A Flexible-Input, Desired-Output Motor Controller for Engineering Design Classes

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***Abstract*—The flexible-input, desired-output (FIDO) motor controller is a robust wireless motor controller specifically designed for engineering design classes where students design and build radio-controlled devices that are typically featured in an end-of-semester celebration or competition. The controller receives bidirectional control signals from a standard 72-MHz band hobby radio transmitter and proportionally drives four motors with up to 3 A of current in each. The controller is designed to accommodate changes to the battery voltage as well as motors with different voltage ratings. It is also designed to be built easily by teaching assistants and can be reused year after year. These capabilities are designed to lower the cost of running this type of class and reduce the organizational work load required of the instructors. Specifically, this motor controller enables the use of commercial cordless drill batteries as inexpensive, portable sources to power motors at a wide range of voltage ratings. The drills are also used during the class as construction tools and can be used by the student after the class. The FIDO motor controller has been successfully tested in the 2.007—Design and Manufacturing classes at the Massachusetts Institute of Technology (MIT) Cambridge, and its utility and acceptance are confirmed by a class survey. Detailed circuit schematics are provided in the Appendix.**

***Index Terms*—Engineering design, motor control, robot competition.**

I. Introduction

ENGINEERING design competitions are great educational tools for teaching students about the design process [1]–[3]. The competitive atmosphere of a contest engage students' interest; the practical construction work teaches students hands-on skills; and the time constraints forces students to exercise their project management skills. Consequently, and not surprisingly, many engineering programs in the U.S. and around the world have incorporated such classes in their curricula [2]–[5].

The usual format of these classes involves building a radio-controlled machine (often, even though they are not autonomous, they are referred to as a "robot") to accomplish a specific task. At the start, students are given identical kits of parts and raw materials, and over the semester the students are led through a deterministic design process to arrive at a machine for accomplishing the goal. At the end of the semester, students compete in a final celebration of machine-versus-machine contest.

Developing and organizing such a class, however, can often be difficult because of the wide range of materials required and the often tight financial constraints. In most cases, the class budget or desired volumes are not sufficient to purchase components with the appropriate specifications. As a result, instructors often have to resort to surplus suppliers and corporate donations for parts, such as motors, gear boxes, and batteries. To further complicate things, motors, batteries, and motor controllers that have compatible ratings are often difficult to find, thus forcing the instructors to develop temporary fixes to make them work together. This scenario can repeat itself year after year and consume a large amount of the instructors' time and energy.

This project proposes to solve this problem by developing a flexible motor controller that is robust enough to be reused year after year, flexible enough to accept a wide range of battery voltages, and capable of reconfiguration to drive motors with different voltage ratings. The flexible-input, desirable-output (FIDO) motor controller was originally developed for the 2.007—Design and Manufacturing class at the Mechanical Engineering Department of the Massachusetts Institute of Technology (MIT), Cambridge. The 2004 and 2005 offering of the 2.007 class was used to test the motor controller, and a student survey was used to gather feedback and assessment data.

A secondary purpose of this project is to investigate the feasibility of adding electronic design to the Mechanical Engineering (ME) curriculum. Electronic skills are becoming increasingly important to ME design students. As ME departments begin to build electronics into their curriculum, this project provides an opportunity to answer some key questions such as, When should electronics be taught? Can exposure to the design of a robot control system help engage students' interest in electronics? Can an integrated electrical and mechanical design class be built into the ME curriculum?

II. Motivation and Background

A. Motivation

A second-year ME class 2.007 is intended to teach the creative design process and provide an introduction to machine elements.[1] Students learn fundamental engineering principles, appropriate analysis tools, and experimental methods that they use to design and manufacture a remote-controlled machine for a contest at the end of the semester. The objectives and parameters

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[1]For materials on the 2.007 classes and contest, see http://pergatory.mit.edu/2.007

of the contest change year to year and are designed by the students from the previous year. Some examples of what has been required of past 2.007 robots include depositing weights into bins, climbing ramps, climbing poles, jumping over chasms, and spinning ball-laden pendulum beams.

Throughout the evolution of 2.007 classes, several different methods have been used to power the students' machines. Originally, the 2.007 robots were tethered to a stationary dc power supply. The mobility of the robots was drastically limited because the tether would often tangle in the robot. As a result, cable management often affected the outcome of the contest and distracted students from their primary focus. When the 2.007 contest first went to a wireless format, the students used tethered power for testing and purchased their own alkaline batteries for the contest. This scheme led to inconsistent robot behavior because of the different power levels from the battery versus the tether. Furthermore, purchasing these batteries is an enormous expense to the students, also creating a waste disposal problem. The option of purchasing a laboratory supply of rechargeable batteries has been considered; however, without the students' personal responsibility, the batteries would degrade quickly because of misuse or be misplaced altogether. In reality, the laboratory supply of batteries needs to be replaced after each year.

The ideal solution is a high-capacity rechargeable battery for each student to use and maintain over the course of the semester. Commercial rechargeable batteries and charging systems are prohibitively expensive to purchase and are useless to the students at the end of the class. One of the revelations that led to this work is that high-capacity rechargeable batteries are available in consumer cordless power tools. In recent years, stiff competition and mass production has drastically reduced the price of these tools. For example, a typical 14.4-V cordless drill, including two batteries and a charger, can be purchased for approximately $75 U.S., the equivalent price of a college textbook. In addition to providing power for their robots, the cordless drill is an extremely versatile tool for helping the students to build their robots. In a crowded undergraduate laboratory, personalized drills greatly reduce congestion caused by the availability of tools. After the conclusion of the class, the students can also keep the tools for their own use. After all, what engineer does not need a drill?

The barrier in using consumer cordless drill batteries to power the 2.007 robots is the motor controller. Commercial motor controllers are prohibitively expensive, while off-the-shelf hobby motor controllers are not designed to work at the standard drill battery voltages of 12, 14.4, 18, or 24 V. Furthermore, inexpensive motors generally come from hobby suppliers and are often rated for much lower voltages, which are not directly compatible with these batteries. Consequently, the primary motivation for this work was to develop a flexible motor controller that accepts batteries of different voltages and can be configured to drive motors in a range of desirable output voltages. Using this device, instructors for courses such as 2.007 can put together inexpensive laboratory kits from surplus suppliers without worrying about the continuity of part supply for the next year's class. A secondary motive was to document the design and make it freely available so as to increase ME students' interest in electronics and enable them to build their own controllers.

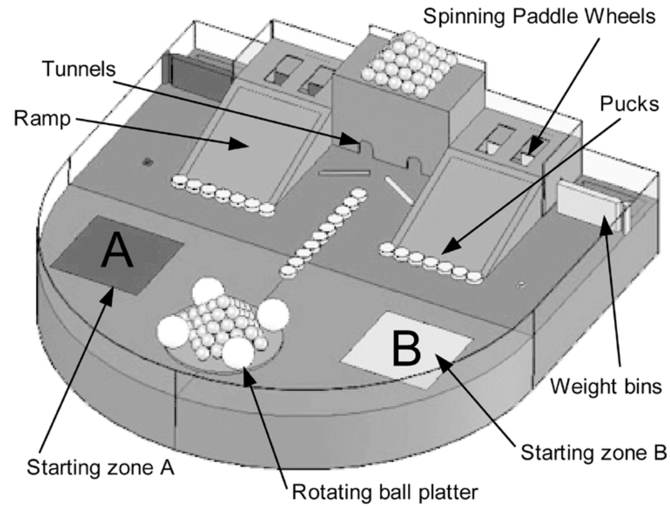

Fig. 1. 2004 2.007 two-player contest arena.

B. Background on 2.007

The 2004 offering of 2.007 was initially used as a field test for the FIDO motor controller. The name of this contest was called "the Big Dig," in honor of Boston's landmark construction project. A solid model of the contest arena is shown in Fig. 1. The robots start on opposite sides of the table and run head to head in 45-second-long rounds. The robot arena consisted of six major elements: starting zones, the rotating ball platter, pucks, tunnels, weight bins, and ramp and paddle wheels. The students can score by pushing balls and pucks into the weight bins, pushing balls into tunnels, and spinning the paddle wheels at the top of the ramp.

The students controlled their robots from control podiums located near each side of the contest table. Each robot was allowed a maximum of four motors, which can be controlled by signals from the podium. Four, one-dimensional video-game joysticks were located on each podium, generating analog signals indicating forward and reverse amplitudes. The motor-control signals are transmitted using standard 72-MHz hobby band radio transmitters (Futaba 4YF-FM). The joystick voltages are converted by another circuit to hobby radio signals and are patched into the transmitter via the "trainer" port. To minimize setup time delays, two identical tables are running during the contest with four control podiums. The control podiums are identified by the colors red, yellow, green, and blue and communicate to the robots on unique frequencies.

At the start of the 2004 offering of 2.007, each student was supplied with a kit that included a Black and Decker Firestorm 14.4-V cordless drill, four motors with gear boxes, and a variety of stock materials, such as metals, plastics, rubber, fasteners, and adhesives. The drill includes two 1.4-Ah rechargeable nickel-cadmium batteries and a charger.

The motors used in this year's class were brushed dc motors used in toy cars. They were purchased from Mabuchi Motors (Part Number: RC-260RA-18 130).[2] These motors are specified for a maximum 6-V input with a 2-A stall current. However, instructors imperially determined that operating the motor under

[2]http://www.mabuchi-motor.co.jp/english/

9 V and 3 A for the duration of the contest and testing did not degrade the motor. The gear boxes, with compatible shafts to the motor, were purchased from Tamiya.[3]

III. System Design

A. Functional Requirements

The functional requirements in designing the FIDO motor controller involve wirelessly controlling four motors with each motor channel capable of providing up to 3 A of current in both forward and reverse directions. The acceptable battery voltages and motor output must be flexible to accommodate year to year changes at both the input and output. The control signal is transmitted over a single channel in the 72-MHz band and received using a standard hobby radio receiver. Mechanically, the motor controller should be robust and compact. The electrical connectors should be secure over the course of the contest. The control box should also be electrically protected against improper handling, such as short-circuiting the output and reversing the battery terminals.

B. Battery and Motor Flexibility

The main innovation of this control box is its ability to accept a wide range of battery sources and then be reconfigured to drive motors at different voltage ratings. The general design strategy for accomplishing this goal is to use motor driver chips that can tolerate a wide power supply range and then use pulsewidth modulation (PWM) to limit the output range.

PWM is a simple technique for controlling the voltage applied to an electrical load. This technique involves applying a full scale, square wave to the load with a frequency that is usually much greater than the bandwidth of the load. The resulting net output voltage is the average dc value of the square wave. The output voltage can be varied by modulating the duty-cycle of the square wave to obtain values from zero to 100%. In high performance motor control applications, the chopping PWM drive can result in higher losses, which limits the power delivered to the motors. However, these limitations are negligible for classroom use and are outweighed by the gains in simplicity.

To interface motors rated at lower voltages than the power supply, the PWM range should be scaled by the ratio of motor to battery voltages. For example, for a 14.4-V battery, which is used to drive 9-V motors, the PWM range should be scaled so that maximum output equals 9/14.4% or 62.5% duty. Therefore, as the motor command signal varies from zero to 100%, the output signal varies proportionally from zero to 62.5%.

For the FIDO motor controller, simple setting of the motor-to-battery ratio is important for customizing each year's class needs. A 16-position switch is included on the interior of the box to select the appropriate motor-to-battery ratio in 6.25% increments.

C. System-Level Organization

A system level diagram of the FIDO motor controller is shown in Fig. 2 and consists of a hobby radio receiver, four H-bridge drivers, a microprocessor with appropriate firmware, switches for selecting the motor-to-battery ratio, ON/OFF button, calibration button, motor command indicators, and status indicators.

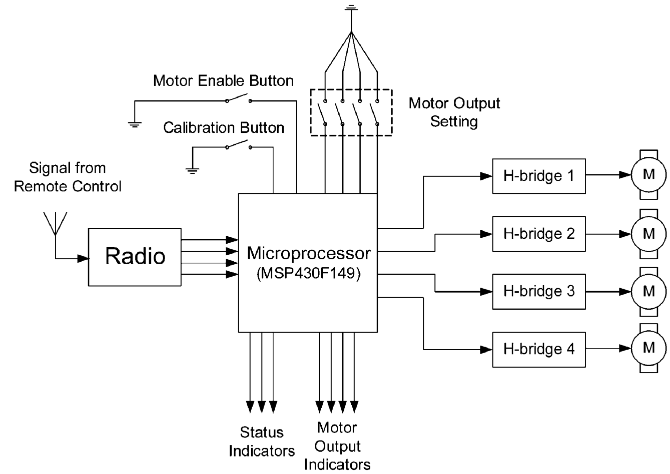

Fig. 2. FIDO motor controller system-level diagram.

D. H-Bridge Motor Drivers

H-bridge motor drivers are basic power electronics circuit topology used to drive a motor in either forward or reverse direction. Although the H-bridge circuit can be found in most standard textbooks [6], a prepackaged part, the LMD18200, is available from National Semiconductor [7], [8] and will deliver up to 3 A of current to each motor.

The supply voltage to the LMD18200 can range from 11 to 55 V, which provides the flexibility of using different battery sources. Since the highest commonly available drill battery voltage is 24 V, the FIDO motor control is designed for a maximum 30-V power supply to avoid the cost of purchasing high voltage capacitors.

The LMD18200 produces a bipolar output to the students' motors. This output terminal is linked to the screw terminals on the printed circuit board (PCB), which is then linked to connectors on the exterior of the control box. The output polarity is controlled by the direction terminal, and modulation is applied at the PWM terminal. The signal going to each LMD18200 H-Bridge is controlled via a digital port from the microprocessor. The control lines are buffered using a standard HC-series buffer driver SN74HC540 [9] to protect the sensitive microprocessor input from voltage glitches in the LMD18200. Each LMD18200 H-bridge is decoupled using a 1000 μf electrolytic capacitor and a 0.1-μf ceramic capacitor. The large electrolytic capacitor is critical for damping the large voltage spikes caused by inductive kickback from the motor and wiring. The current spikes would also, otherwise, interfere with the circuits of the analog radio and could cause reception glitches.

The high output current of the FIDO control box can cause the interior of the control box to heat up. At maximum operating current, each LMD18200 H-bridge can produce up to 0.5 W of wasted heat energy. Heat sinks mounted on the back of the H-bridges help to dissipate the heat energy and limit the temperature rise of the H-bridge chips. A central fan placed between

[3][Online] Available: http://pergatory.mit.edu/2.007/kit/actuator/Tamiya/assembly/tamiya_instructions.pdf

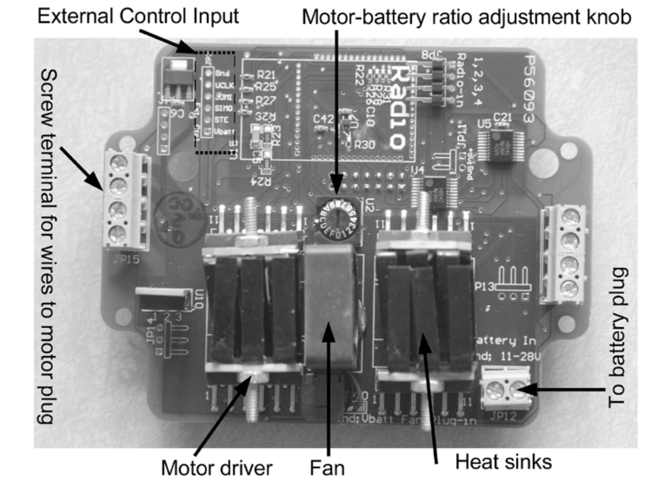

Fig. 3. Back side of the FIDO motor controller; output adjustment knob shown at center.

the heat sinks, as shown in Fig. 3, circulates cooling air through vents cut into the side of the control box.

The LMD18200 also has built-in protection against over heating. An internal temperature sensor produces a thermal warning output when the chip package reaches 140 °C and automatically shuts off the output when the chip reaches 170 °C. The thermal warning pins are open collector output, which means that outputs from all four LMD18200s can be OR'ed together by a single wire to drive an indicator light-emitting diode (LED).

E. Radio Communication and Signal Processing

The command signal for the four motors are multiplexed and transmitted over a single channel on the 72-MHz hobby radio band. A radio receiver (GWS Naro) in the control box receives the signal and demultiplexes them into four separate digital lines. The signal from the radio receiver is in a pulse width coded format, repeating every 100 ms, as shown in Fig. 4. The nominal pulse length is 12.5 ms long and can be longer or shorter to represent positive and negative values, respectively. The length of the pulse is measured using compare–capture functions on the microprocessor timer. The captured pulse length is used to set the duration of another timer loop, which is used to control the duty-cycle PWM output scaled according to the motor-to-battery ratio.

Since the pulse-coded signal originating from the radio receiver is continuous from negative through to positive values, the zero position is ambiguous and can be different based on the transmitter and receiver combination. Therefore, occasionally one must calibrate and store the zero position. The calibration function is controlled via a switch on the control box and an LED at the front of the box shown in Fig. 5. The calibration routine is designed to be hidden from the student and is activated by a timed sequence of button presses according to the state of the calibration LED. After the calibration routine has been activated, the nominal zero values for each channel are permanently stored in the nonvolatile flash memory on the microprocessor.

F. Microprocessor and User Interface

The heart of the FIDO motor controller is a MSP430F149 microprocessor from Texas Instruments [10]. The MSP430F149 is a low-power 16-bit microprocessor that contains digital input/output, analog-to-digital converter, programmable flash memory, comparator, timers, serial peripheral interface (SPI), universal asynchronous transmit/receive (UART), and JTAG serial programming interface.

The motor-to-battery ratio is selected with a hex digital encoder wheel, which has 16 possible positions representing ratios 1:16 through 16:16. The hex encoder is located on the inside of the control box and at the back side of the PCB shown in Fig. 3. For a 9-V motor and 14.4-V battery, the desired ratio is 0.625, or exactly 10/16, which means the hex encoder wheel will be set to the "B" position.

To help the students debug their wiring, as shown in Fig. 5, three LEDs are on each channel: a red LED indicating stop position, a green LED indicating the forward direction, and a blue LED indicating the reverse direction. The LEDs are driven with the same HC-series octal buffer/driver as the LMD18200 H-bridges. The glue logic provides the 5 V necessary to power the LEDs and relieves the microprocessor from the heavy current-carrying duties. LEDs also indicate low battery, thermal warning, calibration, and external control. The circuit for each LED involves a 300 Ω, current-limiting resistor. The LEDs are not shown in the schematic diagrams.

Two external switches are on the control boxes: one for enabling the motors, and the other for calibrating the input. Two connectors are also on the control box: one for the motors, and one for the battery. Both connectors use AMP connectors (AMP Part Numbers: 206 429-1 and 206 044-1). The female half of the connectors is permanently installed on the box, and the students assemble the male connectors to their own wiring. The drill batteries use standard $1/4$-inch tabs, which can be connected using standard crimp connectors.

G. Power Considerations

The battery is used to power three sets of devices in the FIDO motor controller. The H-bridges are powered from the batteries directly. The radio, indicator LEDs, and H-bridge control-line buffers are powered via a linear 5-V regulator. The microprocessor is powered via a linear 3.3-V regulator. Even though they are less efficient, linear voltage regulators are chosen over switching regulators because they are more tolerant of supply voltage variations.

The quiescent current draw of the controller without supplying power to the motors is approximately 200 mA when powered from a 14.4-V battery. The drill batteries have a rated capacity of 1.4 Ah, which means that the ambient draw of the controller can be powered continuously for 7 h. In future iterations of this motor controller, the ambient power draw can be reduced by decreasing the intensity of the LED indicators and using a more power-efficient digital radio.

The maximum current draw of the FIDO motor controller is 12 A when all four motors are stalled. Under this condition, the battery will theoretically last 7 min. In reality, students rarely stall all four motors. From class observations, one battery charge

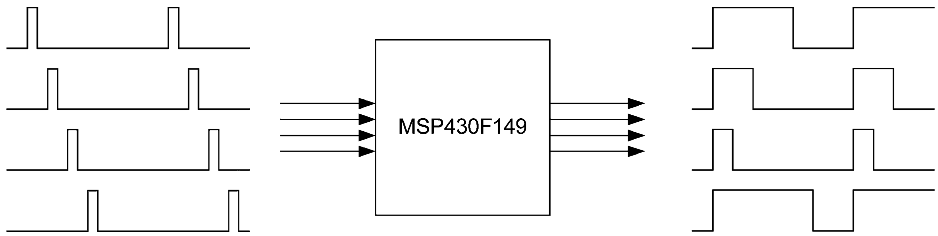

Fig. 4. Signal conversion from radio to H-Bridge.

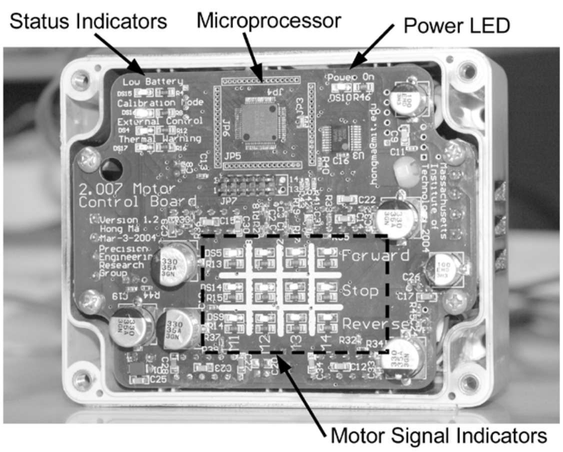

Fig. 5. FIDO front panel without its transparent plastic cover.

is usually sufficient for more than an hour of testing, which is more than enough for the 45-second rounds during the competition.

H. Robustness Features

A number of safety features are built into the FIDO motor controller to make it robust to the student's handling. The box is both tough and compact; the output is protected against short-circuiting; and the battery input is protected against battery terminal reversal; and a low battery warning notifies the student when a battery swap is necessary.

The control box enclosure is a polycarbonate enclosure (Bud Industries Part Number: PN-1323-C) with a transparent lid. The enclosure is machined with holes for the connectors, slots for the buttons, and also cooling vents at the side. A metal mesh is installed over the cooling vents to prevent screws from falling into the inside of the box.

The FIDO motor controller is designed to withstand short-circuiting at its output. The LMD18200 H-bridges are current limited to 3-A average and 6-A peak. When the output is short-circuited, the initial maximum allowed current is 6 A and settles to 3 A over time. If the output short-circuiting persists for a sufficiently long time, the LMD18200 would heat up, and eventually its internal thermal protection would be triggered to shut off the device.

The FIDO motor controller is also protected against reversed battery connector via a diode connected in series with the battery. In addition, a piezoelectric buzzer is installed in parallel with the battery connection, producing a high-pitched squeal to warn students of this error. For abnormally high voltages at the battery terminal, such as those produced by inductive kickback from the motor, a 30-V trans-orb diode is connected in parallel with the battery terminal to absorb these voltage spikes.

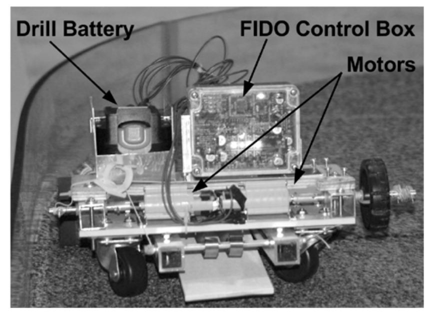

Fig. 6. Control box and drill battery mounted on a 2.007 student robot.

The battery voltage is monitored using the microprocessor's on-board comparator. When the battery voltage drops below a preset value, a warning light is produced to notify the student for a battery change.

I. External Control

The FIDO motor controller can also be used for autonomous robot contests. A six-wire connector allows the control box to communicate with another microprocessor. In this scenario, a separate electronics board with sensors and processing would be connected and would send motor commands based on sensor readings. Communications between the FIDO and the sensor board can be configured for either the synchronous SPI or the asynchronous UART protocol.

J. Manufacturing and Cost

In total, ten control boxes were manufactured, and they were more than enough to run the 120-student class. There was a primary and a backup for each control podium, plus two additional backups.

Without cost optimization and at prototyping quantities, the total cost of components per box is approximately $100 U.S. with $35 being the cost of the H-bridges. The manufacturing costs are approximately $100 per box.

IV. Assessment of Educational Benefits

The goal of this project was to develop a wireless motor controller for engineering design classes that can be reused year after year and is flexible enough to tolerate changes in battery voltages, adapting them to drive motors that may have incompatible voltage ratings. The necessity for this device comes from a lack of inexpensive and continuous supply of motors, batteries, and controllers that can be used for these classes. The flexibility

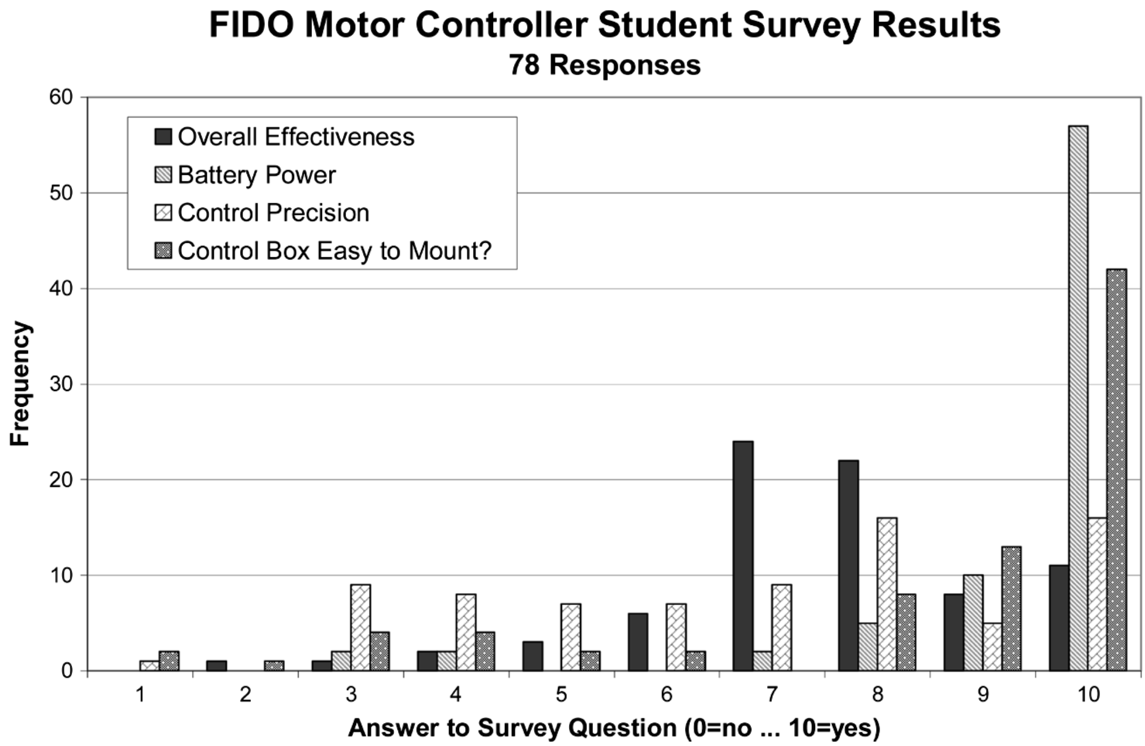

Fig. 7. Student survey results on the FIDO motor controller.

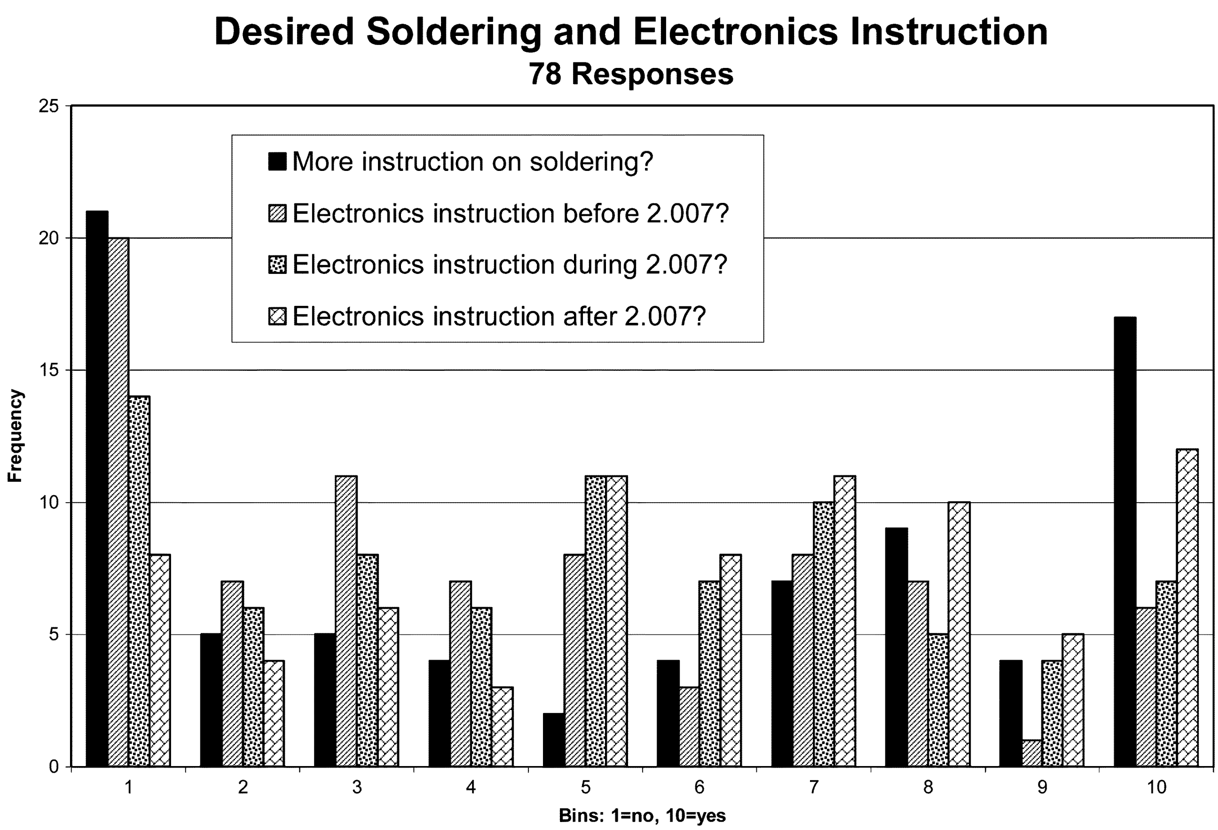

Fig. 8. Student survey results on soldering and electronics instruction.

of the FIDO motor controller makes it a one-time investment and allows educators to purchase motors and batteries from inexpensive surplus suppliers without being concerned about their compatibility.

The immediate application of the FIDO motor controller was for the 2.007—Design and Manufacturing class at MIT to enable wireless control of student-designed robots. The power supply flexibility of the FIDO motor controller allowed the classes to use consumer cordless drill batteries as an inexpensive source of rechargeable batteries. A photograph of the control box and drill battery mounted on a typical 2.007 student machine is shown in Fig. 6.

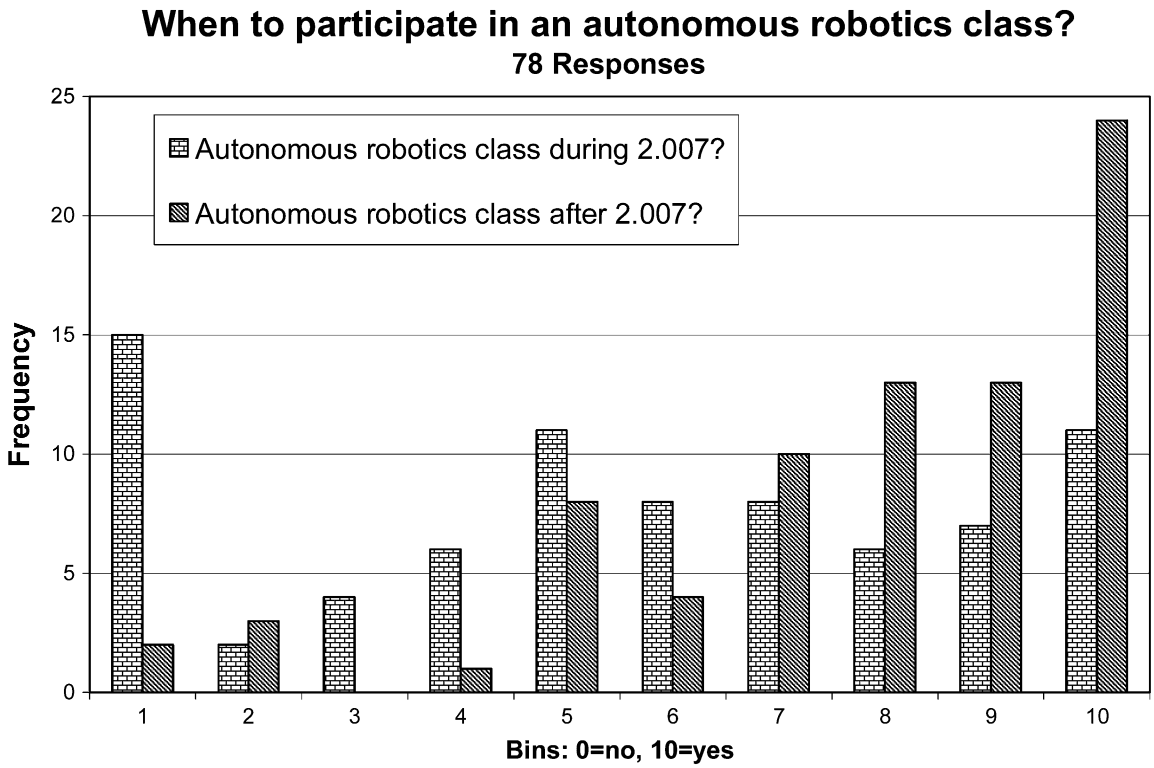

Fig. 9. Student survey results on when to participate in an autonomous robotics class.

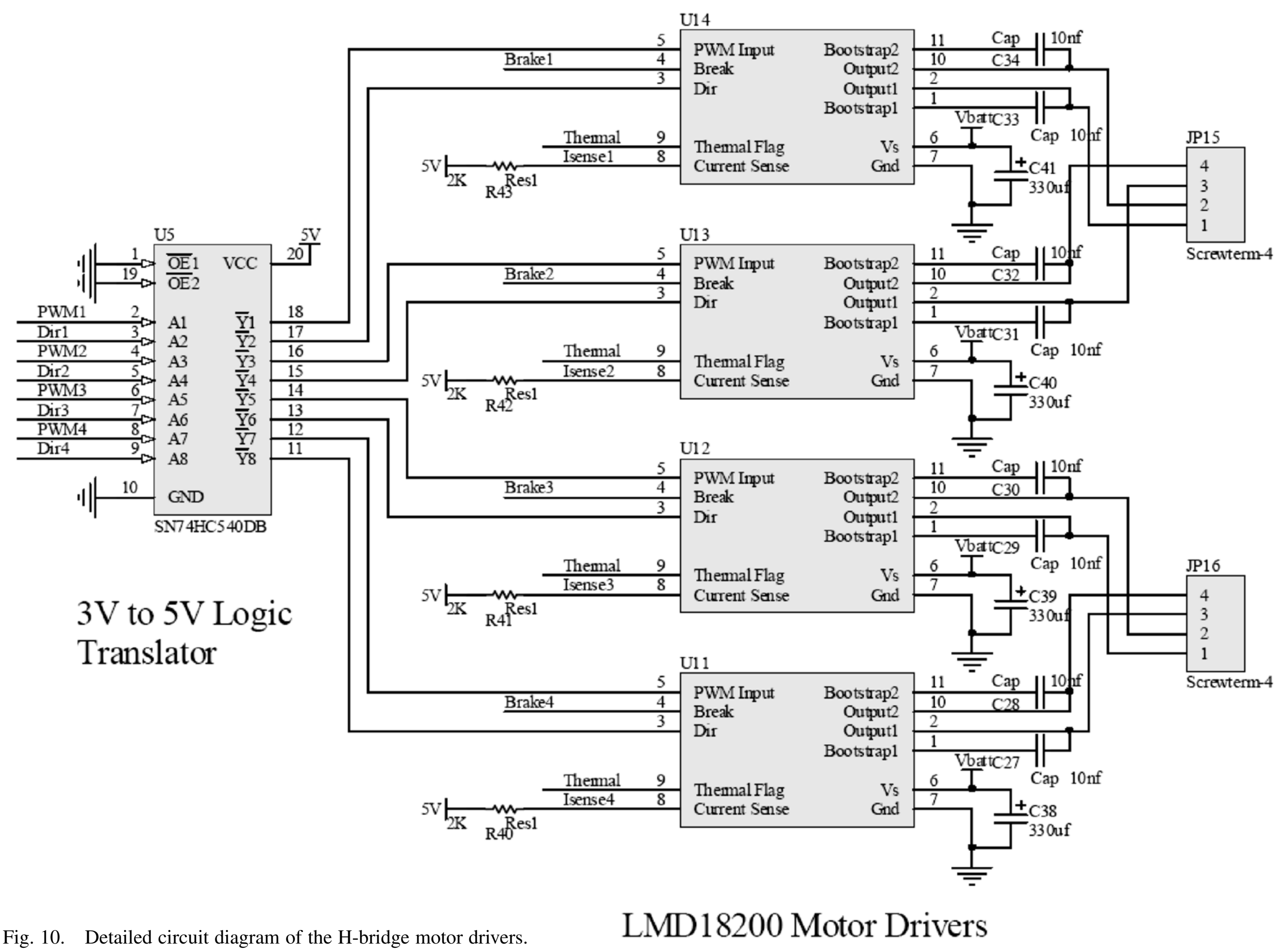

Fig. 10. Detailed circuit diagram of the H-bridge motor drivers.

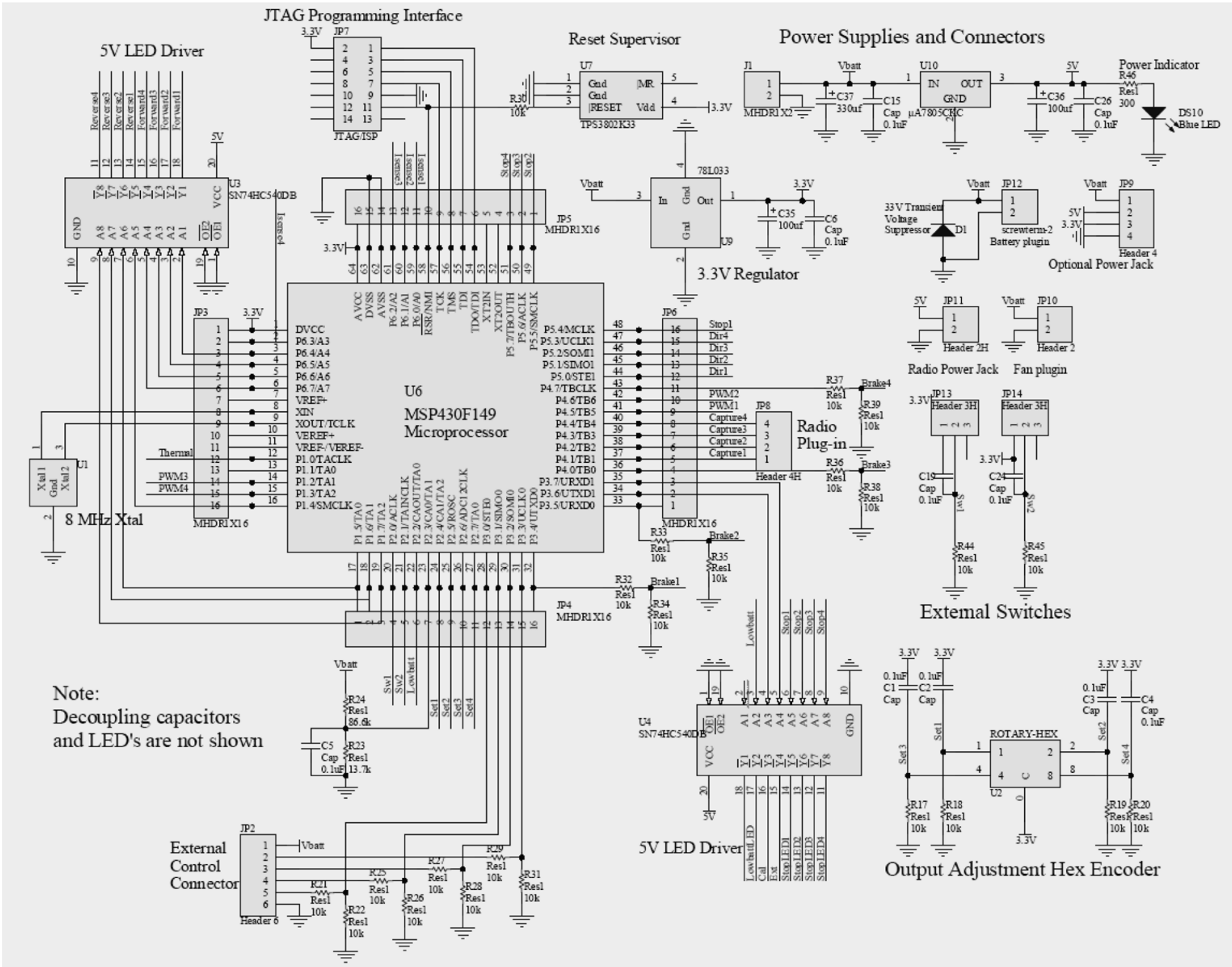

Fig. 11. Detailed circuit diagram of the microprocessor.

The FIDO motor controller greatly improved the 2.007 contest compared with previous years. These improvements can be summarized in the following observations.

- Controlling the robot wirelessly greatly increased the mobility of the robots and reduced the uncertainties caused by cable management.
- The high-capacity cordless drill batteries were a great improvement over nonrechargeable alkaline battery packs used previously. The alkaline battery packs had insufficient capacity, were costly to the students, and were not environmentally friendly. The drill batteries provided a consistent output for both testing and competition.
- Ownership of the batteries gave the students the responsibility of charging and discharging the batteries. As a result, the batteries were well maintained and continued to be useful as part of the cordless drill after the class was finished.
- The cordless drill is a versatile tool for the construction of the students' machines, which greatly reduced the congestion at the drill presses in the laboratory.
- Having two batteries was very convenient for the students to test their robot with one battery while the second one is being recharged.
- The cost of the cordless drill is comparable to that of a university textbook and will be useful to the students for many years to come.

The students in the 2005 offering of the 2.007 class were surveyed to analyze the effectiveness of the control system. Fig. 7 shows their responses from the following four questions. 1) Did the drill batteries provide sufficient power for your machine? 2) Did the control system provide sufficient precision for controlling your machine? 3) How would you rate the overall effectiveness of the control system? and 4) Was the control box easy to mount? The data shows that the students overwhelmingly agreed that the drill batteries were a sufficient power source, and the control boxes were easy to mount. The students responded positively to the precision of the control system and its overall effectiveness with average ratings of 6.83 and 7.56 out of 10.

The student survey was also used to reflect students' interest in learning electronics as part of the ME design curriculum.

Fig. 8 shows the students' responses when they were asked if more instruction on soldering was desired and if they would have liked to have an electronics class before, during, or after 2.007. On the soldering question, the students seems to be divided into a "strongly yes" group and a "strongly no" group. Presumably, this outcome exists because the students who already knew how to solder did not need the instruction, and vice versa for the students who did not know how to solder. On the question of an electronics class, the students were slightly negative about taking it before 2.007 (average response 4.28), mixed about instruction concurrent with 2.007 (average response 4.96), and positive about taking it after 2.007 (average response 6.04). Apparently, exposure to the controller increased the students' interest to learn electronic design once their mechanical design skills have solidified.

Given the students' new-found interest in the integration of electrical and mechanical design, Fig. 9 shows the students' responses when asked if they would participate in an autonomous robotics or mechatronics class concurrent with 2.007 or after 2.007. The students were mixed about an autonomous class concurrent with 2.007 (average response 5.58), but they were more positive about taking it after 2.007 (average response 7.78).

V. Conclusion and Future Work

A wireless motor controller was designed for engineering design classes that can be reused from year to year and be tolerant to different power sources and motors. Reusing the same motor controller each year greatly reduces the cost of running the class, and being able to drive a number of different motors from a wide range of battery voltages greatly simplifies the process of selecting batteries and motors for each year's class. Consequently, not only does this device make these classes less expensive to administer, it also allows the instructors to devote less time to searching for parts and more time to mentoring the students.

This motor controller was successfully tested in the 2004 and 2005 offering of MITs 2.007 class, where a cordless drill was purchased for each student and the drill batteries were used as the portable power source. The students responded positively to having their own rechargeable batteries and also used the drill extensively.

The open-architecture nature of this controller also helped to expose ME students to the electronic aspects of electromechanical systems. Student surveys indicate that ME students were interested in learning some electronics design and applying it to autonomous robots or mechatronics systems.

Future work for the FIDO motor controller involves developing a sensor and signal-processing attachment that can be used to run autonomous robot competitions.

Appendix

Figs. 10 and 11 show the detailed circuit diagram of the H-bridge motor drivers and the microprocessor.

Acknowledgment

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