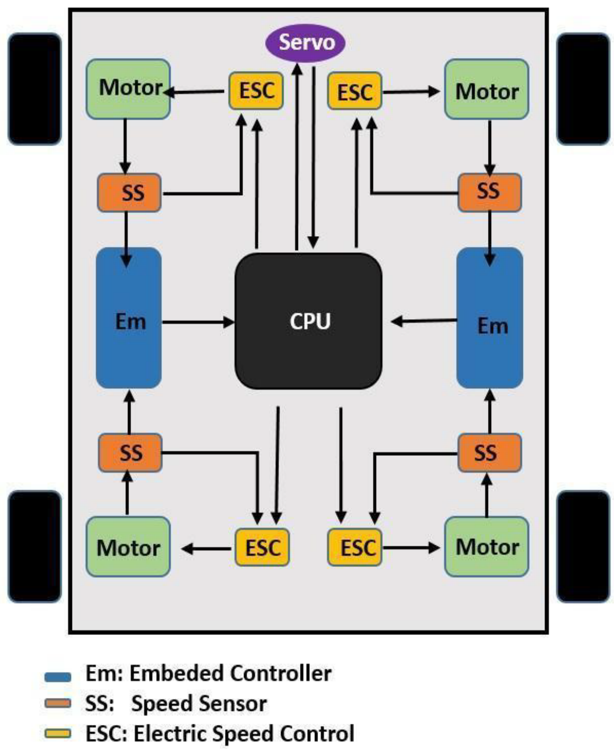


Figure 4: Diagram of electrical control system components

When the vehicle is turning, sliding will happen if all the wheels are turning at the same speed. To avoid sliding, *differential drive* is used. By letting the inner wheels turn at a lower speed while letting the outer wheels turn at a higher speed, all the wheels will be able to follow their tractions. The differential drive is achieved by having four separately driven wheels with synchronized speeds. When the vehicle turns, the CPU will sense the turning action and increase the desired speeds of the outer two wheels and decrease the inner wheels' speeds. Through this control action, the vehicle will be able to make turns without drifting or sliding. This allows for tighter turns even at high speeds.

Third, *the differential drive function* is achieved by setting the turning speeds of the individual wheels according to the turning angle of the vehicle. As shown in Figure 5, R is the turning radius of the vehicle, R_1 is turning radius of rear axle, l is wheelbase, w is the track, δ_i is the front inner wheel turning angle, and δ_o is the front outer wheel turning angle. The angular velocity of the vehicle, ω, can be calculated by dividing the velocity by R. The speed of each wheel can be acquired through the following four equations:

$$V_{ri} = (R_1 - w/2)*V/R, \quad (1)$$

$$V_{ro} = (R_1 + w/2)*V/R, \quad (2)$$

$$V_{fi} = (l/\sin(\delta_i))*V/R, \quad (3)$$

$$V_{fo} = (l/\sin(\delta_o))*V/R, \quad (4)$$

where V_{ri} is the turning speed of the rear inner wheel, V_{ro} is the turning speed of the rear outer wheel, V_{fi} is the turning speed of the front inner wheel, V_{fo} is the turning speed of the front outer wheel, and V is the velocity of the vehicle.

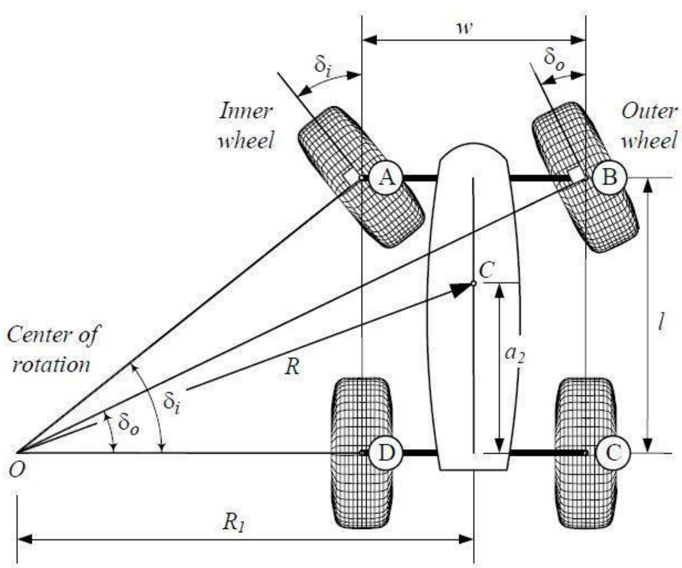


Figure 5: Visualization of differential drive[13]

It requires a good amount of processing resources to directly apply these equations, which would increase the program's run time and thus its response time, reducing the reliability and safety of the entire system. In order to avoid this, pre-calculated tables are used to store the ratio of desired wheel speed to the desired vehicle speed at different turning angles. Four differential tables were used to store these ratios. Each table maps to one of the four wheels and stores an array of the ratios at different turning angles. The command chip acquires the turning angle data and finds the appropriate ratio for each wheel. It then uses these ratios and the desired car speed to calculate each desired wheel speed. Next, it acquires the current wheel speed data from the two data collector chips and adjusts the PWM signal until the actual wheel speeds match the desired wheel speeds. This process is shown as a flowchart in Figure 6.

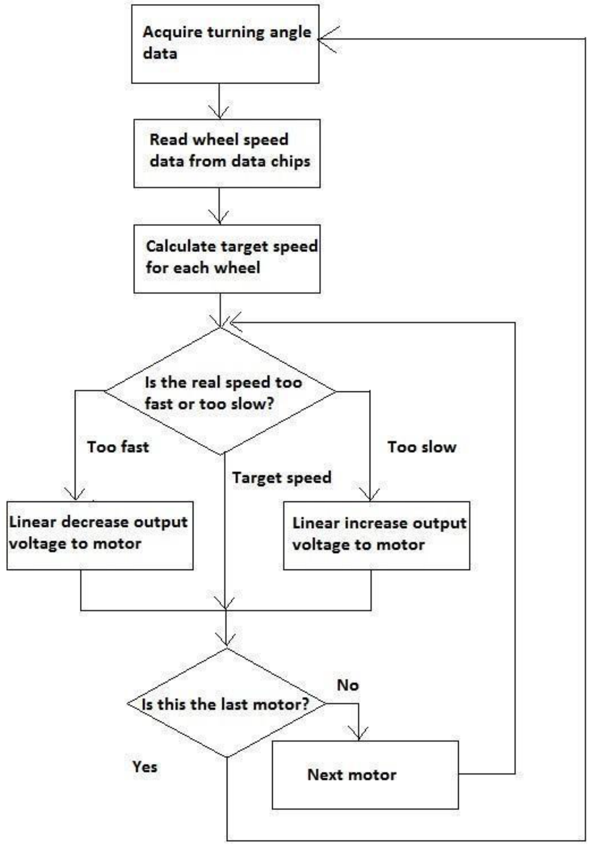


Figure 6: Flowchart to determine the desired speed for wheels

Two electronic circuits were designed and prototyped on a breadboard to implement the drive control. These are shown in Figure 7. The potentiometers could be manually controlled by a user and the Zigbee chip circuit would transmit the signals to the control module. The flowchart was implemented by embedding C Codes into the CPU (specifically the mbed NXP LPC 1768 rapid prototyping microcontroller) of the control module installed on the prototype model car.

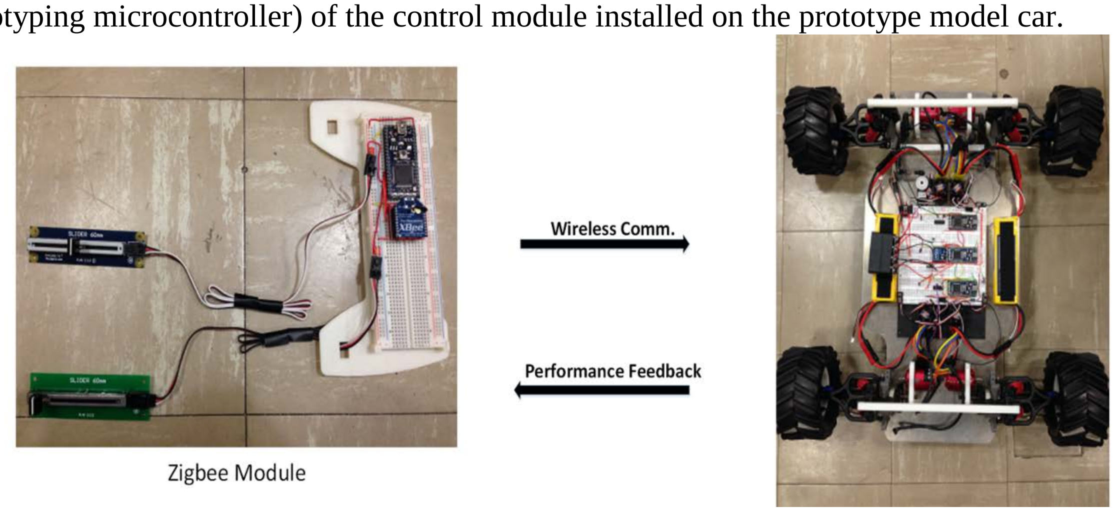


Figure 7: Physical implementation of user interface and control system

Student/Project Assessment

The Capstone/Senior Design course is one of the most important elements for the development and assessment of student professional competencies for ABET accreditation. Faculty from both schools played an important role during the problem formulation phase to ensure that the project scope was adequate to allow students from the two different disciplines to learn and demonstrate their knowledge (ABET Engineering Criterion 3[14] – student outcome 3.a), identify discipline specific engineering requirements for design (ABET Engineering criterion outcome 3.c) and provide opportunities to identify, formulate and solve engineering problems (ABET Engineering criterion outcome 3.e).

The entire ME/ECE student team had regular in-person meetings with the ME faculty advisor and would occasionally seek advice from the ECE faculty advisor. Although this arrangement relatively led to more burden on the ME faculty than the ECE, both instructors were cooperative. Throughout the course of the semester, the team submitted two written progress reports and oral presentations, followed by a final semester end report and a final presentation. To differentiate individual assessment from team assessment, students had to submit peer evaluations as well.

The project was assessed by testing the vehicle running with the differential drive function on and off. By visually comparing the traction of the two runs, the team demonstrated the functionality of their design. Visually, in the turning condition, it showed that when the differential drive function was on, the vehicle ran smoothly with no visible sliding and that when the differential drive function was off, there was sliding. However, no quantitative results were available since the traction varied in different run tests due to different frictions for the different road surfaces.

Multidisciplinary Capstone Design Experience

Design Process

The team worked upon this project by mainly using a problem to solution co-evolution model[15]. The problem space evolved from one design phase to another and accordingly the solution to the problem co-evolved, which led to the final design. Through the development of the project, the team realized some of the initial design was not feasible while some realistic problems were not even thoroughly considered in the first place. For example, the team initially decided to make a life-size prototype of the vehicle. During the initial phases of the project, the ECE faculty advisor strongly advised the team to narrow down the scope of the project. After several in-person discussions among the team members, the following agreements were reached. Firstly, the goal of the project was to show the feasibility of a four-wheel attached motor car. Secondly, due to the goal of the project, the team decided that the size of the vehicle would be a model car size, instead of life-size so that the team could avoid unnecessary difficulties during the prototyping process. Thirdly, the electrical control system, especially the deferential drive function, would be the main focus of the project, since the electrical control system was the most important component of the vehicle, and this component can be easily scaled for life-size cars once it was proven to be functional. After these agreements were reached, the team decided to focus the project on the electrical control system and the differential drive function of the vehicle.

Teamwork
The team was formed with members of different knowledge background: Being mechanical engineering students, Shijiao and Hongrui did the 3D modeling and the fabrication of the chassis; being computer engineering students, Howard and Chong were responsible for the control system of the car. Charles, being an electrical engineering major student, was responsible for testing the electrical components of the car. Hence, the team identified its own strengths and distributed the work load to allow members to work independently whenever possible. The team strategized the tasks to allow enough parallel activities among its different members so that the members had as less dependency as possible. For example, while Charles did the testing of the motors, Shijiao and Hongrui were designing the chassis at the same time. The team maximized the parallel efforts in the schedule to achieve fastest possible progress of the project. Therefore, this team formation essentially formed a community of interests, in which multiple knowledge centers were formed with each member considered to be knowledgeable in a particular aspect of the problem. In such a form, it could turn barriers into opportunities for collaborative design which promotes social creativity[16].

For multidisciplinary teamwork, the team met up every week to discuss the work done and the steps to be taken in order to proceed. Along with meeting face-to-face, the team members also made use of online tools, such as Google docs and Skype video meetings. This enabled to perform seamless online team collaboration, while promoting team creativity. Furthermore, the team collaborated closely during the final assembly of the vehicle. This was because the assembly of the car required a large amount of mechanical work and in-depth testing from the ECE side. Face-to-face communications enabled the team to solve many problems on-site during the test of the vehicle as a whole. Although it was not easy for the team members to establish a shared understanding, this kind of multidisciplinary work approached to the problem successfully by constant communication and collaboration that was not possible by a single discipline. It became increasingly obvious that understanding perfectly what other teammates were doing can avoid potential unnecessary problems and made the project progress substantially faster. For example, the advisor from mechanical engineering was not able to grasp the idea of the project during the first few weeks due to the team's poor communications and presentations. However, not long before the design process started, all the team members were on the same page and presented the design problems and ideas clearly to the advisor, which made the advisor offer effective advice on the design process.

Concluding Remarks

This paper presents a multidisciplinary Capstone Design project in which a case study of the design process of an electric drive control system for a multi-motor vehicle with independently driven wheels was reported. From the testing and validation results, we can see that the prototype is able to achieve the requirements listed in Table 1. However, due to the time and budget constraints, the differential drive function was only assessed visually and it showed that when the differential drive function was on, the vehicle ran smoothly with no visible sliding. We were not able to obtain quantitative results due to the fact that the traction varied in different run tests for different road surfaces.

The team was formed by two students from ME and three students from the ECE at the Georgia Institute of Technology using an internal online project management portal. The motivation factors from students' perspective were to gain more realistic real-world experience and to increase their chances of gaining recognition and reward at the semester end expo. Students participated in an interdisciplinary design environment from idea generation to final assembly and testing. The team identified each individual's knowledge background and skills and distributed leadership on various aspects of the project accordingly. The team was able to effectively contribute to the success of the project by frequent interaction and communication. The team strategized the tasks such that each member could contribute individually by identifying parallel tasks and scheduling them such that they could converge together as a team during weekly meetings and then diverge while performing specialized tasks. Faculty support from both the schools was crucial in making sure that the team participants met their individual school's academic requirements by following a common deliverable guideline.

The final results demonstrated a successful design project. From this specific case study, along with six other multidisciplinary projects that were experimented in the Fall 2013 (all of which had similar successful outcomes), we learned that few essential components for an Institute-wide Capstone Course include – administrative support for team formation (online project marketplace), student motivation (expo), faculty support during problem formulation, uniform set of deliverables, identification of team skills (self-awareness) and effective activity planning and coordination. As we continue to develop a more sustainable model for an Institute-wide course, we have yet to identify a balanced approach for sharing the load of mentoring teams. As suggested by Hotaling et al.[2], we believe that with the incorporation of multidisciplinary Capstone Design across all engineering majors, students would potentially develop more successful and innovative projects and better prepare themselves for the qualities valued in professional practice.

Acknowledgements

We thank all our generous corporate sponsors for their support to our Capstone Design Program: John Deere, Ford, Caterpillar, Lockheed Martin, Bechtel, NCR, Rolls Royce, Whirlpool, Eaton's Cooper Lighting, National Instruments, Integrated Environmental Services, E-Z-Go, Textron, Jacobsen, Coca-Cola, Formetco, Delta, Michelin, Autodesk, Angelica, Southern States, Medtronic, TriVantage, Boeing, Pratt & Whitney, Viracon, Weyerhaeuser, Shell, BP, Panasonic, DKF Investments, CyborFusion, VinoSpout, HarrellNut Company, General Motors, General Electric, and American Fiber.

References

[1] J. Wahlquist, and D. D. Jensen, "Using Mini Design Competitions in Capstone. Courses to Teach the Design Process," in 120th ASEE Annual Conference & Exposition, Atlanta, GA, 2013.

[2] N. Hotaling, B. B. Fasse, L. F. Bost, C. D. Hermann, and C. R. Forest, "A Quantitative Analysis of the Effects of a Multidisciplinary Engineering Capstone Design Course," *Journal of Engineering Education*, vol. 101, no. 4, pp. 630-656, 2012.

[3] L. Leifer, "Design Team Performance: Metrics and the Impact of Technology," *Evaluating corporate training: Models and issues*, S. M. Brown and C. J. Seidner, eds., pp. 297-319: Springer, 1998.

[4] R. L. Miller, and B. M. Olds, "A Model Curriculum for a Capstone Course in Multidisciplinary Engineering Design," *Journal of Engineering Education*, vol. 83, no. 4, pp. 311-316, 1994.

[5] S. Howe, and J. Wilbarger, "2005 National Survey of Engineering Capstone Design Courses," in ASEE Annual Conference and Exposition, Chicago, IL, 2006.

[6] A. Chandak. "Tech student body integrates for capstone," 2013; http://nique.net/life/2013/09/12/tech-student-body-integrates-for-capstone/, 12/31/2013.

[7] B. Tabbache, A. Kheloui, and M. E. H. Benbouzid, "An Adaptive Electric Differential for Electric Vehicles Motion Stabilization," *Vehicular Technology, IEEE Transactions on*, vol. 60, no. 1, pp. 104-110, 2011.

[8] G. Pahl, and W. Beitz, *Engineering design: A Systematic Approach*, London, UK: Springer, 2007.

[9] P. Patton, "M.I.T. CityCar, Renamed Hiriko, Is Headed to Production," *New York Times*, 2012.

[10] J. Feustel, S. Land, and M. Hand, "The Electric Super Sport Car SLS AMG Electric Drive," *Springer Automotive Media*, vol. 115, no. Jan, pp. 4-10, 2013.

[11] D. Anderson, "An Evaluation of Current and Future Costs for Lithium-Ion Batteries for Use in Electrified Vehicle Powertrains," Master Thesis, Nicholas School of the Environment, Duke University, 2009.

[12] "IEEE Wireless Personal Network Standard, IEEE Standard 802.15," 2013.

[13] R. N. Jazar, "Steering Dynamics," *Vehicle Dynamics: Theory and Application*, pp. 379-454: Springer US, 2008.

[14] "Criteria for Accrediting Engineering Programs," http://www.abet.org/uploadedFiles/Accreditation/Accreditation_Process/Accreditation_Documents/Current/eac-criteria-2012-2013.pdf, 12/31/2013.

[15] K. Dorst, and N. Cross, "Creativity in the design process: co-evolution of problem–solution," *Design Studies*, vol. 22, no. 5, pp. 425-437, 2001.

[16] G. Fischer, "Social creativity: turning barriers into opportunities for collaborative design," in Proceedings of the eighth conference on Participatory design: Artful integration: interweaving media, materials and practices - Volume 1, Toronto, Ontario, Canada, pp. 152-161, 2004.