The design and construction of electronic motor control and network interface hardware for advanced concept urban mobility vehicles.

By

Bryan L. Morrissey

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN ENGINEERING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2008

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Submitted to the Department of Mechanical Engineering
on May 9, 2008 in partial fulfillment of the
requirements for the Degree of Bachelor of Science in Engineering
as recommended by the Department of Mechanical Engineering

ABSTRACT

Over the past several years, the Smart Cities Group at MIT's Media Lab has engaged in research to develop several advanced concepts for vehicles to improve urban mobility. This research has focused on developing a modular vehicle architecture, centered around the concept of the self-contained Wheel Robot. The goal is to develop Wheel Robot systems in which all power, transmission, suspension, and steering functions are incorporated into self-contained units with a simple, standardized interface providing for mechanical mounting, electrical power distribution, and access to the vehicle control network. This thesis outlines my research and design work implementing several electronic power and control systems that contribute to ongoing Wheel Robot development efforts. The designs for a high-current motor controller and two electronic sensing and control interfaces are described, and several strategies for further control systems development are proposed.

Thesis Supervisor: William J. Mitchell
Title: Alexander W. Dreyfoos, Jr. (1954) Professor of
Architecture and Media Arts and Sciences

BIOGRAPHICAL NOTE

Bryan Morrissey is grateful for the opportunity to return to MIT as a member of the class of 2008 during the past academic year. Bryan graduated from Pequannock Township High School in Pompton Plains, NJ in June of 1994. He first entered the Department of Mechanical Engineering in 1995 as a sophomore and member of the class of 1998.

ACKNOWLEDGMENTS

None of this would have been possible without:

Misha Rosenberg, my loving partner of four years, for her endless support and for holding me to the promises that I made to myself to return to MIT to finish my degree.

Raul-David "Retro" Poblano, for recommending me to the Smart Cities group, and providing the opportunity to work on such an exciting set of projects. While our long-time friendship is based on far more than just speakers and cars, we somehow seem to return to the same topics over and over again.

Ryan Chin, for warmly welcoming me to the Smart Cities Urban Mobility research group, which he ably oversees under the direction of Professor Mitchell.

Michael Lin, for designing the truly amazing RoboScooter prototype, which turned out to be perfectly ridable even though the manufacturers had no idea that they were building anything more than a show-quality mockup.

Kevin Brown, for employing me at Brown Innovations from January 1999 through the present, for providing me the opportunities I needed to prove myself, and for the encouragement and freedom to return to MIT to complete my academic work after many years.

Grateful thanks also to:

Russell "RJ" Ryan, class of 2010, whose software development expertise quickly brought my USB interface board to life.

Charles Guan, class of 2011, whose unbounded energy and unashamed enthusiasm for all things electro-mechanical frequently reminded me why I wanted to become an engineer in the first place. "Is it working yet?" "How hard is it to build a motor controller, anyway?"

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I. Introduction

A. Smart Cities Urban Mobility Research

Over the course of the 20th century, privately owned and gasoline powered automobiles became the dominant means of personal transportation in most of the developed world. Car ownership is associated with personal freedom, mobility, and status by both car owners and non-owners alike. The rising fortunes of many developing societies, especially in rapidly growing Asian economies, means that number of people who can afford to purchase their own cars has risen dramatically and continues to grow. However, as the number of cars crowding into dense city centers increases faster than the urban infrastructures can adapt, the advantages of personal freedom and mobility inevitably disappear, as people find themselves trapped in traffic jams for longer and longer periods of time.[1]

The Smart Cities Group, directed by Professor William Mitchell, at MIT's Media Lab has been investigating ways to alleviate the inconvenience, inefficiency and pollution that results from having too many vehicles crowding into dense urban centers that are ill-equipped to handle them. One of the major goals of the Smart Cities Group is to develop efficient and environmentally friendly systems for personal urban transportation that offer attractive alternatives to driving a car while complementing existing and future mass transit infrastructure.

The Smart Cities Group takes a highly multi-disciplinary approach to solving problems. Much of the work done by Smart Cities addresses mobility issues from a top-down, urban planning point of view. Many of these advanced urban mobility concepts rely on the development and introduction of flexible electric vehicles that could be efficiently shared by many users. To address this need, the group is also working to develop an entirely new class of vehicles that will be better suited for city driving than the private car, and would enable kind of coordinated and efficient shared-ownership models being developed on the urban planning side.

B. The Wheel Robot Concept

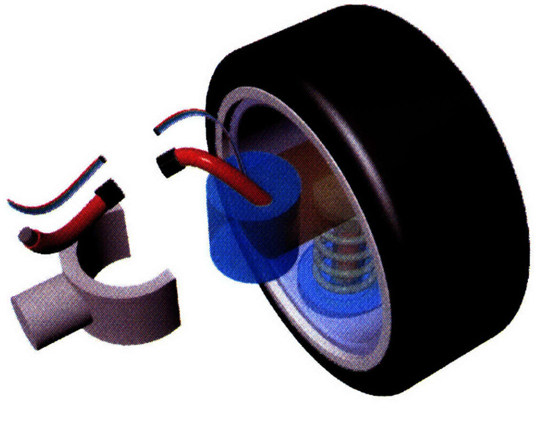

Figure 1: Power, Signal, Mechanical connection of the Wheel Robot

Diagram by Patrik Künzler

In particular, Smart Cities is developing a new architecture for electric vehicles in which all power, transmission, and steering components are integrated into independent and intelligent wheel modules. These modules will allow custom vehicles to be constructed in a "plug-and-play" fashion. In practice, this will mean that simple frames can be designed to provide mechanical mounting points and electrical connections for power distribution and digital communication. This will be accomplished by developing independent "Wheel Robot" modules that communicate through a digital control network to adapt to the frame and coordinate with the other Wheel Robots in the

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[1] Chin et al. 2006. City Car: A New Design Approach Enabling Urban Mobility.

vehicle.

The Wheel Robot vehicle architecture eliminates many of the constraints in traditional vehicle design. These constraints are imposed by the need to transmit mechanical power from a single, centrally located engine to the wheels through complex steering and suspension linkages. When all of these power, steering and suspension functions are moved out to the wheels, there is much more flexibility to design the vehicle body to adapt to the tight constraints of urban environments.

Image: Michael Chia-Liang Lin

Figure 2: The prototype RoboScooter in open and folded configurations

C. The RoboScooter and City Car Concept Vehicles

The flexibility enabled by the Wheel Robot is clearly displayed in the folding body designs of the RoboScooter and the City Car. Both of these concept vehicles are being designed to incorporate active Wheel Robots for all of their wheels. One of the goals for the RoboScooter is to use the independent drive capability in the front and rear wheels to enable it to fold itself into its compact configuration when parked in a charging rack, as well as to balance itself as an inverted pendulum when folded with its wheels next to each other.

Like the RoboScooter, The City Car is also being designed to fold into a compact configuration when it is not in use. In the City Car, however, the capacity for four wheel independent steering is also intended to provide unprecedented mobility for a four wheel vehicle. While the ability to either rotate on its own axis or to slide sideways into a narrow parking spot are obvious examples, it is expected that the full range possibilities offered by the City Car's maneuverability will become clear only after the initial full scale prototype has been completely built and enters active testing.

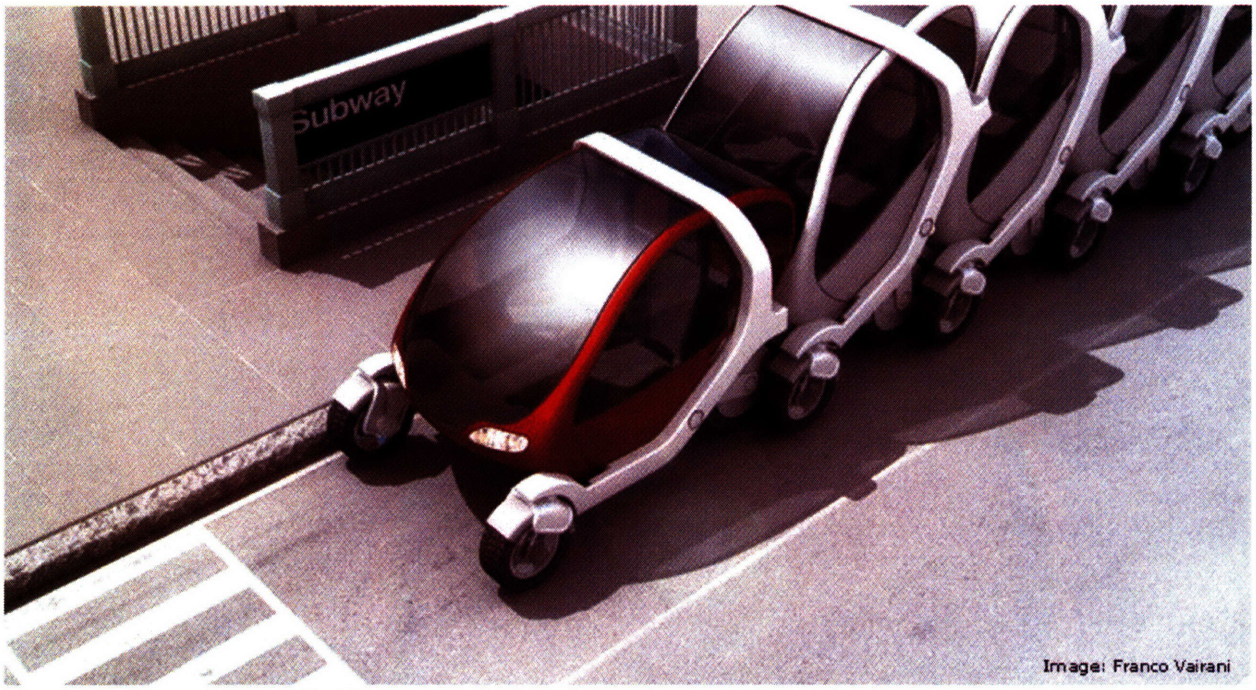

Figure 3: Conceptual rendering of a "stack" of folding City Cars

II. Background

A. Current status of urban mobility vehicle research

The RoboScooter concept began to emerge early in 2007, with the design effort being spearheaded by Smart Cities graduate student Michael Lin. Through an active and fruitful collaboration with Taiwan's Industrial Technology Research Institute (ITRI) and Sanyang Motors (SYM), the first RoboScooter was designed and built in Taiwan in roughly eight months. The resulting show-quality prototype was sent to Italy to be revealed for the first time at the Milan Motorcycle Show in early November. This prototype was then shipped to the Media Lab in January 2008 for further development. The goal was to make the show-quality prototype into a ridable vehicle. At this point, the primary goal of my thesis research was to develop a brushless direct-current (BLDC) motor controller with a digital vehicle network interface to drive the traction motors for the RoboScooter's implementation of the Wheel Robot. During the first two months of 2008, I designed and built a pair of these prototype motor controllers, the design for which is described in detail in the next section IV.

Shortly before the start of the Spring 2008 semester, the decision was made to commence building a full scale prototype of the City Car in parallel with the ongoing RoboScooter development work. This new effort began in earnest in February 2008, with the plan to have functional City Car Wheel Robot demonstrations in time for the Media Lab's Sponsor Week, April 1-3, 2008. As the City Car demonstration prototype was being designed and built on an extremely tight schedule, most of the team's engineering effort was necessarily focused on building the chassis and developing the mechanical steering, transmission and suspension components for the new Wheel Robot prototype.

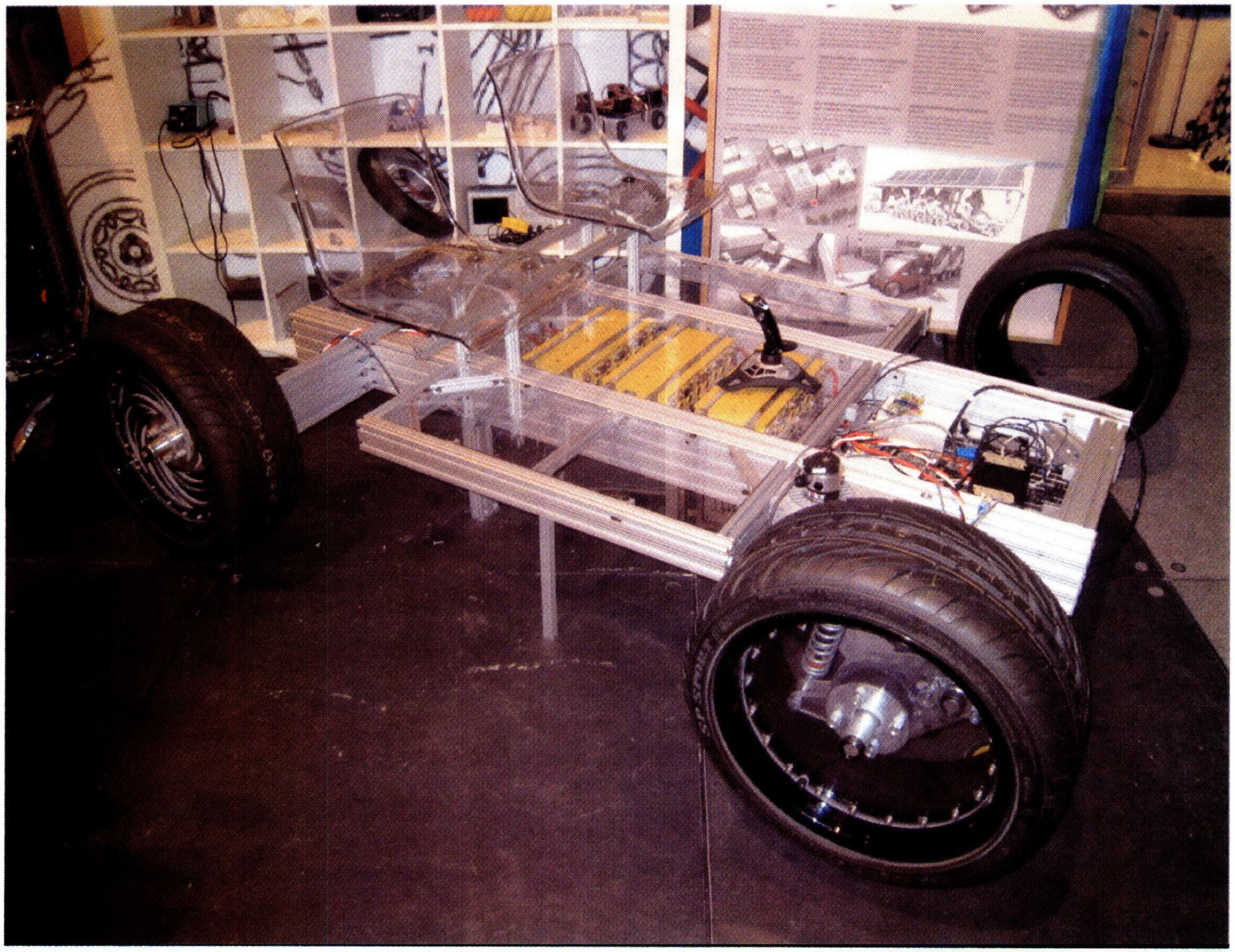

Figure 4: The City Car demonstration chassis, May 5, 2008

The emphasis for Sponsor Week was to produce and demonstrate a mechanically functional Wheel Robot system. The design work necessary to develop custom control electronics for a fully self-contained Wheel Robot module was – and still is – at an early stage of development, so the electronic power and control systems were implemented primarily using commercially available, off-the-shelf components. As Sponsor Week approached, it became clear that we needed to quickly find a way to link some of the components to the central vehicle computer. In order to meet this need, as well as a similar need for a control and sensor interface to support the continuing RoboScooter development effort, I quickly shifted my focus away from the BLDC motor controller board to design a flexible USB-based control interface (see Design Process and Results, part B, p19).

B. The Vehicle Control Network concept

Figure 5 shows how a basic vehicle control network for a RoboScooter-type vehicle might be implemented. The figure is drawn to emphasize the two Wheel Robot motors and controllers that will drive the front and rear wheels of the vehicle. While the City Car is planned to use the same basic control network ideas, a comparable figure for the City Car control network will be substantially more complicated, as it will need to include independent steering motor that is paired with each of the four drive motors.

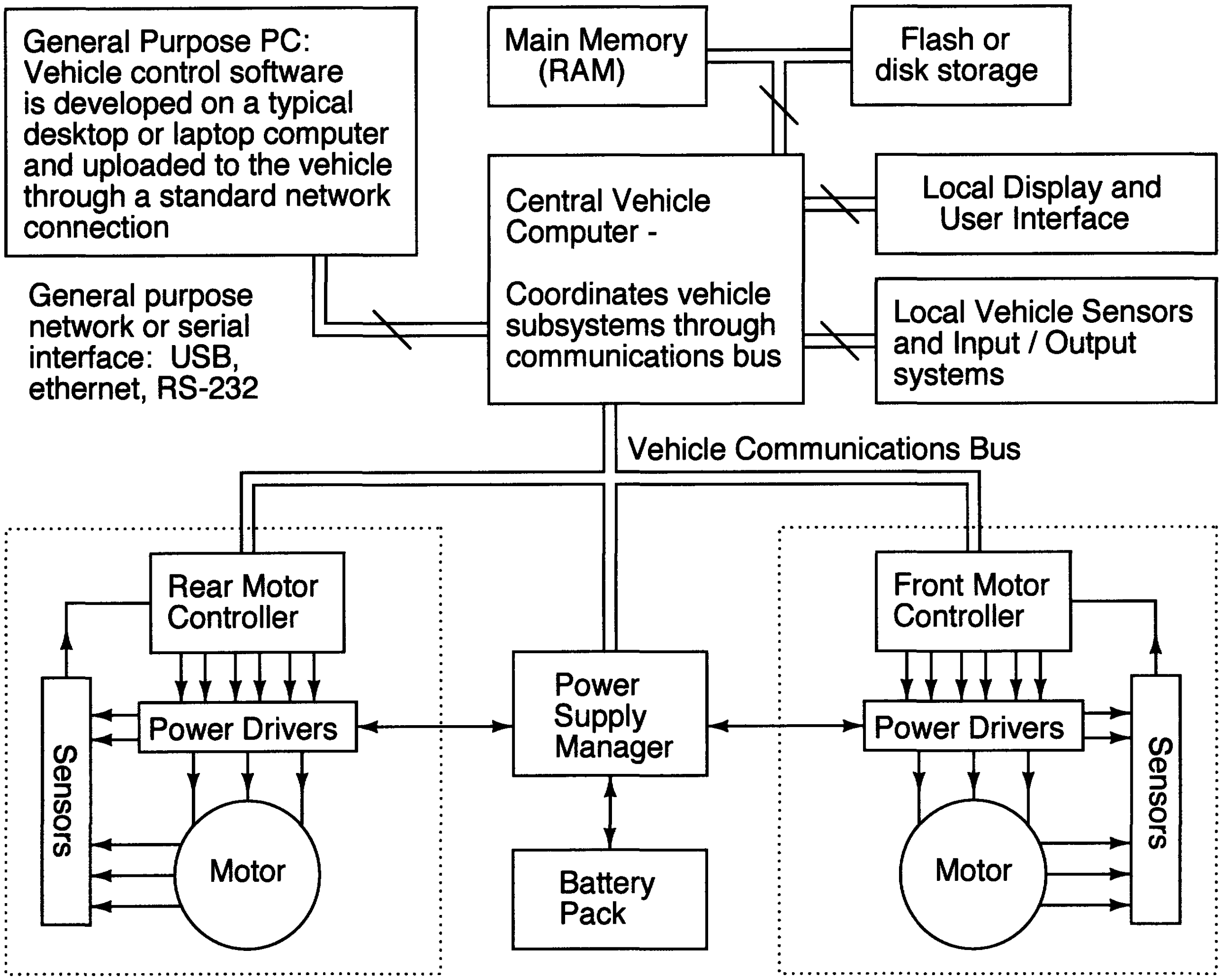

Figure 5: Proposed vehicle control network for the RoboScooter

C. Motivation for thesis research: the need to develop a customized motor controller

The goal of my thesis research was to design and produce a system that will allow a general-purpose computer to control an electric motor. Stated in this simple way, there is nothing particularly novel about this goal as digital computers have been used to control motorized industrial equipment for decades. However, research into the wide variety of commercially available motor controllers quickly reveals that there is no simple approach to developing control systems that can be generalized to all possible applications. Moreover, new applications for advanced motorized control systems continue to be found and developed as the technologies underlying computers, digital networking, power electronics, batteries and electric motors continue to advance. Virtually any control system designed with technology from five years ago could be completely redesigned with current technology to be faster, cheaper, smaller, lighter, and higher performing today. As long as this trend continues, there will be many opportunities to develop systems for applications that would have been impractical only a few years earlier.

Part of the reason that the Smart Cities Group has supported my effort to develop a custom motor controller for their electric vehicles is that we have so far been unsuccessful in finding any commercially available systems which would be practical and cost effective, while also providing all of the functionality desired for the wheel robot. There are compact and inexpensive brushless motor controllers for electric scooters,[2] but they are limited to a simple thumb throttle control method and are generally unable to reverse direction or provide regenerative braking. There are also larger and more sophisticated controllers designed for small and midsize four wheel vehicles;[3] these are capable of reversing directions and provide regenerative braking, but generally lack the advanced digital network interface for computerized control. One of the serious shortcoming of the controller currently used for the City Car's traction motor is that it does not allow a continuous transition from de-accelerating in one direction to accelerating in another direction; it cannot provide continuous torque while reversing direction. Instead, this controller will only begin to accelerate the motor in either rotational direction when it is starting from a halt.

Finally, the industrial motor controllers designed by Elmo Motion Control (www.elmomc.com) appear to provide virtually all of the desired features – a digital control network interface, options for position and velocity control, and regenerative braking – but the cost of these systems appears to make it prohibitive to incorporate them into the vehicle designs. While the Elmo Motion Control systems may prove useful at some point for advanced prototype testing, their availability does not negate the long term need to develop a compact and cost-effective system to incorporate into the Wheel Robot design.

III. Methods

A. Technologies used to implement the vehicle control network

With their sleek and futuristic designs, the vehicles being developed by the Smart Cities Group clearly convey their high-technology aspirations. The designs are technologically advanced beneath the surface as well: while the first generation of production RoboScooters will likely be based on currently available technology, many features planned for the City Car and for future RoboScooter generations will depend on the development of materials and systems that are not yet commercially available.

The RoboScooter and the City Car projects will only be truly successful if they produce vehicles that are practical, cost-effective, and reliable. This section outlines the considerations motivating several of my choices regarding the tools and technology used to develop the motor control system. In almost all cases, the choices were made on pragmatic grounds, focusing on cost, commercial acceptance and availability, and design simplicity. In some cases, these factors pushed the adoption of newly available components; this occurred most frequently in the selection of integrated circuit chips for my control board. In other cases, notably the use of the Controller Area Network (CAN-bus) and Universal Serial Bus (USB), the specifications were selected for their low cost, simplicity of implementation, and near universal industry acceptance.

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[2] The brushless motor and controller available from http://powerpackmotors.com is typical of this. The "BMC PowerPack" scooter motor from this company is the target for my motor controller design.

[3] The motor controller currently used in the first City Car prototype was purchased from Kelly Controls. The controller description can be found at http://www.kellycontroller.com/mot/Brushless-DC-Motor-Controller.html

B. Schematic capture and board layout

All printed circuit board (PCB) design work for this thesis was done using the ExpressSCH schematic capture program and ExpressPCB board layout program, both of which can be downloaded free of charge from the ExpressPCB website at www.expresspcb.com

I have several years of experience using the circuit design software and board manufacturing service provided by ExpressPCB, in addition to more limited experience using a handful of other design programs. The main advantages offered by the ExpressPCB software are its cost (free) and reasonably simple and intuitive user interface.[4] In addition, the Express PCB board layout package provides an online service that allows the user to submit a design file and order boards for purchase directly though a pop-up dialog interface.

However, this convenience is offset by a number of disadvantages associated with using this service. Part of the price to be paid for the simple user interface is a certain degree of rigidity: there are certain fairly common boards layout features that are prohibited by the software in order to maintain the simplicity of the interface. The Express PCB schematic capture and board layout programs are not available for any computing platform other than Microsoft Windows OS. Finally, the file formats are proprietary to ExpressPCB, so that any board designed using their software are locked to their manufacturing service.

As the controller and interface designs become more mature, it may prove worthwhile to port the design to a software package that uses a well documented, open format that could be read and edited by more than one company's board design system. More importantly, the design software should be able to generate manufacturing specification files in the industry-standard Gerber file format, which can be submitted to any printed circuit board manufacturer.

C. Digital network and data interfaces

The design for the digital control and feedback network is currently being designed around the Controller Area Network specification, commonly abbreviated as either CAN or CAN-bus. The CAN specification was developed by Bosch in the late 1980's as a high-speed serial data bus for the electrically noisy automotive environment. The specification defines the standard for a data bus which consists of a single pair of wires to which multiple devices can be connected.

The protocol provides mechanisms to detect errors and data collision conditions on the data bus, to distinguish high priority messages from lower priority messages, and to define data addresses for up to 127 devices. With a data signaling rate of 1 Megabit per second, the CAN protocol would not be considered "high speed" compared to current technology, but it has become established as the standard network for diagnostics, control and automation in all current cars. The standard has also been adapted for use in agricultural equipment as well as aviation and industrial control networks.

While there are newer and more advanced protocols that could be used for a Wheel Robot

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[4] "Simple" and "intuitive" at least in comparison with other circuit board layout packages. PCB design software in general is not noted for intuitive, elegant, or user-friendly interface design.

vehicle control network, the mature state of the CAN protocol offers many advantages which offset its relatively low data rate. The protocol is designed for control networks, in which many short messages need to be accurately transmitted to their destinations in a timely manner. The mechanisms for priority arbitration and error detection allow for reliable and timely message transmission, while still being simple enough that the hardware and software requirements to implement the network can be reasonably inexpensive.

One alternative to CAN that was considered for the control network was the Universal Serial Bus, commonly known as USB. USB has the advantage of being standard on virtually every desktop and laptop computer sold today; if the motor controllers were designed with USB device interfaces, they could theoretically be connected directly to virtually any available computer. The primary disadvantage of USB is that it is a point-to-point protocol, so that all communication needs to pass through the central vehicle computer (CVC). With a CAN-based system, a single Wheel Robot module could theoretically take on the role of network coordinator, but with a network based on USB this would not be possible.

The vehicle network in the current City Car prototype is controlled by a central computer, and the first computerized RoboScooter is also planned to have a central controller. Currently the CVC is a general purpose small form-factor PC, with multiple USB ports but no built-in CAN-bus interface. While the vehicle-wide control network will not be based on USB, the CVC will interface with the control network using its USB ports by way of a CAN to USB adapter module.[5]

D. Brushless Direct Current (BLDC) traction motors

One of the long term goals of the Wheel Robot vehicle concept is for the Wheel Robot modules to be interchangeable between vehicles. As long as the concept encompasses both two- and four-wheel vehicles, however, the vastly different constraints of the two vehicle types will require at least two different Wheel Robot module designs: car modules which incorporate steering motors, and scooter modules which do not. While the different constraints will almost certainly lead to vastly different module designs, one feature that they will share in common will be their digitally controlled BLDC traction motors.

BLDC motors offer many advantages over traditional DC brushmotors in high-power traction applications. In a DC brushmotor, electric current is distributed to rotating electromagnet coil windings of the moving rotor though a sliding electrical contact, known as a commutator. Typical commutators consist of one or more pairs of graphite "brushes" which slide against a ring of metal contacts which turn with the rotor. The friction and sparks generated by this sliding electrical contact inevitably cause the brushes to wear down over time, eventually leading to motor failure or at least the need for replacement brushes.

BLDC motors eliminate the commutator as a failure point and potential loss mechanism. Instead of having stationary brushes which direct current to a sequence of of windings on a spinning rotor, the BLDC motor is constructed so that permanent magnets rotate around stationary electric

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[5] Initial development and testing of the CAN-bus based vehicle network will use the USB-CAN converter module developed and sold by Apox Controls. http://www.apoxcontrols.com/

windings. The three electromagnet windings which form the stationary "stator" are not required to move, so they are hard-wired to their power connections. The spinning permanent magnet rotor does not require any electrical connections, so the need for sliding electrical contacts is eliminated.

From the point of view of the motor controller, the BLDC motor looks much like an industrial three-phase induction motor. The BLDC motor controller generates simulated three-phase power, rapidly switching its power transistors on and off to synthesize three alternating current outputs. These three outputs are separated by 120 degrees of phase, energizing each winding in sequence to produce a rotating magnetic field which exerts a torque against the permanent magnets of the rotor.

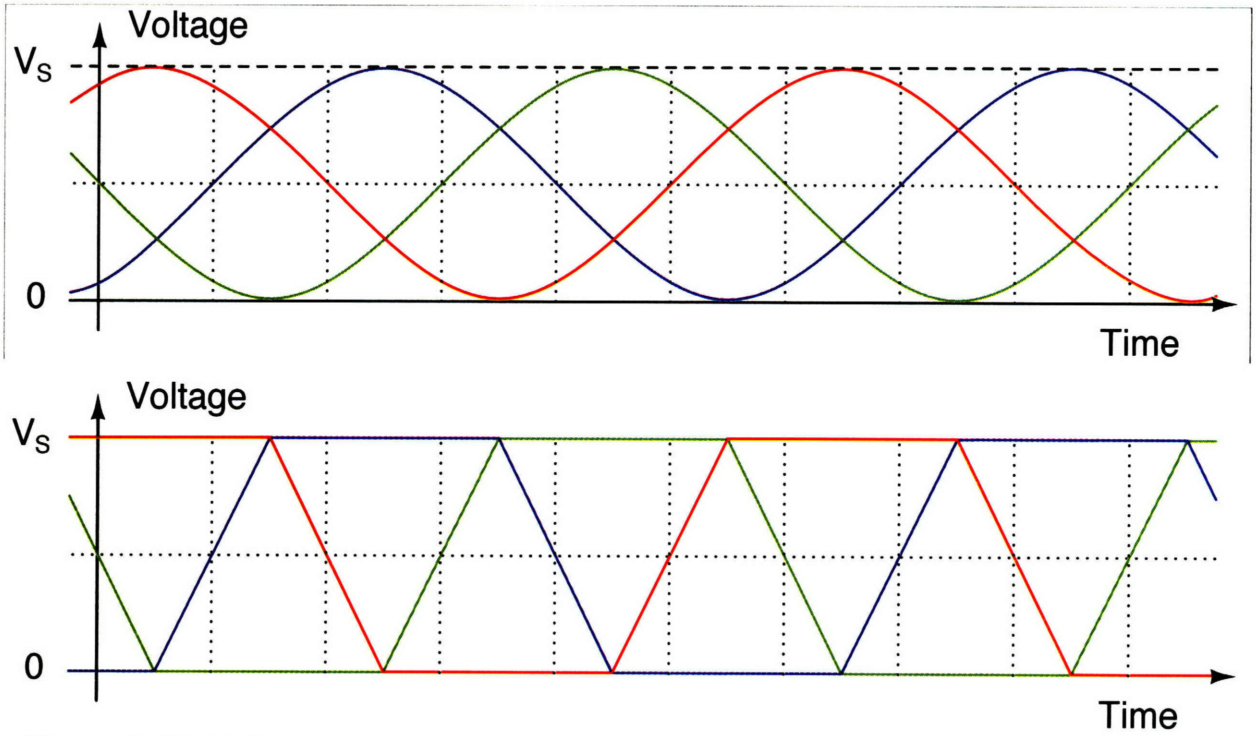


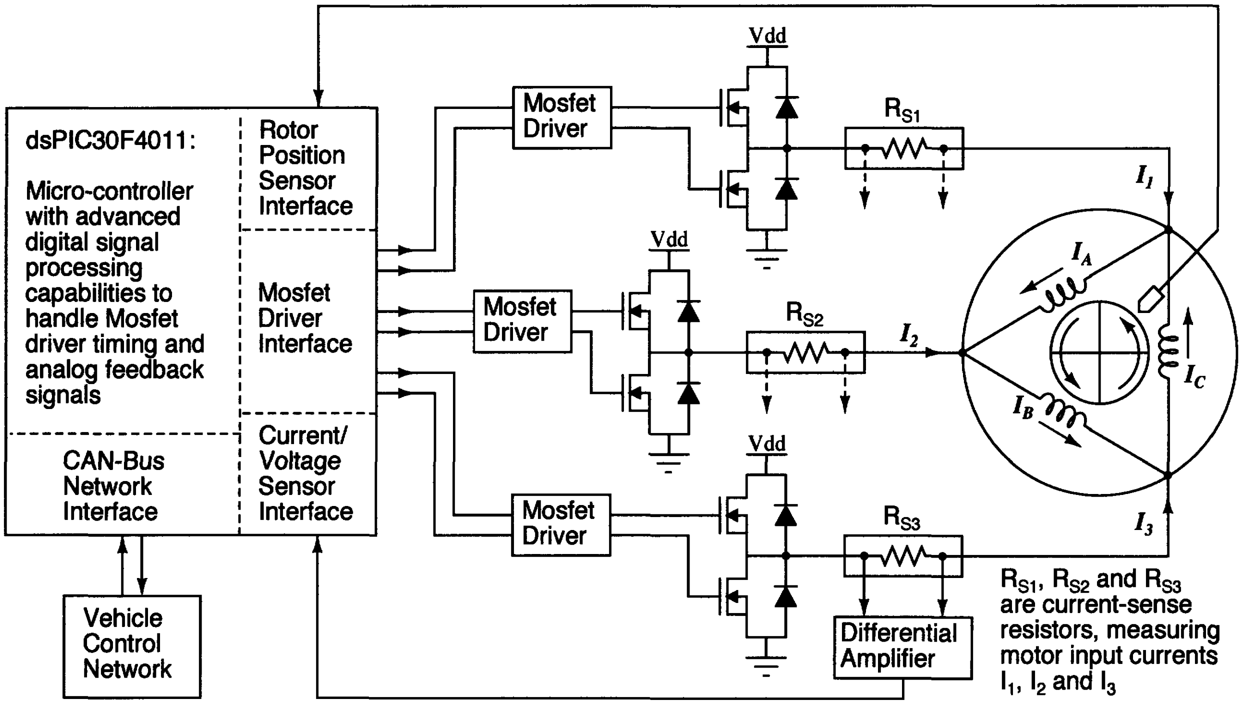
Figure 6: A BLDC motor controller can approximate the sinusoidal waveforms of three phase power using a piecewise-linear trapezoidal function. At any point in time, a typical motor controller will only drive the two motor terminals which are being held at a constant voltage while leaving the third motor terminal undriven.

While the BLDC motor appears to behave like a three-phase AC induction motor when viewed from the three motor terminals, the entire system will appear to behave like an ordinary DC motor when viewed from the power terminals of the motor controller. With the controller taking the commutator function of directing current to the motor windings, the entire system taken as a unit will have torque-speed and voltage-current characteristics that are almost identical to those of a traditional DC brushmotor. This similarity is why BLDC motors are referred to as direct-current motors in spite of their requirement for three phase power: when motor and controller are taken together, a BLDC motor system will behave just like a DC brushmotor without the failure-prone brushes.

IV. Design Process and Results

A. BLDC motor controller with CAN-bus interface

The immediate goal of my BLDC motor controller design is to match the power performance of a motor controller that is sold with the BMC PowerPack motor, while producing a smaller package and providing several functions absent from the commercial controller. These additional functions include regenerative braking, torque control, position and velocity feedback, reversibility, and the ability to command all of these capabilities through the digital control network interface.



R_{S1}, R_{S2} and R_{S3} are current-sense resistors, measuring motor input currents I_1, I_2 and I_3

Figure 7: Basic Three-Phase Brushless DC Motor Controller

The BMC PowerPack motor and controller is sold as a performance upgrade kit for existing electric scooters. The system is marketed as being able to propel a scooter in excess of 30 miles per hour on level ground; the test data available from www.powerpackmotors.com claims a peak power output of 1.545 Horsepower (1153 Watts) while drawing 32.4 Amps at 48 Volts, for a power conversion efficiency of 74.1%. It is not completely clear if the ultimate limit on performance is due to the motor or controller, so I planned my design under the assumption that a more capable controller could exceed these performance specifications. In order to meet or surpass these parameters, I planned a target output of at least 50 Amps with a 48 Volt power supply.

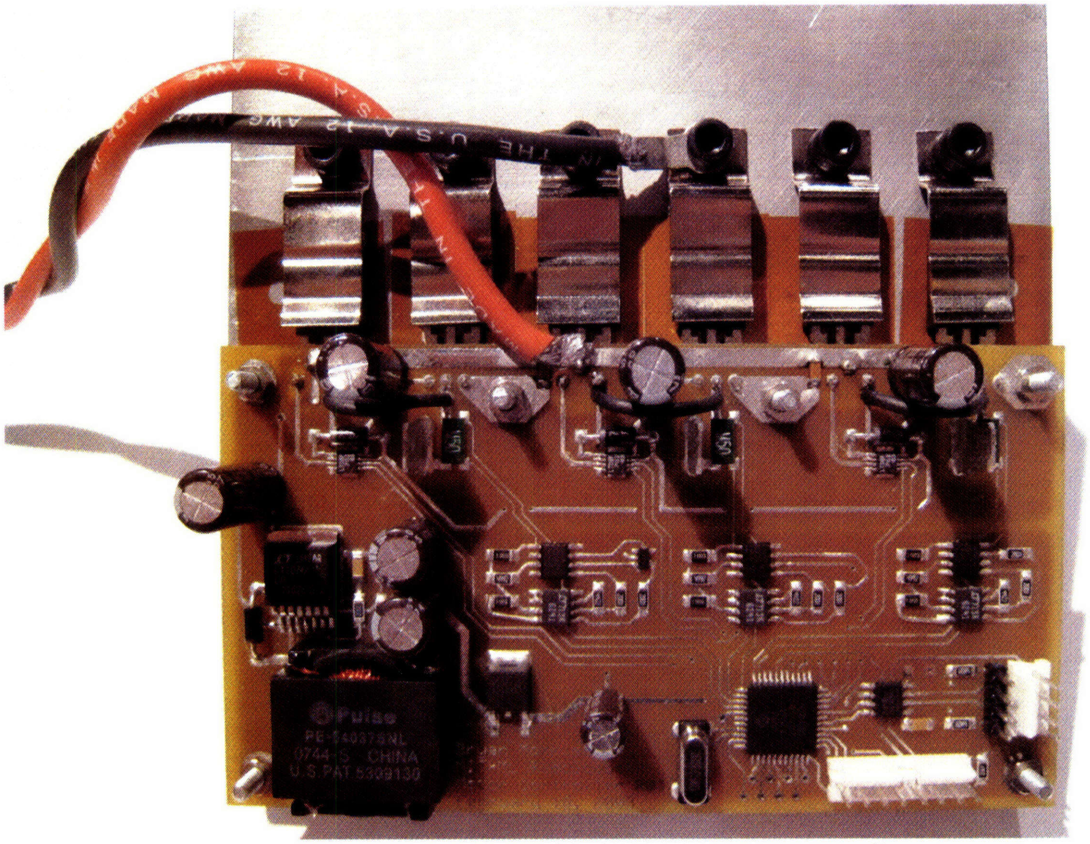


Figure 8: Assembled BLDC motor controller

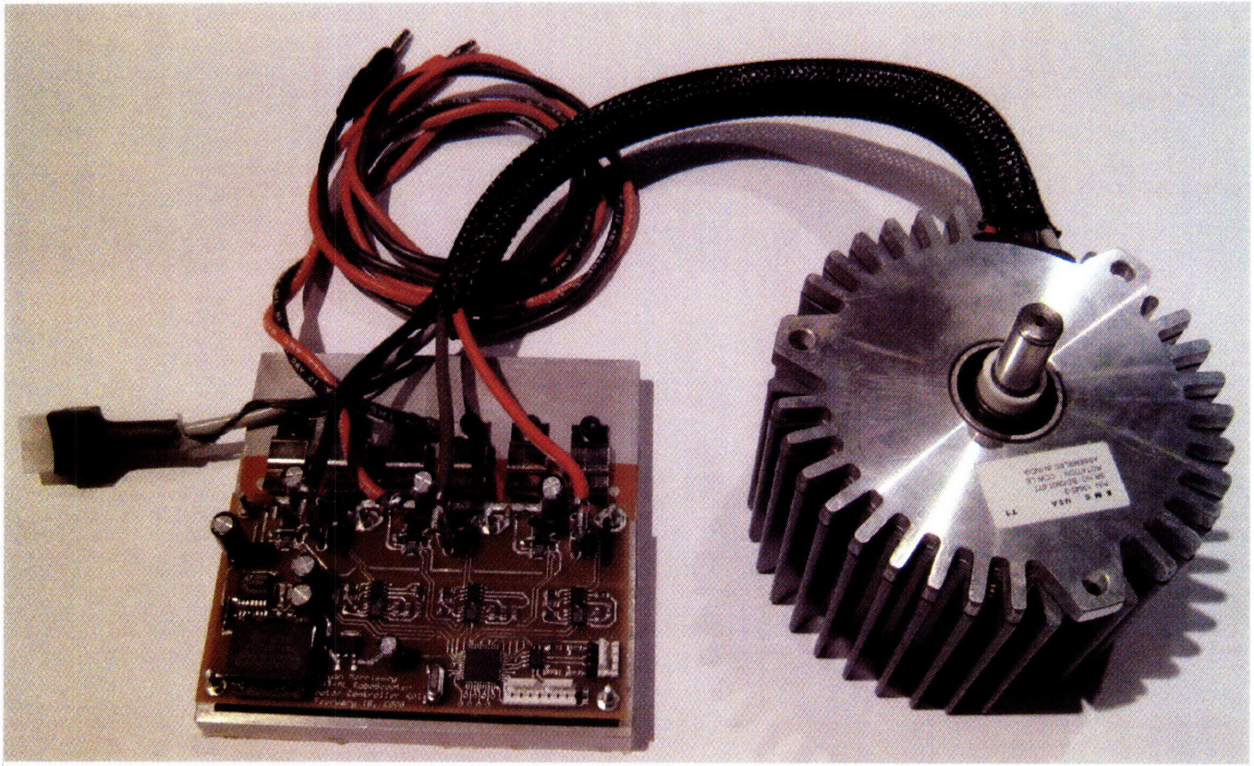


Figure 9: Finished BLDC motor controller with BMC scooter motor

Listed below are the functional blocks for my BLDC motor controller, shown in Figures 8 and 9. The circuit schematics are in Appendix A.

Power regulation systems:

- The step-down DC switching voltage regulator is built with the LT1076HV adjustable output switching regulator from Linear Technology. This voltage supply powers the MOSFET gate drivers. The regulator is designed to provide up to 2 Amps at 12 Volts from an unregulated input voltage up to 60 Volts.

- The 5 V supply for the microcontroller and the signal processing devices is generated from the 12 V supply by a surface-mount 7805 linear voltage regulator.

- A high precision 2.5 V reference for the signal processing block is provided by the ADR03 voltage reference device from Analog Devices.

High Current Switching:

- The power transistors are International Rectifier IRFB1405BA power MOSFETs. These devices are rated to operate with a supply of up to 55 V. They are rated current to handle over 90 Amps of current, but this ultimately depends on the effectiveness of the heat sink and thermal management. The rated on-state resistance is roughly 5 milli-ohm; a 50 A current will cause a 250mV drop while dissipating 12.5 Watts of thermal power in the device.

- The MOSFET gate driver circuit is the Linear Technology LTC4444 dual high-low gate driver chip. This is a very recently developed device, having been announced in November of 2007. It is attractive in that it provides a single chip solution for driving the gates for both the high- and low-side MOSFETs for each of the three motor controller legs (Figure 7 and Appendix A). This single chip solution substantially reduces the circuit complexity and simplifies the board layout.

Sensing and Feedback:

- Each of the three motor drive currents generated by the power circuitry passes through a 0.0005 Ohm (0.5mOhm) current sensing resistor before leaving the controller board (Figure 7). The small differential voltage across this resistor (0.5 mV/A) is detected, amplified, and converted to a single-ended voltage by the Analog Devices AD8216 difference amplifier. This chip is designed to detect and amplify small differential voltages in the presence of large common mode voltages between -4V and +65V while operating on a single 5V power supply. The output signal is three times the difference between the two input signals, referenced to the 2.5V precision voltage reference.

- The output signal from the AD8216 is amplified further using half of a Linear Technology LTC6241 rail-to-rail dual operational amplifier chip. The second op-amp in the package is used to scale and offset the total voltage on the output terminals to be measured directly by the dsPIC microcontroller.

- The 0.5 mOhm current sense resistor has a nominal power rating of 3 Watts. Using the

$P = I^2R$ relationship this corresponds to a current of roughly 75 Amps. The target current rating of the motor controller is 50 Amps output, but it is possible that peak current may be much higher than this, especially during regenerative braking. It should be noted that the current sense resistor is a relatively small surface-mount device, so the nominal power ratings will be regarded as optimistic until demonstrated otherwise. It may eventually prove necessary to find another sense resistor to replace the current device.

Data processing and communication:

- The data processing will be handled by the a chip from Microchip's family of "digital signal microcontrollers," the dsPIC30F4011. These chips offer many advantages traditionally associated with microcontrollers, in particular low cost and ease of implementation due to the integration of hardware to handle common analog measurement tasks. This architecture also provides much more computational power than traditional microcontrollers, making them suitable for the fast computation necessary to process feedback and update the output signals in real time. The dsPIC30F4011 is specifically targeted for three-phase BLDC control applications, implementing six PWM outputs to drive the six MOSFETS of a three-phase driver bridge, as well as nine high speed ADC inputs and a dedicated interface for a quadrature position encoder. Finally, the dsPIC30F4011 has a built-in CAN controller interface which implements the timing, addressing and error checking defined by the CAN protocol in hardware. All that is necessary to implement a full CAN-bus network interface is a CAN transceiver to convert the CMOS logic levels to the differential signaling used on the network bus.

- The MCP2551 is Microchip's transceiver chip. It's function is to translate incoming logic signals into differential signals to be asserted on the bus, and detects the signals which other devices assert, converting them into the logic signals to be relayed to the microcontroller.

A design and implementation of high-current pathways:

Printed circuit boards from ExpressPCB are manufactured with a 0.0017 inch thick layer of copper. No matter how wide the traces are, this thickness of copper will produce a substantial voltage drop in the high current paths in the motor controller. Substantial effort was made to mitigate this problem. Whenever possible, high current contact points are placed adjacent to each other, and connected with traces on both the top and bottom board layers. In many cases these traces are almost as wide as they are long. When a high-current pathway needed to travel any distance greater than ½ inch on the board, the connection was completed with 18 AWG solid copper wire. This strategy allowed me to keep many traces both shorter and wider than one tenth of an inch. Finally, the heat sink was designed to double as ground plane, with aluminum standoffs providing multiple redundant connections between the board ground plane and the thick aluminum heat sink block. In spite of this effort, the success of these strategies in mitigating power loss will not be fully known until full power testing is performed.

BLDC Controller Design Status:

By the end of March, I was able to demonstrate that both the high-voltage switching power supply and the 5V linear voltage regulator are fully functional. The 2.5V precision reference also tests properly, and gate drivers as well as all of the signal conditioning components produce voltage levels that are consistent with design expectations for quiescent operation. The next step in the design process will be to write some preliminary diagnostic and testing routines to run on the dsPIC microcontroller to make sure that all blocks continue to function as expected before testing the motor and controller under load.

However, I was unable to proceed further with the necessary testing and programming because I diverted my efforts to quickly develop a control interface system in support of the City Car demonstration for Sponsor Week.

I plan to continue with further testing and development on the motor control system at the end of the term.

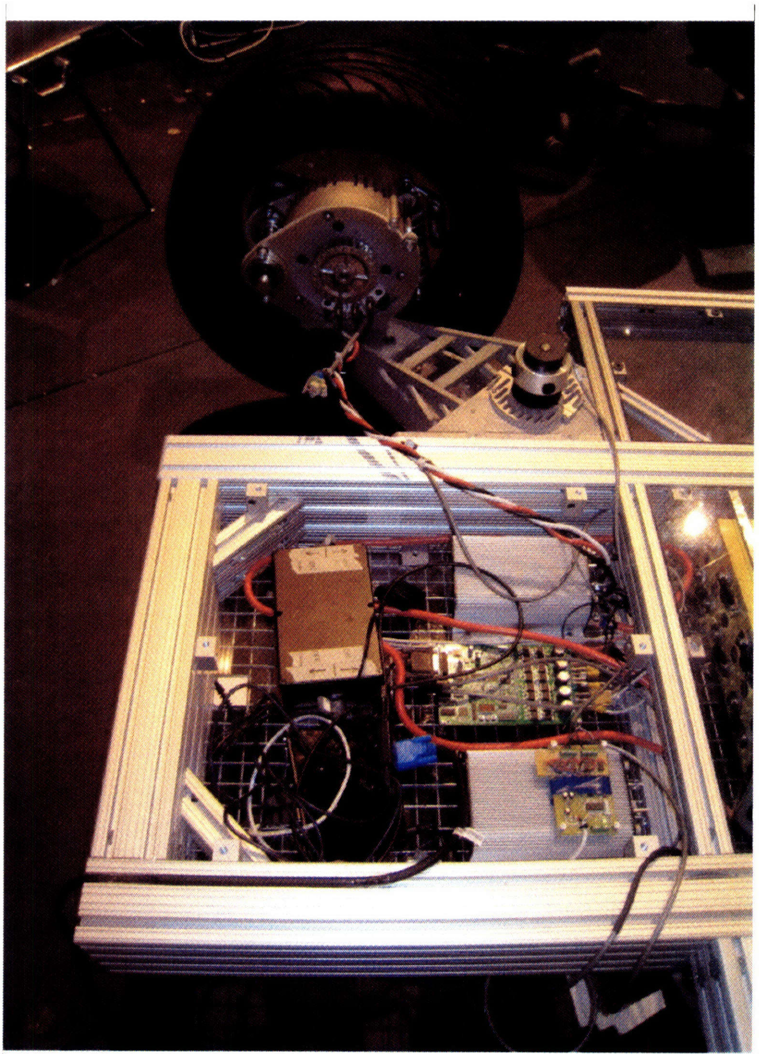


Figure 10: Power and control electronics for the City Car demonstration prototype

B. USB sensor and control interface boards for the City Car and RoboScooter projects

I immediately proceeded with the development of a USB-based control and sensor interface which can be assembled in two different ways, to be used in both the City Car and the RoboScooter. In order to get the City Car demonstration working, we needed an interface that would allow us to control the Kelly Controls BLDC motor controller already installed in the City Car with a standard computer

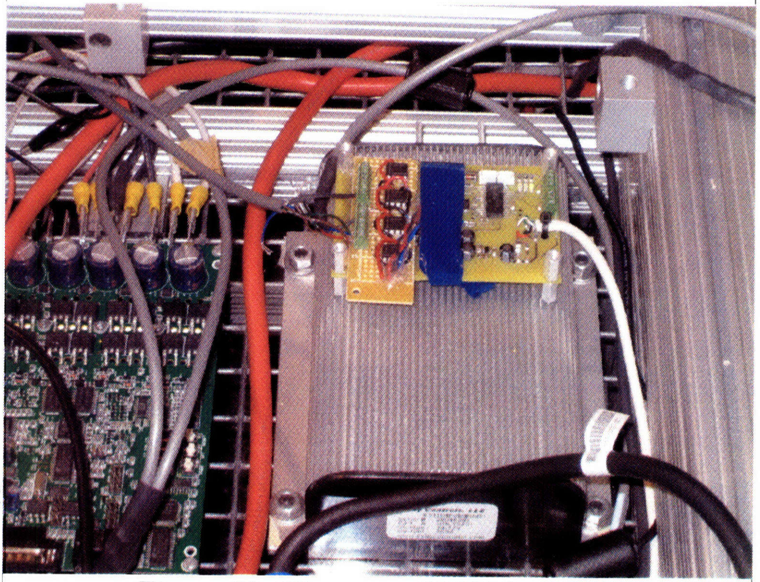


Figure 11: Close-up of USB Interface

running the Linux operating system. To accomplish this, I built a powered USB interface board which can provide eight independent analog voltage sources with 0-5V range, which is enough to provide full drive control for two Kelley BLDC drive motor controllers.

The board was designed to support a second set of components so that it could also be used as a computer control interface for the RoboScooter. When assembled in this second way, the board supports a set of accelerometer and gyroscope sensors intended to enable inverted-pendulum style balancing operation while the scooter is folded. The board also provides several high-precision ADC inputs for the scooter's throttle and folding control potentiometers, and a pair of PWM output signals which can be filtered to provide precision analog outputs.

The schematic for the interface boards is included in Appendix B.

Common features between the two interface boards:

- Both of the USB interface boards are based on the PIC18F2458, part of a family of inexpensive microcontrollers offered by Microchip. In addition to the USB interface, this chip provides 10 ADC inputs with 12-bit conversion precision, along with a standard I2C serial interface (used to control the Maxim DACs, described in the next section) and two PWM outputs which can be filtered to produce precise analog signal levels.

- Both boards also had to contend with a problem cause by relying on the USB port for power. The voltage specification for USB port power has wide tolerances, and even variations in the processor load can cause easily measurable variations in USB port voltage. This can be a problem when a steady supply voltage is necessary to produce a steady control output signal. The interface boards use a capacitor charge pump, the Semtech SC1462, to double the voltage received from the USB port. This doubled voltage is stepped down by a high-precision linear voltage regulator, the LP2950. This system produces an extremely stable current, at the cost of consuming twice as much current from the USB port as is available on the supply.

USB – analog output interface for the City Car Demo (Figures 10 and 11)

- The interface board uses the Maxim MAX518 Digital/Analog Converter (DAC) to generate the voltages. Each of these chips provides two independently addressable 8 bit precision outputs, along with a pair of pins which can be used to assign a 2-bit address to each chip. This allows four chips to be addressed on a single I2C bus, for a total of 8 independent outputs.

- The board was originally designed to use these chips in a surface-mount package; this package was out of stock when the chips were ordered, so the DAC interface was implemented as a hand-wired daughterboard using through-hole packages.

USB – analog and digital interface for RoboScooter

- One of the long term goals of the RoboScooter project is to develop the capacity for fully automated folding and inverted-pendulum balancing while the scooter's wheels are next to each other in the folded configuration. Automated folding will require feedback from a position sensor in the folding joint, and balancing will require gyroscope and accelerometer feedback. The interface board was designed to accept a daughterboard with a MEMS gyroscope and two-axis accelerometer from Analog Devices.

- The daughterboard is an Inertial Measurement Unit (IMU) Combo Board purchased from Spark Fun Electronics (www.sparkfun.com). The board uses the ADXL203 accelerometer and ADXRS401 gyroscope from Analog Devices

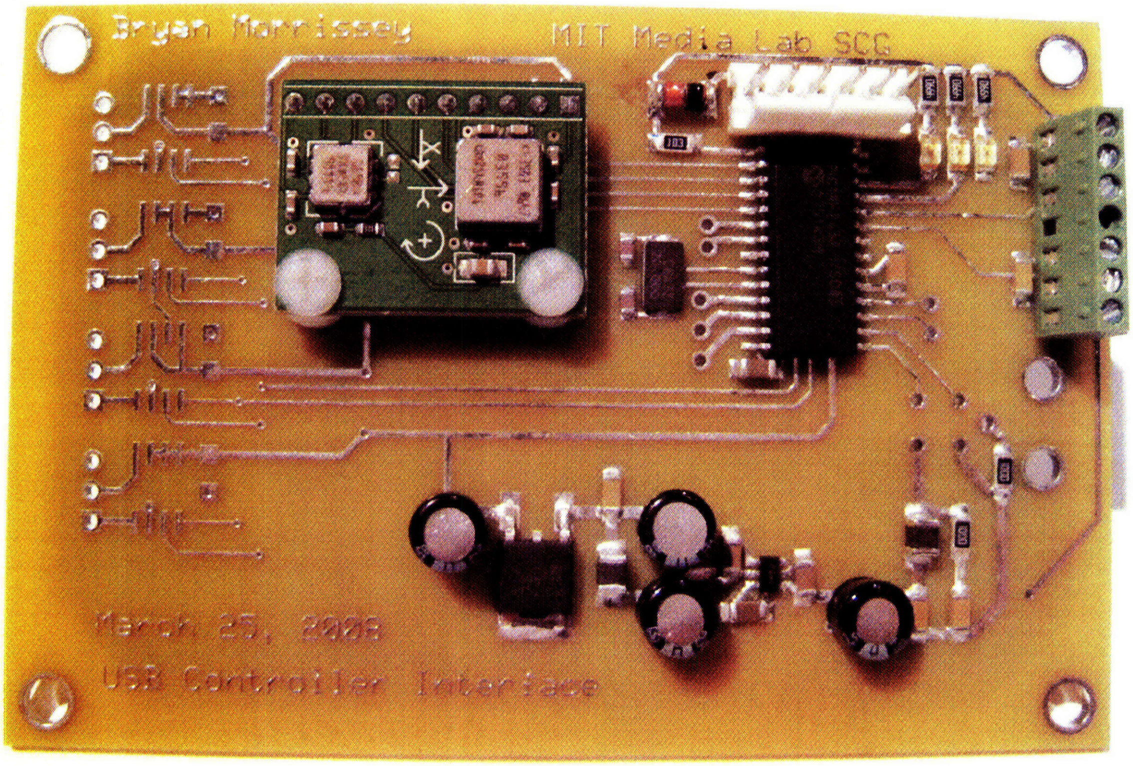


Figure 12: USB Interface with MEMS gyroscope and accelerometer daughterboard

V. Analysis and Discussion

In the course of my thesis research, I designed and built three electronic control systems to support the development of the City Car and RoboScooter electric vehicle projects. The first system is a brushless DC motor controller with a digital network interface, which will be used to test and develop methods to coordinate multiple drive motors through a single vehicle control network. The other two systems are USB-based control and sensor interfaces, which provide a way for an ordinary computer to send commands to the simple analog control interfaces on the control systems already present in the prototype vehicles.

As the Smart Cities continues to develop these vehicles, we are hoping to develop the digital motor control technology necessary to realize the full potential of the Wheel Robot concept and the advanced vehicles which will incorporate it. Some of the hardware described in this thesis may provide a basis for future control systems development in the group, and I hope that some of the lessons which I learned will help to guide the next stages of this research.

One possible extension of the work described hear would be to build upon the USB control and sensor interfaces to include a CAN-bus network interface. This would be a fairly straightforward feature to implement in hardware, as inexpensive integrated circuits are available from multiple vendors which convert the CAN protocol to serial protocols which are commonly implemented on microcontrollers. This would provide the group with the ability to implement both ends of the proposed vehicle control network with home-built hardware, and any laptop or desktop computer with a USB port could be connected to the vehicle control network, which could be immensely valuable for software testing and development.

The USB interfaces were fairly simple to design and build. The BLDC motor controller is substantially more complicated than those circuits, and much work remains to be done before it will be ready to drive a traction motor in a real vehicle. Algorithms for internal feedback controls will need to be developed and tested, and a communication and control protocol to run on top of the CAN-bus network need to be designed. Finally, the power electronics need to be thoroughly tested driving high current levels into the motor under severe conditions before they can be guaranteed to be safe. At this early stage, it is difficult even to guess how efficient the system will be or what switching frequency will be optimal under which conditions. While basic calculations have been performed, any new design for a high power electronic system needs to be treated carefully and tested gradually before it can be trusted to meet its design specification.

VI. Conclusion: Looking Forward, Ongoing Research

Many questions remain open as we decide our next steps to continue pushing the motor control system development.

One question that remains open is which feedback control techniques will be most effective way for the motor controller to generate the necessary output signals. The current motor controller is designed in an open-ended fashion to allow experimentation with at least the three control methods listed here:

- So called "sensorless" motor control is a technique in which the controller measures the relationships between the two driven motor inputs, the third undriven input, and the current in the three winding legs. This technique determines the instantaneous position and rotational velocity of the permanent magnet rotor with respect to the three stator windings by separating the components of current and voltage generated as back-EMF in the motor from the components due to the driving voltage. This method is not truly "sensorless" in that it requires accurate and simultaneous measurement of currents and voltages. This technique also requires substantial computational capacity to generate the necessary waveform timing. This method is mostly implemented in cost-sensitive systems like fans and blowers, where the load is relatively constant and there is a substantial benefit gained by eliminating the need for Hall-effect sensors or position encoders.

- Hall-effect sensors are typically used in BLDC traction motors to indicate the current position of the permanent magnet poles phases of the rotor with respect to the stationary windings. The resolution provided by this technique is usually not adequate to enable a BLDC motor to do position feedback and control, it is sufficient to determine the phase and polarity of the drive currents based of the position of the rotor magnets.

- Direct position feedback and control is possible through the use of a high resolution optical encoder. This method offers the flexibility of enabling either position or velocity control; torque control can also be implemented by measuring the current in the motor windings.

Another important question is what PWM switching frequency will provide optimal efficiency and performance. This remains difficult to determine. On one hand, it would seem that resistive losses are minimized when the switching frequency is high enough that the inductive reactance of the coils exceeds the coil resistance. For the BMC PowerPack motor, this crossover occurs at roughly 100 kHz; these high frequencies present problems, as the apparent resistance of the thick copper wires in the winding increases due to the "skin effect," as the electrically conductive region becomes increasingly restricted to the surface of the copper at high frequencies. Other problems that occur at high frequencies include the losses incurred each time a MOSFET turns on or off. Each time the MOSFET has a switching transition, there is a brief period when the resistance is large but not infinite, and any current through the device at that point will induce thermal heating and resistive losses. Also lost is the energy with charges the MOSFET gate each time the device is turned on; this charge is dumped to ground when the switch is turned back off. At low frequencies these switching losses are minimal, but they can dominate at high frequencies and offset any gains that might be made through high frequency operation. Many current BLDC controllers operate in the frequency range of 5 to 20 kHz, but this has gone up as the power devices and data processing improves; it is not clear yet what the optimal operating point of our motor controller will be.

VII. References

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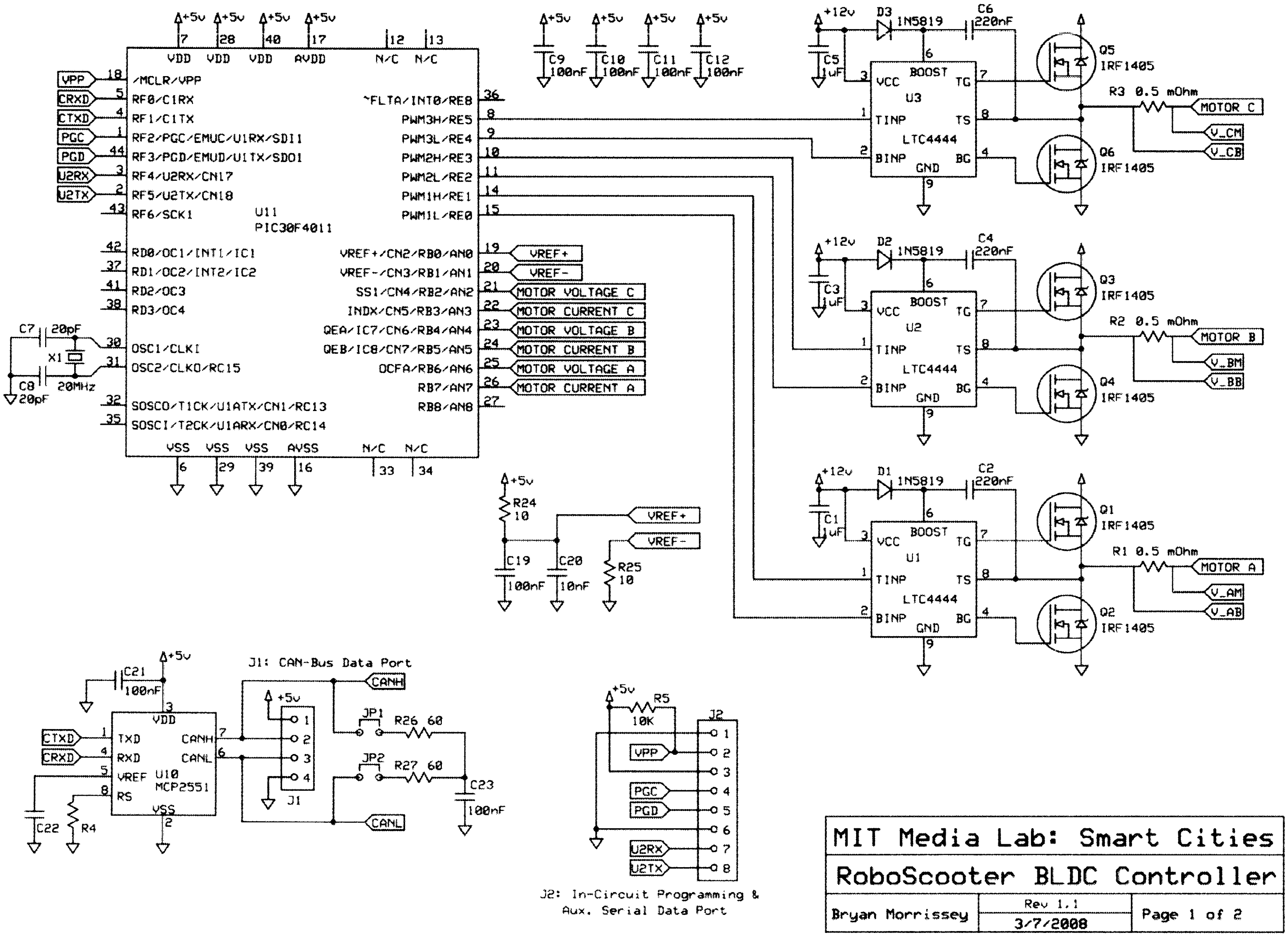
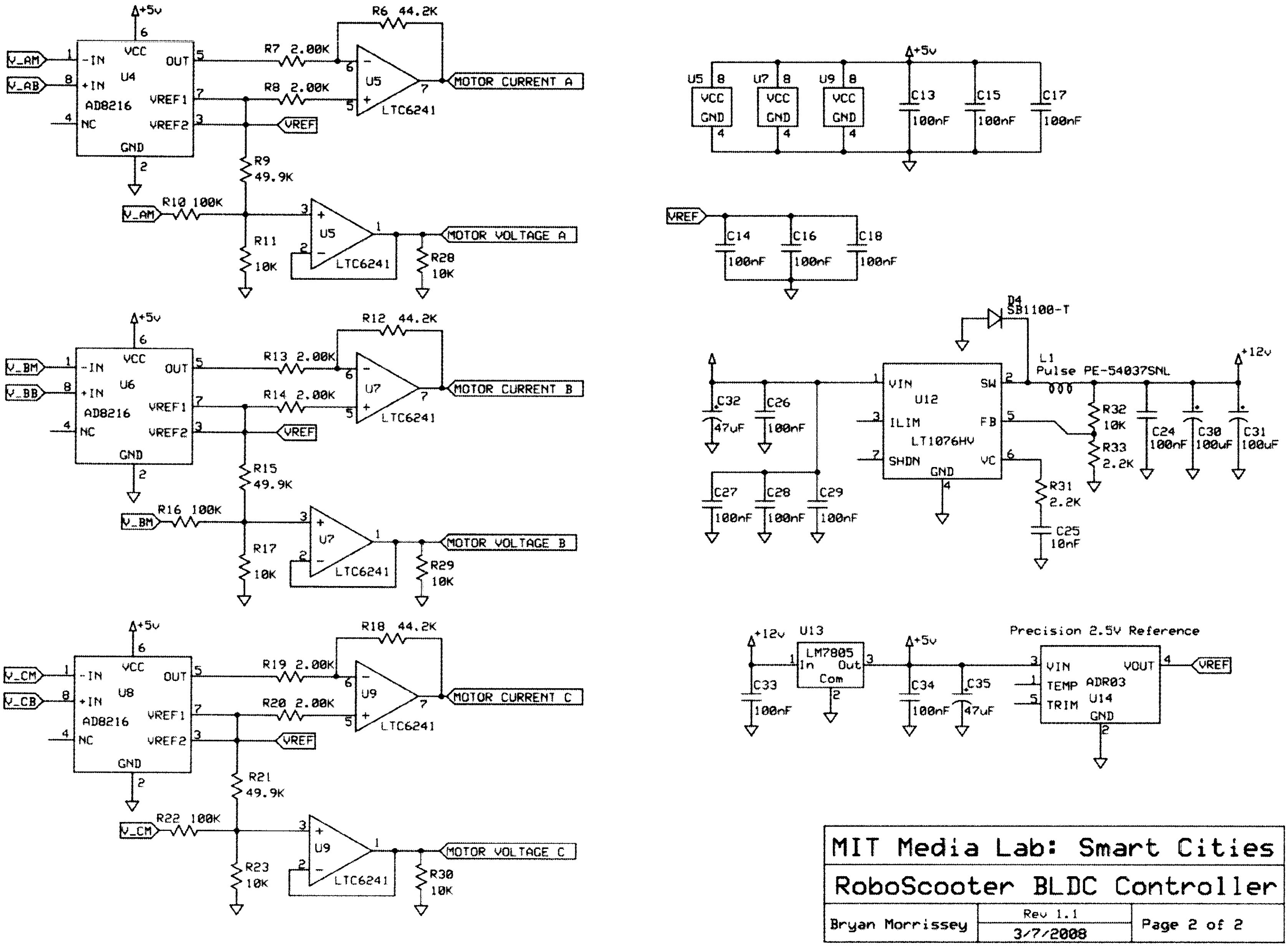
Appendix A: Motor Controller Schematic





MIT Media Lab: Smart Cities

RoboScooter BLDC Controller

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Appendix B: USB Control Interface Schematic