Design of a Motor Control Board for the NASA Lunabotics Mining Competition

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***Abstract*—Motor controllers allow users to control motor speed. A custom motor controller was designed, implemented, and tested that is capable of full bidirectional control of up to four motors. The design underwent three major revisions, each one adding more functionality to the controller.**

***Index Terms*—Motor controller; H-bridge; PWM**

I. INTRODUCTION

In modern systems, electric motors are often used to perform intensive tasks. To allow for variable conditions and reduce the chance of malfunctions in these systems, motor controllers are required. Motor controllers allow a user to fully alter the speed at which a motor runs. If feedback is included, they can also be used to prevent dangerous situations, such as high currents that could damage the motor and other electronics.

II. SYSTEM REQUIREMENTS

The objective of the NASA Lunabotics Mining Competition is to build a robot that is capable of navigating around obstacles, excavating lunar regolith, and depositing the regolith into a collection bin. The lunar excavator must be capable of travelling in forward and reverse directions as well as having a turning mechanism to allow for full mobility during navigation. This requires that the motors are capable of travelling forward and reverse.

To allow for such control, a circuit topology such as an H-bridge can be used. An H-bridge consists of two parallel stacks of two MOSFETs in series. A motor can be inserted with its terminals attached to the common points in these stacks. Complimentary pulse-width modulation (PWM) signals applied to the MOSFETs in a particular fashion allow the motor current to be bidirectional, resulting in the ability for the motor to operate in all four quadrants between full forward and full reverse speed configurations.

During operation large currents can occur due to heavily loaded or stalled motors. These dangerous situations can cause damage to the motors, motor controller, and other system electronics. Further control to prevent or alleviate these fault conditions can be achieved by monitoring the current flowing into the motor through a current sense resistor. This can be done by putting a resistor in series with the input current path, and then measuring the voltage across this known resistor to determine the current. Operational amplifiers can then be used to determine when the current reaches a maximum acceptable value and shut down the complimentary PWM signals immediately, helping prevent damage to the motors and various electronics throughout the system.

III. DESIGN ITERATIONS

A. First Iteration

The first design iteration, shown in Figure 1, was a prototype for the motor controller. The system consists of a serial interface for external control, a PIC microcontroller, logic level shifters, and high power p-channel and n-channel MOSFETs. The high power MOSFETs were required due to the motor selection, high-torque winch motors. The system was designed using application notes and general electronics knowledge. The board was assembled on a perf-board and was point-to-point wired on the bottom side of the board. This board is capable of up to 20A continuous current through any of the four motor channels

B. Second Iteration

The second design iteration, shown in Figure 2, was a printed circuit board (PCB) design of the prototype with slight design modifications. Due to the motor setup on the robot, 5 channels were required. Two of the motors would never be on during one time, so a relay was included to switch between these two motors while maintaining bidirectional control on a single channel. The board also required point-to-point wiring for the channels to accommodate the large required currents, so wires were used for the power connections of the MOSFETs as well as the motor terminals.

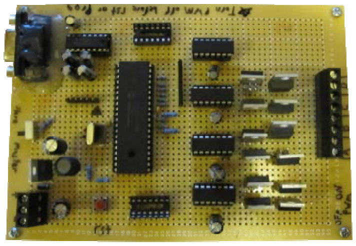

Figure 1. First Iteration.

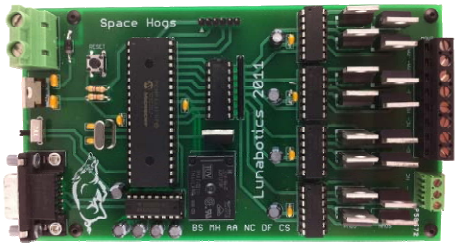

Figure 2. Second Iteartion.

C. Third Iteration

The third design iteration, shown in Figure 3, was designed from the bottom up to be more functional and electrically robust than the previous designs. This PCB included four different modes of communication: Mini-USB, XBee (wireless), and two expansion headers for alternate forms of communication. Additional switches and headers were included to allow for further development as needed. Status indicator LEDs were added to display when each channel was on or off and if any dangerous situations occurred on the channel. This allows the user to easily identify malfunctions and troubleshoot any issues. This design consisted of mainly surface-mount components, resulting in a fast reflow assembly. No point-to-point wiring was required due to thick power traces for the MOSFETs. Also, the driver circuit is capable of using matched n-channel MOSFETs for the high and low sides of the H-bridge, reducing power losses and heating concerns incurred previously from the p-channel MOSFETs.

To prevent over-current operation, a hardware limit of 25A per channel was set using an operational amplifier in a feedback network. This limit can be altered by changing resistor values. When the current increases beyond 25A, the operational amplifier pulls the PWM signals for the channel to ground, effectively disabling the channel. Each channel's current is monitored using the PIC's analog to digital converters (ADCs) during operation. This allows a lower current software limit to be set if desired.

The feedback circuits were designed using LTSpice, a SPICE simulation from Linear Technology. A single channel was designed and simulated to ensure proper functionality, shown in Figure 4. A simulation using a motor model that would require more than 25A was included to ensure that the current would be limited to 25A. The green waveform is the current through the sense resistor, and the blue waveform is the motor current, which is limited to 25A. This occurs because the PWM signals, shown in the bottom waveform, are also pulled to ground when the current limit is reached.

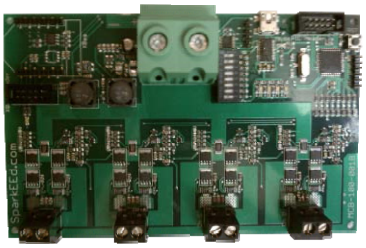

Figure 3. Third Iteration.

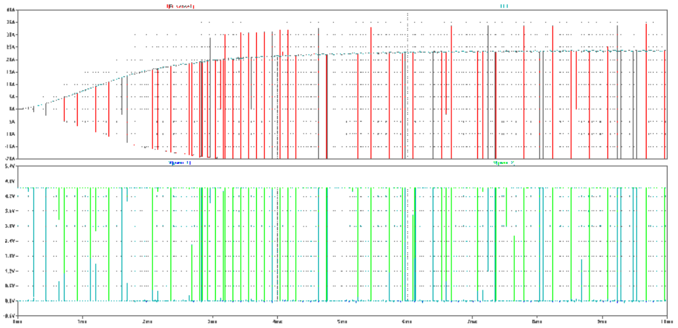

Figure 4. Circuit Simulation

IV. TROUBLESHOOTING

Throughout the design of the motor controller, a large amount of troubleshooting was required. One of the main issues encountered was the power MOSFETs overheating and failing. This was occurring due to the inductive kickback from the large motors. As the PWM would switch directions, a large voltage spike would appear across the MOSFETs. The body diodes in the FETs would activate, dissipating the excess voltage in the form of heat. A fan was included in the second design iteration to reduce device overheating. On the final iteration of the board, this was mitigated by using extremely low on-resistance MOSFETs along with transorbs (transient voltage suppressors) to reduce heating and dissipate any extra energy away from the MOSFETs. Snubber capacitors were also used across the motor terminals to limit the voltage transients seen by the MOSFETs and driver circuits due to the changing currents through the motors.

V. CONCLUSION

Over the past three years, a motor control board was designed for the annual NASA Lunabotics Mining Competition to drive the motors for an excavating robot. The design has undergone three iterations. The prototype design was a basic motor controller using an H-bridge designed on a perf-board with wires for connections. The second iteration was a PCB including a relay that allowed for one of the channels to control two motors, although both could not be on at the same time. The final PCB design included many additional improvements. Feedback was added to each of the four channels to monitor the current through the channel for over-current detection. If the over-current detector circuit was tripped, the channel was immediately shut down, preventing damage. LEDs show the status of each channel and indicate if any fault conditions have occurred. Communication interfaces were also greatly expanded. Options available include Mini-USB (wired), XBee (wireless), and two expansion headers for alternate communication standards.

VI. BIBLIOGRAPHIC INFORMATION

Chris Farnell is a PhD student in the Department of Electrical Engineering at the University of Arkansas; he graduated with his BSEE from University of Arkansas in 2010.

Brett Sparkman is a PhD student in the Department of Electrical Engineering at the University of Arkansas; he graduated with his BSEE from University of Arkansas in 2011.

Scott C. Smith is an Associate Professor of Electrical Engineering at the University of Arkansas. He received his PhD in Computer Engineering from University of Central Florida in 2001, a MSEE from University of Missouri – Columbia in 1998, and BSEE and BSCpE degrees from University of Missouri – Columbia in 1996.

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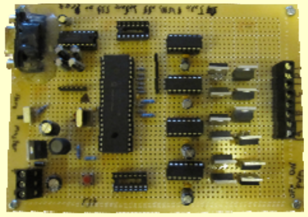
Abstract

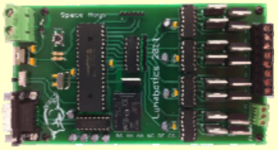
- ❖ Electric motors are often used to perform intensive tasks
- ❖ Motor controllers allow for variable control of these motors
  - Bidirectional control
  - Protection circuitry for faults
- ❖ A custom motor controller was designed for the NASA Lunabotics Mining Competition
  - Three design iterations
  - Four communication options
  - Feedback circuit for over-current protection with status indicators

Design Iterations

- ❖ Revision 1: Perf-board Prototype
  - Point-to-point wiring for all connections
  - Serial communication for control
  - PIC 18F4431 microcontroller
  - Logic level shifters
  - High power p-channel and n-channel MOSFETs
  - 20A continuous current per channel

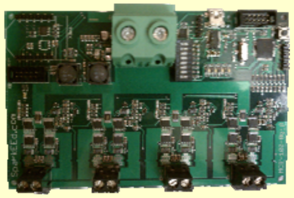


- ❖ Revision 2: Printed Circuit Board (PCB)
  - Point-to-point wiring for power MOSFETs only
  - Robot design required 5 motors
    - Added relay to control fourth channel motor selection

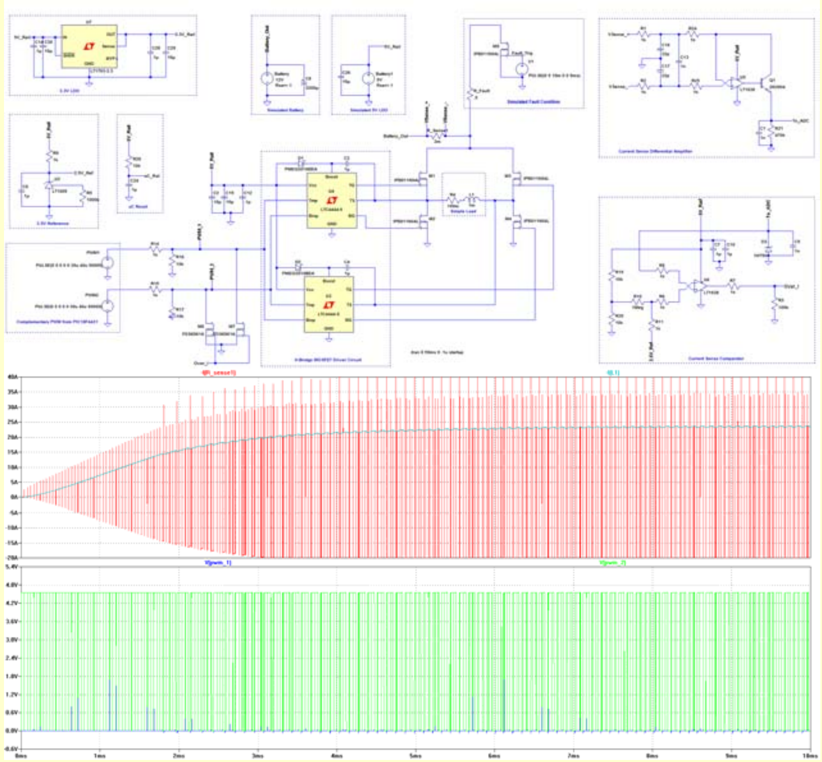


Design Iterations

- ❖ Revision 3: Additional Functionality and Robustness
  - Completely routed on PCB
    - Mostly surface mount components for reflow assembly
  - High power n-channel MOSFETs only
    - Lower losses and heat
  - Four options for communication
    - Mini-USB
    - Xbee (wireless)
    - Two expansion headers for alternate forms
  - Switches for further development
  - Status LEDs for channel indicators
    - On, off, or over-current conditions
    - Allows user to easily troubleshoot
  - Feedback network
    - Hardware op-amp to limit current at 25A
    - PIC analog to digital converters to set software limit



Schematic and Simulation



Troubleshooting

- ❖ Heat in power MOSFETs caused component failure
  - Destructive to other portions of design
  - Conduction losses during on-time
  - Voltage transient losses from inductive kickback during turn-off in MOSFET body diodes
- ❖ Solutions
  - Add fan to sink heat
  - Use only n-channel MOSFETs for lower conduction losses during on-time
  - Add transorbs (transient voltage suppressors) to sink power during large transient voltage spikes
  - Add snubber capacitors to reduce transient voltage spike peaks

Conclusion

- ❖ A custom motor controller was designed for the NASA Lunabotics Mining Competition
  - PCB design with surface mount components for reflow assembly
  - PIC 18F4431 microcontroller
  - Improved H-bridge using only n-channel MOSFETs
  - Four options for communication
    - Wired or wireless
  - Status LEDs
    - Power and fault conditions
  - Feedback circuitry
    - Hardware limit of 25A
      - Customizable with resistor values
    - Customizable software limit
- ❖ Future development and use in competition

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- ❖ Coilcraft and Linear Technology for providing sample parts