BRADLEY
UNIVERSITY

Design of a Simulink-Based Control Workstation for Mobile Wheeled Vehicles with Variable-Velocity Differential Motor Drives

Kevin Block, Timothy De Pasion, Benjamin Roos, Alexander Schmidt

Dr. Gary Dempsey

Electrical Engineering Department

October 15, 2015

EXECUTIVE SUMMARY

Direct current (DC) electric motors are plagued with nonlinear characteristics when applied in low velocity applications. These nonlinearities, as well as the effects of various internal and external disturbances, can be reduced when closed loop control algorithms are applied. Unfortunately, designing, developing, and implementing control algorithms can be an arduous and expensive project.

The goal of this project is to provide the faculty and students of the Bradley University Department of Electrical and Computer Engineering with a research and development tool for performing the aforementioned tasks. This tool will take the form of a control workstation that is composed of three subsystems: a Simulink based vehicle model, an experimental platform for implementation, and a graphical user interface (GUI) for integrating the other two subsystems.

The Simulink based vehicle model is based on a theoretical vehicle. This theoretical vehicle is designed with components that are commonly used in autonomous wheeled mobile vehicle applications. Detailed kinematic and dynamic models will be developed based upon the theoretical vehicle. The vehicle models along with other modeled components such as a DC motor platform will then be utilized to develop a control algorithm for the vehicle. The motor platform model will incorporate a model for cogging torque, one of the more complex nonlinearities inherent in the motor. The incorporation of the dynamic vehicle model as well as cogging torque into the controller development is what sets this project apart from similar systems.

In order to provide data for comparison with the Simulink model, an experimental platform is going to be designed and developed simultaneously. The experimental platform is composed of an ATmega128 microcontroller, four DC motors, rotary encoders, and a dual H-bridge package. The ATmega128 will contain the controller software as well as any code needed to communicate with the GUI. The DC motors will be paired into two motor-generator sets. The motors will provide the rotational motion and the generators will provide opposition torque to the motors thus simulating that the motors are operating the theoretical vehicle. The rotary encoders provide feedback to the controller and the H-bridges step up the voltage and current coming from the microcontroller.

In order for the workstation to be usable for the students and faculty it will be integrated into a single GUI on a lab computer. The GUI will be created using MATLAB and designed to be user friendly. Because the GUI will be created in MATLAB, it is able to communicate natively with the Simulink models and via serial communication with the ATmega128.

Some of the major costs for this project are: MATLAB/Simulink licenses, DC motors, and microcontroller development boards. The total cost of this project is $5,987 with $100 for miscellaneous testing equipment. Fortunately, the Department of Electrical and Computer Engineering at Bradley already has the majority of the components in stock. The net total cost of this project is the $100 for miscellaneous expenditures of components not in stock.

ABSTRACT

A differential drive system consisting of two direct current motors can be utilized in mobile wheeled vehicles for forward, reverse, and steering operating modes, but are plagued with nonlinear characteristics in low velocity applications. Static and Coulomb friction are the most well documented of these nonlinear effects; however, cogging torque and encoder resolution can also have a significant role at low velocity. A common method of controlling differential drive systems is proportional, integral, and derivative (PID) control. When PID control is used in conjunction with a model-based design approach, the effects of the aforementioned nonlinear characteristics can be reduced. The purpose of this project is to design and implement a Simulink-based workstation that will be utilized in the development, simulation, and implementation of model-based controllers for differential drive systems. The workstation will consist of two primary subsystems: the Simulink subsystem and the experimental platform. The Simulink subsystem will consist of dynamic and kinematic models of a theoretical vehicle as well as a cogging torque model. The experimental platform will consist of two motors and two generators to simulate the theoretical vehicle models. The experimental platform will be controlled by a microcontroller and communicate with Simulink via serial communication through MATLAB®.

I. INTRODUCTION

A. Problem Background

A differential drive consisting of two direct current (DC) motors is often utilized in mobile wheeled vehicles for forward, reverse, and steering operating modes [1]. DC gear-head motors with integrated rotary encoders are normally used in these applications because of their low cost and the ability for proper matching to load conditions and desired vehicle velocities [2]. The controller and power electronics for this type of system are low cost and usually consist of a microcontroller and a dual H-bridge interface. Closed-loop velocity control can be implemented in software and high power efficiency is possible by utilizing pulse-width modulation to drive the motors.

Proportional plus integral (PI) control strategies are commonly used in differential drive systems because controllers minimize the effects of external disturbances due to motor mismatch, battery supply variation, vehicle payload, and terrain changes [3]. Typically, the PI controller is tuned to minimize steady-state error as well as settling time; however, they are not specifically tuned for optimal rejection of disturbances in most applications. Better control systems can be designed if motor nonlinearities are identified and used to develop model-based control algorithms. The best results are yielded when these algorithms are used in conjunction with PI tuning methods. Adaptive controllers can also improve performance in systems with strong nonlinearities [7, 11-13]. Identification of the nonlinear parameters can be used to explain differences between predicted and actual system performance, which is critical for high-volume applications [4-10].

Although nonlinear characteristics exist in motor drive systems, the three friction (static, Coulomb, and linear viscous) parameter model is considered adequate for the majority of velocity control applications [4]. Nonlinearities such as Stribeck friction [3], cogging torque [14], and rotary encoder resolution [15] become more important in position control and low-velocity applications. Cogging torque results from the interaction between the motor's permanent magnets and the commutator segments. The effect of this nonlinearity is observed as torque or velocity ripple. In velocity control applications, this ripple results in loss of accuracy at low velocities. At medium and high velocities, cogging torque is filtered by the motor's inertia. The part of a closed-loop control system that is the most sensitive to these non-linear effects is the feedback sensor [4]. The quantization error of the rotary encoder will limit the overall accuracy of the velocity or position measurement. It is noted that many motor and sensor nonlinearities can be minimized by purchasing higher cost motors equipped with high resolution rotary encoders.

As previously mentioned, model-based control algorithms can be implemented to reduce motor and vehicle nonlinearities without purchasing higher cost motor platforms; however, in order to reduce vehicle nonlinearities a vehicle model must be developed. Vehicle modeling involves the design of a software or mathematical representation of a physical vehicle. Vehicle models are used in advanced control methods to improve path following [1, 3]. In addition to reducing nonlinearities and improving path following, the vehicle model can be used as a test bed for the differential drive control algorithms. An ideal vehicle test bed would consist of a dynamic and kinematic model [3].

Simulink is one of the most popular platforms for physical system modeling [16]. Publications exist for modeling mobile wheeled vehicles in the Simulink environment; however, the majority of these publications do not include all of the nonlinear characteristics of the drive system at low velocities [3]. Typically, the vehicle models include a kinematic subsystem, but neglect the effect of dynamics (mass, inertia, friction). Simulink is being used by companies such as Caterpillar Incorporated, Northrop-Grumman, and Boeing to model complete products. Many of these large-scale products require years to develop actual prototypes for engineering testing. Development of a physical system model in the Simulink environment allows multiple engineers to work on their individual subsystems. In many cases, the vehicle or aircraft must be designed in simulation first to minimize engineering costs.

B. Problem Statement

The project objective is to design a control workstation that consists of a Simulink model, an experimental platform, and a graphical user interface (GUI). The Simulink model will accurately depict a physical differential steering control system used in wheeled mobile vehicle applications. The model will include nonlinear motor and sensor characteristics that are present at low velocity as well as a dynamic and kinematic vehicle subsystem. This subsystem will be used to test the tracking performance of the steering control system under various modeled internal and external disturbances such as motor mismatch, vehicle mass and inertia, battery supply changes, and terrain variations. Model-based control algorithms will be developed to reduce the effect of these nonlinearities and disturbances. The best algorithm will be included in the final Simulink product. The experimental platform will be a physical system capable of simulating the use of the theoretical vehicle being modeled in Simulink. The primary components of the experimental platform are four DC brushed motors and an 8-bit microcontroller. The experimental platform will be low-cost and designed to accommodate variable speeds, variable loads, operate reliably over a wide temperature range, and have the ability to minimize the effects of internal and external disturbances. The GUI will be used to control the Simulink model and the experimental platform and will also be used to monitor either system as they operate.

C. Constraints

The constraints in Table I were defined by discussions with Dr. Gary Dempsey.

TABLE I. CONSTRAINTS OF THE PROJECT

Constraints
24 volt pittman motor
8-bit microcontroller
Operate in an ambient temperature range of 0° to 45° Celsius
Blocks and functions from standard Simulink library
Stable
Safe
Commands limited to prevent saturation
Controlled by GUI

The first two constraints deal with the limitations of the physical components of the system. The next five constraints deal with how the system is going to operate and how it will respond to different types of situations. Those five constraints are needed to insure that the control workstation is useable by other individuals and that it can be used repeatedly and provide consistent results over many different tests.

D. Scope

Only linear control methods will be included in the scope of this project, but if time permits, non-linear control methods will be the first priority to investigate. Wheel slip, motor windage, and a three dimensional vehicle model will also be considered out of scope for the modeling aspect of this project. For a complete list of what is in project scope and what is out of scope, please refer to Table II.

TABLE II. TABLE OF SCOPE

Scope	
In Scope	**Out of Scope**
Proportional, integral, and derivative control	State-variable control
Feed-forward control	Bumpless control
Cogging torque modeling	Other non-linear control methods
Static friction modeling	Wheel slip
Coulomb friction modeling	Motor windage
Thermal considerations for motor and H-bridge	3D vehicle model
Dynamic vehicle model	Uneven terrain
Kinematic vehicle model	3th order and higher inputs
Rotary encoder	Bidirectional generator current source
Pulse width modulation	
H-Bridge	
Thermal model of motor	
Thermal model of H-Bridge	
Battery supply changes	
Step inputs	
Ramp inputs	
Parabolic inputs	
Even terrain	

II. STATEMENT OF WORK

A. *System Description*

1) System Block Diagram (Black Box)

A system block diagram or black box can be seen in Fig. 3 in Appendix A. The inputs to the black box are a user input of an unspecified quantity as well as power. The user input indicates that there will be user control of the system; however, the exact amount of control the user will have is not yet defined. The second input, power, is the electricity from an electrical outlet or battery that will provide energy for the system to operate. There are two different output lines coming from the black box. One output line is a set a vehicle attributes. This output consists of position *X*, position *Y*, velocity, acceleration, and orientation of the vehicle. These five outputs are the attributes of the theoretical vehicle that will be measured in testing. The other output is the physical rotational motion of the motors.

2) *Subsystem Block Diagram (Glass Box)*

The glass box of the system can be seen in Fig. 1 and contains three subsystems: the Simulink model, the experimental platform, and the GUI. The Simulink model contains the theoretical vehicle and the differential drive system. The experimental platform is a physical mock-up that will be used to implement the models and control algorithm developed in the Simulink model. The platform consists of a variety of components such as: two 24 volt Pittman Motor GM9236S015-R1 DC motors, two DC generators that are the same model number as the DC motors, a dual H-bridge/pulse-width modulation (PWM) interface, a microcontroller that contains the control algorithm and communication software, and two rotary encoders. The GUI subsystem is the connection between the two other subsystems; it takes user input from the user of the workstation and communicates it to both the Simulink subsystem and the experimental platform. The GUI sends velocity and disturbance commands to both the Simulink models and the experimental platform. In return, the GUI receives motor velocity data from the experimental platform and can use that to calculate various parameters of the theoretical vehicle. The Simulink model returns those same parameters; however, it is able to calculate them prior to sending them. The GUI then takes the information that it receives from the two other subsystems and displays it to the user.

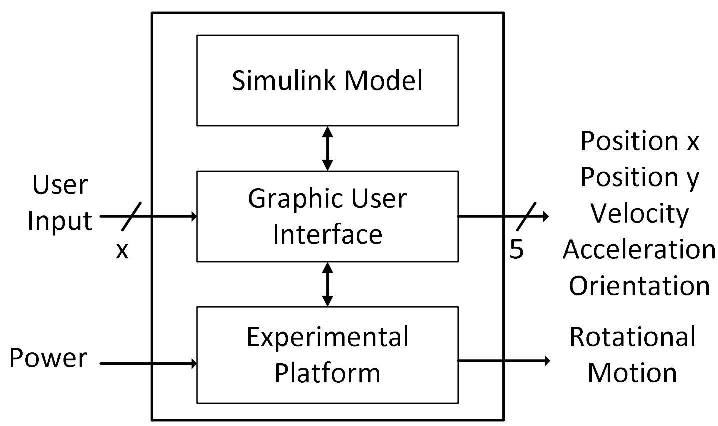

Fig. 1. Glass box of the entire system

The initial glass box in Fig. 1 can be further subdivided into two other glass boxes based on the Simulink model and the experimental platform. The glass box in Appendix B, Fig. 4 is of the Simulink model. The different blocks in Appendix B, Fig. 4 will all be modeled in Simulink and the only input into the system is the user input. This user input goes into the differential motor model and the generator set/dynamic model, which together is called the motor coupling. The user input causes left and right rotational velocity to be produced from the motor coupling. The rotational velocity is sensed by the rotary encoder model, which converts the rotational velocity into pulses per rotation. The measurement of pulses per rotation is an input into the controller block, which will actually hold the control algorithm that will regulate the differential drive system model. The output of the controller is a voltage or PWM command, which will feed into the H-Bridge model, which will in turn control the differential motor model through a voltage input. The rotational velocity is also fed into the vehicle kinematic model which converts the rotational velocity into translational velocity, position *X*, position *Y*, acceleration, and orientation of the vehicle.

Figure 5 in Appendix B shows the glass box of the experimental platform. The inputs into the system are user input and power. The microcontroller receives power from the power input and user input from an RS-232 serial communication port. The microcontroller communicates with the H-Bridge/PWM interface and the generator set/current source. The microcontroller outputs are the motor PWM and the generator PWM, which go the H-Bridge interface and the generator set, respectively. The microcontroller also outputs an inter-integrated circuit (I^2C) signal, which goes into an external digital to analog converter (DAC), which will be used for debugging and testing. The H-Bridge steps up the voltage from the microcontroller to a voltage range that can control the motor over a wide velocity range. The motor platform is coupled to the generator set/current source. The generator set/current source introduces a torque load to the motors to simulate different driving conditions for the motors. The motor platform and the generator set/current source together are called the motor/generator coupling. The generator set causes a change in the motor rotational velocity, and that changed rotational velocity is sensed by the rotary encoder, which translates the rotational velocity into pulses per second. The output of the rotary encoder feeds back into the microcontroller, which is used in the control algorithm to adjust the velocity of the motor.

3) System State Diagram

A high-level state diagram of the system can be seen in Fig. 2. The software consists of four states: *initialization*, the *operating state*, the *read data state*, and the *motor state*. Initialization prepares the microcontroller for serial communication with the GUI and sets up the motor and generator PWM outputs. The software will hold in the operating state until it receives an interrupt command. Depending on the source of the command, the software will move to either the Read Data State or the Motor State. The software should be spending a small amount of time in the Operating State. When in the Read Data State, the software will communicate with the GUI via serial communication. When in the Motor State, the software will be performing the controller algorithm calculations as well as modifying the PWM outputs. The vast majority of software time will be spent in the Motor State as the controller algorithm is computationally intensive.

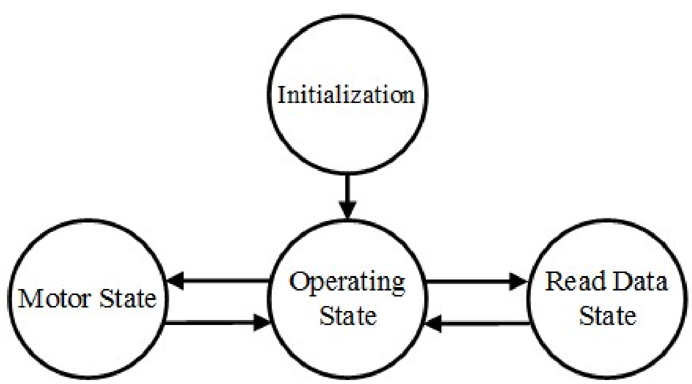

Fig. 2. State Diagram of the microcontroller

4) *Nonfunctional Requirements*

The nonfunctional requirements of the project can be seen in Table III. There are three nonfunctional requirements for the project; they are listed in order of importance from most to least important. Each of the three nonfunctional requirements has a metric which can be seen in Appendix C.

TABLE III. NONFUNCTIONAL REQUIREMENTS OF THE SYSTEM

Nonfunctional Requirements
The experimental platform and Simulink model should be reliable
The velocity command should be easy to issue to the Simulink model and experimental platform
The load of the Simulink model and experimental platform should be easy to manipulate

The first nonfunctional requirement is that the experimental platform and Simulink model shall be reliable. Reliability means that the systems shall provide results within a specified accuracy when operating within a specified range. The second nonfunctional requirement is that the velocity command shall be easy to issue to the Simulink model and the experimental platform. This means that the user should experience minimal difficulty when issuing a velocity command. The third nonfunctional requirement is that the load of the Simulink model and experimental platform shall be easy to manipulate. This nonfunctional requirement means that the load of the system is easy to interchange and that the user can change it without difficulty.

5) *Functional Requirements*

The project has three different subsystems. The three subsystems are: the Simulink subsystem, the experimental platform subsystem, and the GUI subsystem. These three subsystems, when combined, make up the overall system. The functions that correspond to each subsystem can be seen in Table IV. The first subsystem in the project is the Simulink subsystem. This subsystem has five functions, each of the five functions deal with how the Simulink system will model the theoretical vehicle. The five functions all have a specification that starts with the phrase “Model to within…” This phrase means that the Simulink model will have the same result as the experimental platform within a certain percentage. The second subsystem is the experimental platform subsystem. This subsystem has only one function and it relates to the DC generator loads. The specification for this function also starts with the phrase “Model to within…” and it means that the DC generator loads will be the same to within ±50% as the theoretical vehicle torque disturbances. The third group of functions relate to the overall system. There are four functions in this section, two of the specifications for the functions start with the phrase “Difference between input and output of….” These specifications mean that if there is an error of some sort due to an input command, then the output will match the input command to within the specified value. The other type of specification for the controller subsystem is a specification that starts with the phrase “Shaft rotations per minute (RPM) change of….” This phrase means that if there is a change that occurs to the system due to external torque or some other source that the controller will make sure that the RPM does not change outside of the specified range.

TABLE IV. TABLE OF SUBSYSTEMS, THEIR FUNCTIONS, AND SPECIFICATIONS

System	Function	Specification
Simulink Subsystem	The Simulink Motor model shall accurately model the physical motors	Performance Specification: Model to within ±20%
Simulink Subsystem	The rotary encoder shall be accurately modeled	Performance Specification: Model to within ±20%
Simulink Subsystem	Cogging torque shall be accurately modeled	Performance Specification: Model to within ±50%
Simulink Subsystem	Pulse-width modulation shall be accurately modeled	Performance Specification: Model to within ±20%
Simulink Subsystem	Simulink H-Bridge model shall accurately model the physical H-Bridge	Performance Specification: Model to within ±20%
Experimental Platform Subsystem	The DC geneartor loads shall be designed to mimic the prototype vehicle	Performance Specification: Model to within ±50%
Overall	The drive control system shall minimize the effect of external torque disturbances	Performance Specification: Shaft RPM change of less than or equal to 40%
Overall	The drive control system shall reduce vehicle tracking errors for step and ramp commands	Performance Specification: Difference between input and output of less than or equal to 20%
Overall	The drive control system shall reduce vehicle tracking errors for parabolic commands	Performance Specification: Difference between input and output of less than or equal to 40%
Overall	The drive control system shall reduce the effects of motor mismatch	Performance Specification: Shaft RPM change of less than or equal to 15%
Graphical User Interface Subsystem	The graphical user interface shall send and receive commands	Interface Performance Specification: Communicate successfully with the Simulink model and experimental platform

B. *Design Approach and Method of Solution*

The proposed design for the project consists of the three subsystems seen in Fig. 1: the Simulink subsystem, the experimental platform, and the GUI. The design that was chosen uses a PID model-based controller with feed-forward compensation, RS-232 serial communication, a current source, LMD18200 H-Bridge, ATmega128 microcontroller, a combination of standard library blocks and equation-based models for Simulink, and Simulink for the design and implementation of the vehicle kinematic and dynamic models. This design will allow the team to use their experience and expertise to efficiently complete the project. Along with that, the combinations of different parts were analyzed to insure that the specifications of the different parts met the constraints and requirements of the project.

1) Simulink Model

The Simulink system will model all of the experimental platform hardware, the vehicle's motors, and the vehicle kinematic and dynamic subsystems. Vehicle modeling research is required to accurately determine the number of forces to be represented in the dynamic model, including gravity and friction. Nonlinear motor characteristics such as friction forces and cogging torque will also be modeled. Cogging torque will be modeled based on physical motor measurements, and research on best practices for modeling and measurement is underway. A project constraint is to only use standard Simulink library blocks to make the final product accessible to a wider range of interested researchers or academic institutions.

2) *Experimental Platform*

The experimental platform shall consist of two motors each coupled to an additional motor acting as a generator. These motors shall simulate the vehicle's differential drive, and the generators will produce the opposition torque required to mimic the combination of the vehicle's dynamic model and terrain disturbances. Induced voltage from rotation of the generators can be used to power an impedance load, generating current and therefore opposition torque. This opposition torque will be a function of both the vehicle dynamic model and the terrain material and grade, so the opposition current must be a function of both motor speed and an added active load. This active load current source will be realized with the use of an op-amp voltage follower controlling a bipolar junction transistor, offering precise current control. A schematic of the system can be seen in Appendix H, Fig. 10. A digital filter may be used on a current source input into the generators to create dynamic and more realistic vehicle torque disturbances such as a gradual change in slope. An alternative load generation method would be to use a bank of relay-switched resistors for a given desired current. This system was ultimately not chosen because it offers lower torque disturbance resolution and requires a higher number of components as well as control inputs. A schematic of the alternative current control system can be seen in Appendix H, Fig. 11.

The experimental platform will be integrated through an ATmega128 microcontroller. The microcontroller will be programmed with the control algorithm and will handle all communication with the GUI via RS-232 communication. The use of an Intel 8051 architecture microcontroller was briefly considered; however, due to the faculty and student experience with the ATmega128 in the department it was decided to use the ATmega128.

3) *Graphical User Interface*

A GUI will be used to integrate the Simulink models and the experimental platform. The GUI will be developed in MATLAB as that will allow it to communicate natively with the Simulink models. In addition, MATLAB has integrated tools for communicating via serial; therefore, the experimental platform will be able to communicate directly to the GUI. Creating the GUI via Java or Excel was briefly considered an option; however, the team has no experience making GUIs in Java and neither Java nor Excel has integrated tools for communicating with either Simulink or via RS-232.

4) *Testing*

The Simulink and experimental platform will be tested in a variety of different ways. There will be tests that compare the error between parts of the experimental platform and their corresponding Simulink models. There will also be tests that exist in only Simulink and in only the experimental platform. There are some constants that will exist in all of the different tests. The most important constant is that the range that the entire system shall operate over is 20 RPM to 400 RPM. A detailed testing plan for each of the functions can be seen in Appendix D.

C. *Economic Analysis*

The cost of the project can be seen in Appendix E in Table V. The total cost of the project is \$5,987.00. The most expensive items that are needed for the project are the software licenses required for MATLAB/Simulink, which cost \$1,000 each, and the motors, which cost \$283 each. There are four licenses needed for MATLAB/Simulink and five motors needed. Those two items account for the majority of the cost that is associated with the project. One assumption that was made during the project formulation was that Bradley University will have most of the items needed for the project in stock (\$5,887.00 worth of items) so the total cost of the project is only \$100.00 (\$5,987.00-\$5,887.00) for the cost of miscellaneous items. The project will be funded by the Electrical and Computer Engineering Department at Bradley University.

D. *Project Timeline*

A timeline for the work to be completed in the project is essential to be able to finish the project in an efficient and timely manner. A high-level Gantt chart can be seen in Fig. 7 in Appendix F with the milestones and major parts of the project that must be accomplished to have a finished product. Along with the milestones of the project itself, there are also major deliverables in ECE498/499 that can be seen in Fig. 7 in Appendix F. The milestones in the project are the critical path that will need to be followed to assure successful completion of the project. This critical path includes the individual component research and modeling, the Simulink integration, the experimental platform integration, controller development, individual testing of the different subsystems, integration of the Simulink system and the experimental platform together, and lastly the testing of the integrated Simulink and experimental platform. The major deliverables that have to be completed for ECE 498/499 are the project proposal presentation and paper, the project webpage, the two progress presentations, the project demonstration, the final presentation, the final paper, and the poster presentation.

E. *Division of Labor*

Assigning tasks to certain members of a team is essential to meeting the final deadline and to produce a good final product. For this project there are four main areas of work. Alexander Schmidt will be working with cogging torque and modeling the physical motors. Benjamin Roos will be responsible for the generator load that will be applied to the experimental system. Kevin Block will handle the communication between the Simulink model and the experimental platform. Timothy De Pasion will be responsible for the vehicle design and modeling along with rotary encoder resolution methods and models. All team members are involved with creating Simulink models of the different parts of the experimental system. The controller development for the project will be completed by all four members of the team, while Kevin Block will program the control algorithm in the microcontroller. A high level table of the division of labor can be seen in Table VI of Appendix G. A detailed task list of the project and who is going to be assigned to each task can be found in Table VII and Table VIII of Appendix G.

F. *Societal and Environmental Impacts*

The workstation that is to be this project's final product is intended to be used as a research tool and an educational aid for students or professional engineers developing control systems for differential drive vehicles. It is possible that the workstation could be used to perform unethical research such as research aimed at weaponizing robots with malicious intent. It is important to note that this is a characteristic of any product created for research purposes and that it can be considered unlikely that the results of this project will be used in an unethical manner.

There are some small risks associated with use of the workstation. As with any product that has moving parts there is the potential for pinching while using the workstation. This risk should be mitigated by placing all of the workstation's controls within the GUI that will be located on a laboratory computer; by doing so there should be little reason that a user would need to manipulate the actual experimental platform. There is also the potential risk of electrical shock that exists with any product that requires an external power supply. It will be assumed that any individual that will be using the workstation will have adequate electrical safety training to mitigate the risk of shock.

The workstation provides an efficient solution for developing control algorithms which can then be applied to improve the efficiency of other products. Energy efficient engineering solutions are becoming increasingly more important as societal opinion moves in favor of conservation. Even the use of small amounts of energy being wasted, when extrapolated by the whole of the population, can amass to huge amounts of pollution. Through the use of control algorithms the energy efficiency of an electric motor can be increased. These control algorithms are especially important considering that more than 50% of all electricity produced is consumed by electric motors [17]. If a model based approach is used when developing control algorithms other factors such as thermal and efficiency characteristics for power electronics and motors can be considered. Furthermore, if these characteristics are considered the efficiency of the electronics and motors can be even further improved. As society transitions from combustion engines to electric motors, the percentage of power consumed by motors will only continue increasing. This trend makes being able to develop control algorithms quickly and efficiently even more important.

III. SUMMARY/CONCLUSIONS

In summation, a control workstation is being developed to provide the faculty and staff at Bradley University with a tool for researching and learning about control algorithms. The workstation will be composed of three subsystems: a Simulink model, an experimental platform, and a GUI for integration.
The workstation will serve as a platform for future research as well as an educational aid for future Electrical Engineering students at Bradley University. The inclusion of a vehicle dynamic model as well a model of cogging torque is the significant advantage to using this platform over other similar products. In addition, the GUI will be designed with a user focus to further facilitate the workstation's educational function. Some of the key topics covered by this project are: modeling, controller development, system integration, team coordination, and circuit design. The team members will benefit significantly from the experience gained in these topics.

IV. REFERENCES

[1] M. Niţulescu, “Theoretical Aspects in Wheeled Mobile Robot Control”, IEEE International Conference on Automation, Quality and Testing, Robotics, May 2008.
[2] Edouard Ivanjko, Toni Petrinic, Ivan Petrovic, “Modeling of Mobile Robot Dynamics”, University of Zagreb, Faculty of Electrical Engineering and Computing 10000 Zagreb, Unska 3, Croatia, http://www.researchgate.net/profile/Edouard_Ivanjko/publication/228561343_ Modelling_ of_Mobile_Robot_Dynamics/links/004635256b78692e72000000.pdf
[3] J. Cˇerkala, A. Jadlovská, “Mobile Robot Dynamics with Friction in Simulink”, Department of Cybernetics and Artificial Intelligence, Faculty of Electrical Engineering and Informatics, Technical University of Košice, Slovak Republic, http://www2.humusoft.cz/www/papers/ tcb2014/016_cerkala.pdf
[4] Gary Dempsey, “ECE 441 Control Theory I Workbook”, Bradley University, Electrical & Computer Engineering Department, August 2014.
[5] Gary Dempsey, “ECE 442 Control Theory II Workbook”, Bradley University, Electrical & Computer Engineering Department, January 2015.
[6] Michael Barngrover, “Investigation of Precision Modeling and Control for Plants with High Degrees of Friction and Load Variation”, MSEE Thesis, Electrical and Computer Engineering Department, Bradley University, August 2007.
[7] Rukmani Ayyempet Mohanganesh, "Control Methods for Precise Positioning of a 2-DOF Robot Arm System," MSEE Design Project, Electrical and Computer Engineering Department, Bradley University, December 2011.
[8] Simon Benik and Adam Olson, "DC Motor-Clutch-Generator Control Workstation," Bradley University, Electrical & Computer Engineering Senior Project, 2006-2007.
[9] Andrew Fouts and Kurtis Liggett, “An Observer-based Engine/Cooling Control System”, Senior Capstone Project, Electrical and Computer Engineering Department, Bradley University, May 2011.
[10] C. Edwards and E. Smith, “A Design of a Simulink-Based 2-DOF Robot Arm Control Workstation”, Bradley University, Electrical & Computer Engineering Senior Project, May 2007, http://cegt201.bradley.edu/projects/proj2007/twodofra/
[11] Manfred Meissner and Christopher Spevacek, "Implementation of Conventional and Neural Controllers Using Position and Velocity Feedback," Bradley University, Electrical & Computer Engineering Senior Project, 1999-2000.
[12] Gary Dempsey, "Using Conventional Controllers with the CMAC Neural Network," Proceedings of the Artificial Neural Networks in Engineering (ANNIE 99 Conference), St. Louis, Mo., November 1999.
[13] Gary Dempsey, Manfred Meissner, and Christopher Spevacek, “Using a CMAC Neural Network in Noisy Environments”, Proceedings of the Artificial Neural Networks in Engineering (ANNIE) 2003 Conference, St. Louis, Mo., November 2003.
[14] WeiWu, “DC Motor Parameter Identification Using Speed Step Responses”, Hindawi Publishing Corporation, Modelling and Simulation in Engineering, Volume 2012, Article ID 189757, September 2012.
[15] Roberto Petrella, Marco Tursini, Luca Peretti, Mauro Zigliotto, “Speed Measurement Algorithms for Low-Resolution Incremental Encoder Equipped Drives: a Comparative Analysis”, International Aegean Conference on Electrical Machines and Power Electronics, September, 2007.
[16] SIMULINK, Simulation and Model-Based Design, http://www.mathworks.com/ products/simulink/
[17] C. Ta and Y. Hori, “Convergence Improvement of Efficiency-Optimization Control of Induction Motor Drives,” *IEEE Transactions on Industry Applications,* vol. 37, no. 6, pp 1746 – 1753, Dec, 2001.

V. APPENDIX

A. *System Black Box*

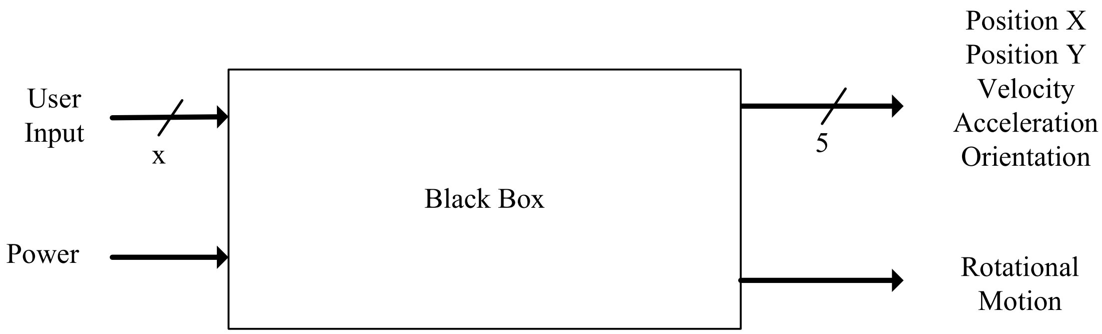

Fig. 3. Black box of the entire project

B. *Detailed Subsystem Glass Boxes*

This section contains the glass boxes of the Simulink system and the experimental platform

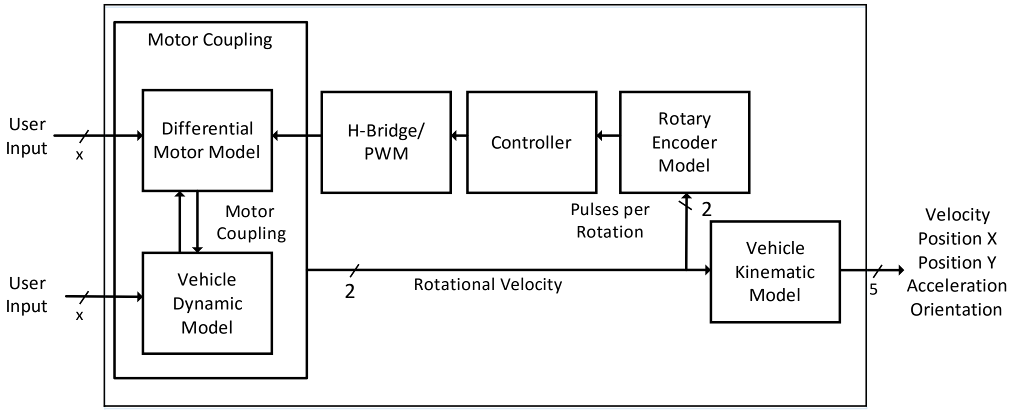

Fig. 4. Glass box of the Simulink Subsystem

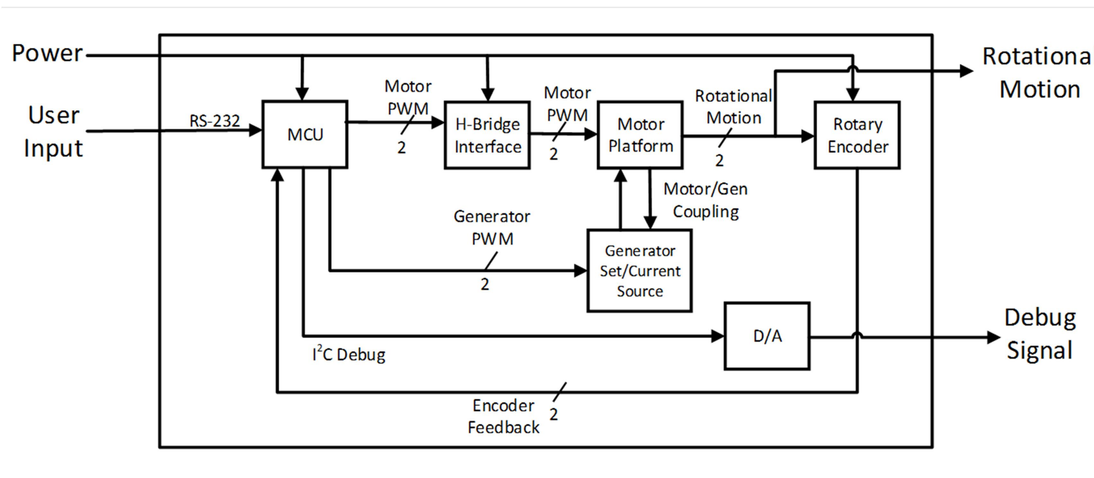

Fig. 5. Glass box of the experimental platform

C. *Metrics*

Objective: The experimental platform and Simulink model should be reliable.
Metric:

- Very reliable 5 points
- Reliable 4 points
- Average Reliability 3 points
- Not reliable 2 points
- Very unreliable 1 point

Objective: The velocity command shall be easy to issue to the Simulink Model and the experimental platform.
Metric:

- Very easy to issue 5 points
- Easy to issue 4 points
- Average difficulty to issue 3 points
- Difficult to issue 2 points
- Very difficult to issue 1 point

Objective: The load of the Simulink model and the experimental platform should be easy to manipulate.
Metric:

- Very easy to manipulate 5 points
- Easy to manipulate 4 points
- Average difficulty to manipulate 3 points
- Difficult to manipulate 2 points
- Very difficult to manipulate 1 point

D. *Detailed Testing Plans for Functional Requirement*

The Simulink motor model shall accurately model the physical motors:
The detailed testing for the Simulink motor model will test the velocity output of the Simulink model against the open-loop physical motors when a range of step inputs is applied between 20 RPM and 400 RPM with a 20 RPM step size. Settling time, percent overshoot, and steady-state error will be recorded from the resulting waveforms of each velocity input for both systems. The average percent difference of these three measurements of the Simulink motor models across the given velocity range must be within 20% of the physical motor's measurements.

The rotary encoder shall be accurately modeled:
The detailed testing for the rotary encoder model will test the output frequency of the Simulink model against the output frequency of the actual rotary encoder that is on the motor. The test will occur over the range of 0 volts to 24 volts and have 0.5 volt steps. The average error will be computed. The error must be within ±20% for the system to meet the specification.

Cogging torque shall be accurately modeled:
The detailed testing for the Cogging torque model will test the motor's cogging torque output against the Simulink model's output. The Simulink motor and the physical motor's current waveforms shall be changed into torque by using the K_t constant. Those two waveforms shall be correlated between each other. The correlation between the two waveforms cannot deviate more than ±50%. The base point for this percentage is based off of the max peak-to-peak values of torque ripple.

Pulse-width modulation shall be accurately modeled:
The detailed testing of the PWM model will consist of a comparison of the microcontroller PWM output to the PWM output of the model. The test will measure the average error in the percent duty cycle over the range of a 0% duty cycle to a 100% duty cycle in 4% steps. The error must be within ±20% for the system to meet the specification.

The Simulink H-bridge model shall accurately model the physical H-bridge:
The detailed testing of the Simulink H-Bridge model will test the output voltage of the H-Bridge model against the output voltage of the actual H-Bridge. The test will occur over the range of 0 volts to 24 volts and will occur in 0.5 volt steps. The average error of each point will be computed and it must be within ±20% for the system to meet the specification.

The DC generator loads shall be designed to mimic the prototype vehicle:
Motor current is directly proportional to motor torque. Motor current in the Simulink model can therefore be compared to motor current in the experimental platform to test torque loads in each system. Using an open-loop motor, a steady-state rotational speed will be set with voltage increments from 4 volts to 24 volts with 4 volt steps in both systems. For a given voltage input, a torque disturbance will be input as a step command in the form of currents ranging between 0.3 amps to 1.5 amps in 0.3 amp increments. Settling time, percent overshoot, and steady-state error will be measured from the resulting motor current waveform in both systems. The average absolute error of the experimental platform generator over the

given voltage and current ranges shall be less than 50% as compared to the Simulink vehicle model for these three measurements.

The drive control system shall minimize the effect of external disturbances:
Both the closed-loop Simulink model and the experimental platform will be set at a steady-state rotational velocity ranging from 20 RPM to 400 RPM in 20 RPM steps. For a given speed, a torque disturbance will be input ranging between 0.3 amps to 1.5 amps in 0.3 amp steps. The average minimum instantaneous resulting rotational speed shall be within 40% of the set steady-state speed over the given speed and current ranges.

The drive control system shall reduce vehicle tracking errors for step and ramp commands:
Both the closed-loop Simulink model and experimental platform will be given step and ramp commands ranging from 20 RPM to 400 RPM in 20 RPM steps lasting 4 seconds. The average maximum instantaneous error between the command and output should be less than or equal to 20% over the given speed range.

The drive control system shall reduce vehicle tracking errors for parabolic commands:
Both the closed-loop Simulink model and experimental platform will be given parabolic commands ranging from 20 RPM to 400 RPM in 20 RPM steps lasting 4 seconds. The average error between the command and output should be less than or equal to 40% over the given speed range and time period.

The drive control system shall reduce the effects of motor mismatch:
The detailed testing for motor mismatch will test the velocity output of both Simulink model motors at worst matched condition, meaning motor friction parameters are varied to their maximums and minimums in each motor respectively. No load will be applied to the motors and 12 data points will be taken from 2 to 24 volts with 2 volt increments. The RPM average deviation at these data points cannot be more than ±15% compared to the same data taken with perfectly matched Simulink motor models.

The graphical user interface shall send and receive commands:
The detailed testing of the graphical user interface will consist of a test to see if the GUI can send and receive signals. Test signals will be sent by the GUI and then both the Simulink model and the experimental platform will be checked to see if the signals have been received. The Simulink model and experimental platform will then send a signal back to the GUI, which will then be checked to see if the GUI has received the signal.

E. *Budget*

This section of the Appendix contains the budget and cost of the individual parts that are needed for the project.

TABLE V. COST OF INDIVIDUAL COMPONENTS

Part	Price
H-Bridge (LMD 18200)	$88.00
Atmel Development Board	$340.00
Atmega128 Microcontroller	$44.00
Motor	$1,415.00
Atmel Studio 6	$0.00
MATLAB/Simulink	$4,000.00
Miscellaneous	$100.00

F. *Detailed Gantt Chart*

This section of the appendix contains a detailed Gantt chart that shows the project schedule.

ACTIVITY	START	DURATION
Individual Component Research and Modeling	1	11
Project Proposal Presentation and Paper	1	5
Project Webpage	6	30
Progress Presentation 1	9	3
Experimental Platform Integration	12	4
Simulink Integration	13	4
Controller Development	16	4
Testing of the Subsystems	20	4
Progress Presentation 2	20	3
Integration of Simulink and Experimental Platform	24	2
Testing of the Integrated System	25	2
Project Demonstration	26	1
Final Report	27	6
Final Presentation	28	2
Poster Presentation	31	2

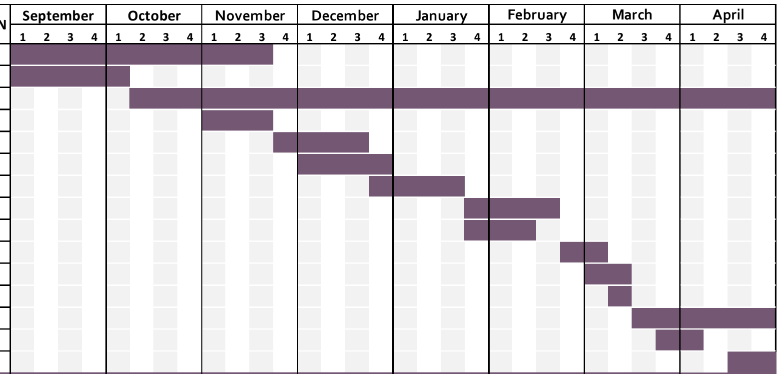

Fig. 6. High level Gantt chart of the project

Task Name	Start Period	Duration
Team Coordination	1	2
Initial Simulink Modeling	1	3
Project Proposal Document	3	10
MATLAB Code Model based on initial Simulink Model	4	2
Cogging Torque Experimental and Research	4	7
Efficiency, Motor, Motor-Gen Load Curve	4	2
Team Coordination	5	1
Generator Simulink Model	5	3
Serial communication research and implementation	5	5
Physical Vehicle Prototype Design	5	3
Initial Controller Development	7	3
Rotary Encoder Resolution Algorithm	7	4
Rotary Encoder Model	7	4
Generator Experimental	8	2
Proposal Presentation	8	4
Team Coordination	9	1
Current Source Research and experimental	9	7
AtMega PWM Setup	10	2
Cogging Torque Model	11	7
Command Conditioning Simulink	11	1
H-Bridge Model	12	2
Team Coordination	13	1
Input Command	13	5
PWM Model	14	7
Experimental Thermal Measurements	15	2
Web Page Development/Updates	15	5
Team Coordination	17	1
PWM Frequency Optimized	17	3
Digital Filter	17	4
Disturbance Command	18	4
Kinematic Model	18	4
Progress Report Presentation 1	20	4
Thermal Simulink Model	20	4
Team Coordination	21	1
I^2C and new D/As	22	4

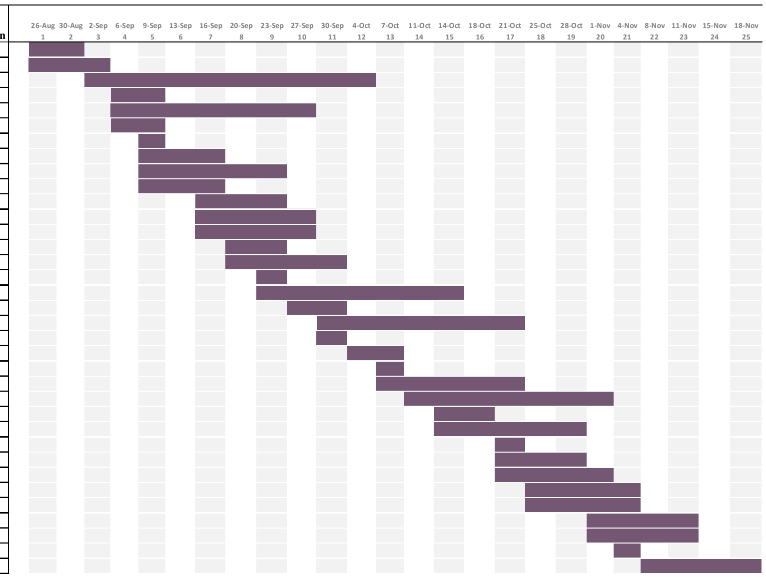

Fig. 7. Part 1 of the detailed Gantt chart

Task Name	Start Period	Duration
Dynamic Model	22	6
Performance Review Document	23	1
Experimental Platform Integration	24	9
Team Coordination	25	1
Efficiency Model	27	4
Simulink Integration	28	8
Team Coordination	29	1
Controller Development	35	8
Team Coordination	37	1
Controller Model	39	8
Team Coordination	41	1
Controller Code	41	5
Terrain Testing	42	1
Simulink GUI Control	42	9
Team Coordination	45	1
Progress Report Presentation 2	46	4
Experimental Platform Testing	47	8
Simulink System Testing	47	8
Team Coordination	49	1

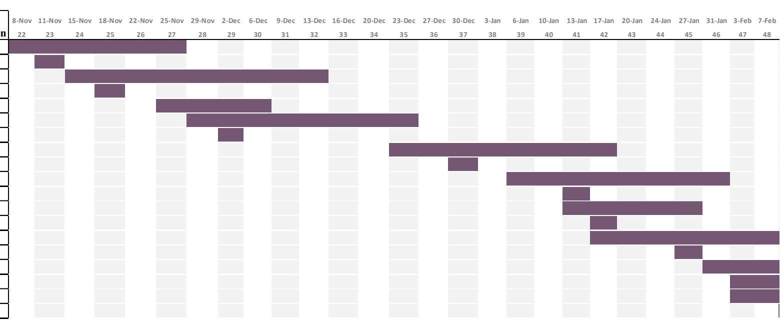

Fig. 8. Part 2 of the detailed Gantt chart

Task Name	Start Period	Duration
Simulink GUI Control	42	9
Team Coordination	45	1
Progress Report Presentation 2	46	4
Experimental Platform Testing	47	8
Simulink System Testing	47	8
Team Coordination	49	1
Experimental Platform and Simulink Integration	52	5
Team Coordination	53	1
Experimental Platform and Simulink Testing	56	8
Team Coordination	57	1
Demo Prep	57	2
Final Report	60	5
Team Coordination	61	1
Final Presentation	62	4
Poster Presentation	64	3
Team Coordination	65	1

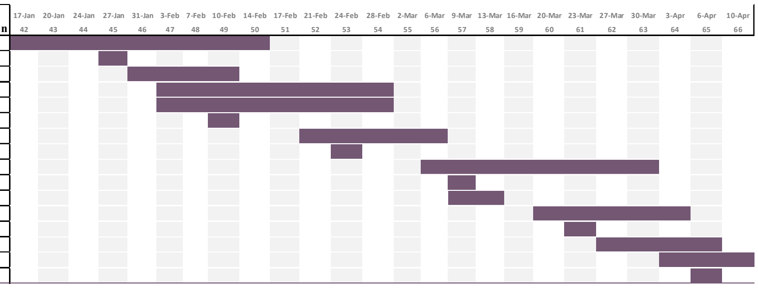

Fig. 9. Part 3 of the detailed Gantt chart

G. *Detailed Division of Labor*

This section of the appendix contains a detailed division of labor that shows who will do every task that is listed in the Gantt Chart. The team coordination events that are present in the Gantt Chart are not present in the division of labor because they are meetings that take place and are necessary to account for in the Gantt chart, but are not necessary to put in the division of labor.

TABLE VI. HIGH LEVEL DIVISION OF LABOR

Task Name	Team Member Name
Cogging Torque	Alexander Schmidt
Motor Models	Alexander Schmidt
Generator Load and Model	Benjamin Roos
Communication	Kevin Block
Controller Code	Kevin Block
Vehicle Design and Modeling	Timothy De Pasion
Rotary encoder resolution	Timothy De Pasion
Controller devlopment and model	All team members
Integration	All team members

TABLE VII. PART 1 OF THE DETAILED DIVISION OF LABOR

Task name	Resource name
Initial Simulink Modeling	Alex, Ben, Kevin, Tim
Project Proposal Document	Alex, Ben, Kevin, Tim
Initial Controller Development	Alex, Ben, Kevin, Tim
Proposal Presentation	Alex, Ben, Kevin, Tim
Web Page Development/Updates	Alex, Ben, Kevin, Tim
Progress Report Presentation 1	Alex, Ben, Kevin, Tim
Performance Review Document	Alex, Ben, Kevin, Tim
Controller Development	Alex, Ben, Kevin, Tim
Controller Model	Alex, Ben, Kevin, Tim
Experimental Platform and Simulink Integration	Alex, Ben, Kevin, Tim
Experimental Platform and Simulink Testing	Alex, Ben, Kevin, Tim
Progress Report Presentation 2	Alex, Ben, Kevin, Tim
Demo Prep	Alex, Ben, Kevin, Tim
Final Report	Alex, Ben, Kevin, Tim
Final Presentation	Alex, Ben, Kevin, Tim
Poster Presentation	Alex, Ben, Kevin, Tim
Dynamic Model	Ben and Tim
Efficiency, Motor, Motor-Gen Load Curve	Alex and Ben
Experimental Thermal Measurements	Alex and Ben
Thermal Simulink Model	Alex and Ben
Experimental Platform Integration	Alex and Ben
Experimental Platform Testing	Alex and Ben
Simulink Integration	Kevin and Tim
Simulink System Testing	Kevin and Tim

TABLE VIII. PART OF THE DETAILED DIVISION OF LABOR

Task name	Resource name
Cogging Torque Experimental and Research	Alex
Cogging Torque Model	Alex
PWM Frequency Optimized	Alex
Efficiency Model	Alex
Generator Simulink Model	Ben
Generator Experimental	Ben
Current Source Research and experimental	Ben
Digital Filter	Ben
Serial communication research and implementation	Kevin
AtMega PWM Setup	Kevin
Input Command	Kevin
Disturbance Command	Kevin
I^2C and new D/As	Kevin
Controller Code	Kevin
Simulink GUI Control	Kevin
MATLAB Code Model based on initial Simulink Model	Tim
Physical Vehicle Prototype Design	Tim
Rotary Encoder Resolution Algorithm	Tim
Rotary Encoder Model	Tim
Command Conditioning Simulink	Tim
H-Bridge Model	Tim
PWM Model	Tim
Kinematic Model	Tim
Terrain Testing	Tim

H. *Current Control for Accurate Torque Disturbance Schematics*

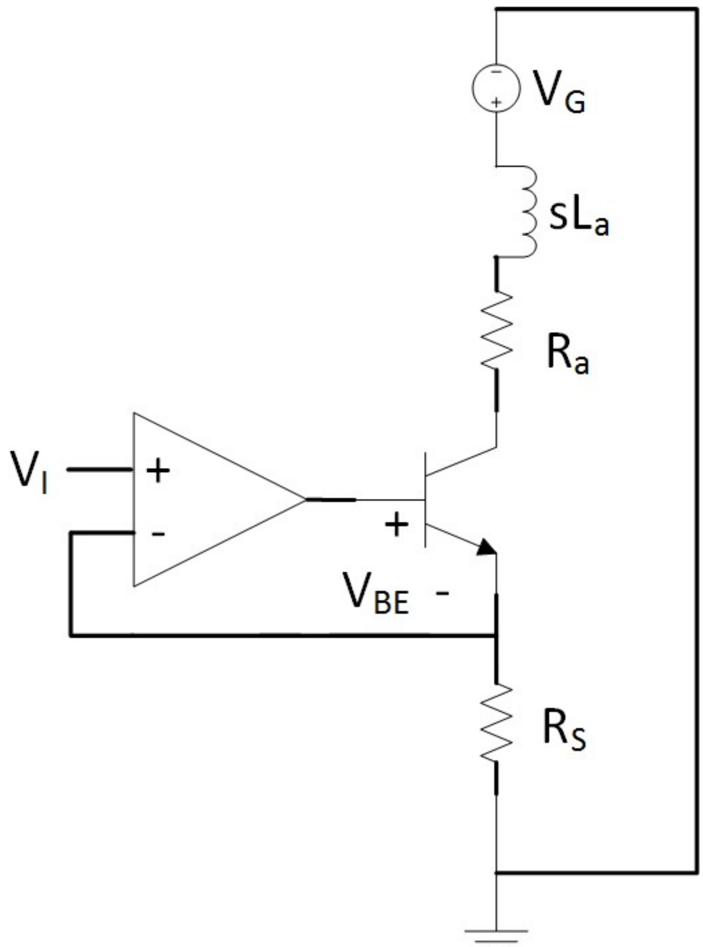

Fig. 10. Op-Amp voltage follower controlled transistor for precise generator torque control

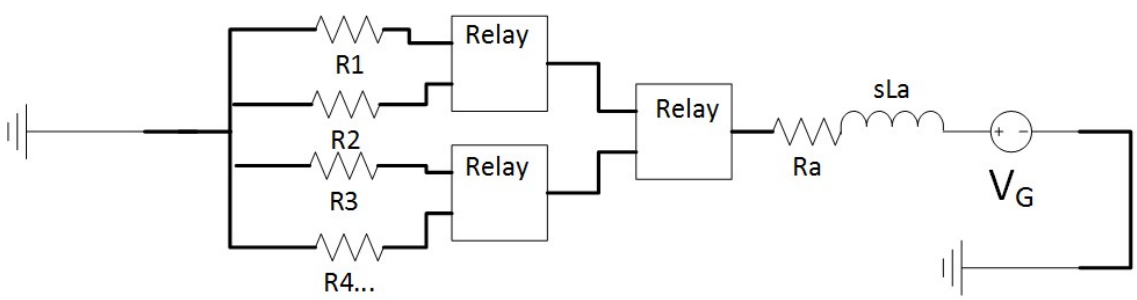

Fig. 11. Alternative current control circuit with relay banks switching between predetermined resistive loads