Work-In-Progress: Closed-Loop Control of a Zumo Robot in an ECE Control Systems Course

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Abstract

Dynamic modeling and the development of control systems can be challenging for ECE students. This course often begins with modeling of dynamic mechanical systems, leading to modeling electromechanical systems, namely the DC motor. The DC motor is ubiquitous in control systems laboratory experiments; however, the impact of the later experiments in the semester can diminish as the students design a controller for velocity control once again, even though they are applying new techniques. To offer a wider range of applications for ECE students to implement control system designs, the Zumo robot platform is investigated to figure out if it is a practical option as a second system to be used within the existing semester course.

Until this study, the ECE students at the Milwaukee School of Engineering enrolled in the required control systems course have only experienced hands-on implementation of control systems for stationary DC motors. With growing interest in robotics, this work aims to provide ECE students with the opportunity to develop an understanding of working with a similar, yet quite different system. The students will have to perform a system identification task followed by the design and application of a closed loop controller that commands the robot to drive toward a target straight ahead even when disturbances are present.

Through this work-in-progress, it is determined that implementation of the Zumo robot within the standard control systems course is outside the scope of the required control systems course, but this platform is well suited for the advanced control systems elective offered at the Milwaukee School of Engineering.

Introduction

One of the core application topics in a typical electrical engineering curriculum is control systems. There are many important applications of control systems in industry and government research, and students greatly benefit from having hands-on control experience. Undergraduate control systems courses typically involve a range of hardware platforms which connect modeling and controller design concepts to real dynamic systems. Commercial units, like those manufactured by Quanser, feature ready-to-use electromechanical plants with integrated software support for typical labs [1,2] in modeling, PID control, and state-space methods. Classic benchmark systems, like inverted pendulums [3] and ball-and-beam [4] setups, are common for illustrating instability, linearization, and feedback design, whether purchased commercially or built in-house. Some programs use magnetic levitation (maglev) systems [5] to give students experience with nonlinear, unstable plants and real-time control implementation. Mobile and aerial robots [6] introduce sensing, estimation, and embedded control, which can complement traditional benchtop experiments. Finally, some schools [7, 8] have gone to a build-your-own DC motor kit, so that students can perform experiments remotely or outside of typical lab hours.

In the current version of the introductory control systems course at the Milwaukee School of Engineering (MSOE), students use Simulink to implement control system designs that are programmed onto an Arduino microcontroller board connected with an H-bridge and a simple DC motor [7]. In researching other hardware platforms for control system applications, the

Pololu Zumo robot [9] was found to be a relatively low-cost option that offers multiple potential applications. The Zumo robot is more challenging to model and program than the simpler DC motor system, and this work considers development of experiments using the Zumo robot for the required introductory control systems course, which also includes dynamic system modeling, as well as an elective control systems applications course.

The Pololu Zumo robot is a small, low-cost robotic vehicle with a dual-motor differential drive train and features quadrature encoders for precise position and velocity tracking as well as proximity sensors for obstacle detection. This robot has been used in a first-year engineering design course focused on modeling and simulation [10], as well as control systems courses [11, 12, 13]. Others have documented its usage in landmine detection research [14] and autonomous navigation through a narrow pathway [15]. This robot has even been used in teaching machine learning and robotics concepts to middle school students in rural Alabama [16]. In [11] and [12], the Zumo robot was used in demonstrations by the instructors to motivate their study of dynamic systems and controls for mechanical engineering and product design and manufacturing engineering students. The authors in [13] used the Zumo robot as an alternative robotic platform to support a constant distance from a building for a course project in a control systems course for engineering technology students.

The main contribution of our work with the Zumo robot is the inclusion of this platform into ECE control systems courses that have historically focused on single DC motor control. This work investigates whether the Zumo robot platform could supplement the existing DC motor laboratory experiments or be used as an alternative to the DC motor and into which of two control systems courses within the ECE department at MSOE it would best fit. Since the existing laboratories within the introductory control systems course focus on applications involving a stationary DC motor, introducing a moving control system adds interest for a student looking to deepen their understanding of control systems.

In the sections that follow, descriptions of the two ECE control systems courses will be provided. These course descriptions are then followed by the goal of the Zumo robot laboratory experiment. The paper then goes into the details about the Zumo robot and how it will be used within the Control Systems Applications elective course at MSOE.

Course Descriptions and Laboratory Learning Outcomes

ELE 3701 - Control Systems

Control Systems, ELE 3701, is a junior-level course required for electrical engineering students, who typically take the course as seniors, and available as an elective for computer engineering students. The prerequisites for this course are differential equations and Circuits 2, which covers topics on transient circuit analysis. The course begins by introducing the fundamentals of modeling mechanical, electrical, and electromechanical systems. Students develop their modeling skills by using first principles of physics to describe a dynamic system through a differential equation. That differential equation is then transformed to the Laplace domain, and a transfer function is obtained. From there, students begin to analyze system responses through the transfer function. Once ideas for step response analysis are established, topics move on to block diagram simplification, system stability, steady state error, and sketching/understanding root locus plots for pole placement of a closed loop system with a single control gain. Throughout these topics, ideas of designing a control system to meet related specifications are covered. After root locus plots are discussed, the design process shifts to a focus on Proportional (P), Proportional-Integral (PI), Proportional-Derivative (PD), and Proportional-Integral-Derivative (PID) controller designs. Finally, the course ends with a few weeks of coverage on state-space representation and state variable feedback control.

The existing laboratory assignments throughout the semester all involve a bring-your-own-experiment (BYOE) DC motor kit [7] that all students buy, which allows connections between class topics and a hands-on system. The BYOE kit includes a low-cost DC motor mounted to a base and controlled via an Arduino sending a pulse-width modulation (PWM) signal to an H-bridge driver. The Arduino is programmed through the MATLAB Simulink interface. These labs span transfer function development for the DC motor system, various iterations of position and velocity control using classical control techniques and state variable feedback. Prior to state space coverage, the students are given a design project where they must determine a system that requires velocity control and reasonable design specifications for their chosen system.

The Zumo robot was considered for a laboratory experiment that would replace one existing experiment in this introduction to control systems course. However, due to this course starting with foundational knowledge in dynamic system modeling and building up to control systems topics, the start-up time to become familiar with the Zumo system would likely take multiple weeks, which could not be afforded in this course. If the Zumo system is to be integrated into ELE 3701, it would need to be the main system focused throughout the semester. At this time, the BYOE laboratories are effective at supporting course learning outcomes, and the Zumo robot will be considered for one or more in-class demonstrations instead of laboratory implementation in ELE 3701.

ELE 4701 – Control Systems Applications

Control Systems Applications is an ECE department elective open to any student with a prerequisite control systems course. In this course, students focus on modern control techniques, expanding state space modeling, and control from ELE 3701. After modern control topics are covered, the course returns to classical control techniques, but now modeling and control is in discrete time. The course concludes by combining the prior ideas with coverage of discrete time state space modeling and control. One goal of the class is to provide students with opportunities to explore and work with multiple systems.

There are currently six laboratory experiments in this elective course. Five of these experiments use a higher performance motor, namely the Quanser SRV02 with various attachments. This is different from the BYOE kits from ELE 3701. The sixth experiment involves a high-level introduction to a hydraulic system and proportional control used for position control of a hydraulic cylinder. As a result of this work-in-progress, a two-part laboratory experiment using the Zumo robot will be added to the set of experiments within this course with a reduction in the time allotted for the first five experiments.

Zumo Robot Laboratory Experiment Learning Objectives

This work-in-progress feasibility study has resulted in the creation of a two-part laboratory experiment using the Zumo robot. In the first draft of the experiment, students learn to connect directly to the sensor data via C programming of an ATmega328P on an Arduino Uno. The students will gain experience finding sensor bias, providing an offset, and importing data from the microcontroller into MATLAB for processing. Another new experience produced by this experiment is the control of DC motors to work together to achieve a trajectory goal (drive straight in the presence of disturbances). Finally, the students will implement PID control schemes directly in C code versus using MATLAB Simulink as is used in all other experiments in this course (progressively adding proportional, integral, and derivative control to see the individual contributions).

Preliminary Laboratory Design and Testing

Hardware Specifications

The Zumo Shield v1.3 [9] is an expansion board provided by Pololu designed to directly interface, communicate, and connect to an Arduino Uno board. The entire shield product includes different electrical and mechanical components that work together through physical connections to provide power and signals to the respective components. These specific components include motor drivers, sensors, and other miscellaneous connections to breakout pins on the board.

Zumo Robot Specifications and Details:

Sub-Section	Specifications:
Motor Control & Power	- Dual Motor Drivers: Integrated DRV8835 dual motor driver which can drive two gear motors from the central Zumo chassis - Battery Input: Connects directly to four AA batteries inserted on the lower side of the Zumo chassis. There is also a boost regulator that connects the battery supply of the Zumo to the Arduino board itself.
Sensors & Added Components	- LSM6DS33: 3-axis (X, Y, and Z) accelerometer, gyroscope, and magnetometer. This is an on-board embedded peripheral, interacted with through C code and a library accessed through GitLab. These peripheral components communicate over I2C. These allow for the robot to detect impacts, movement changes, and orientation. - Buzzer: This is a standard piezo buzzer included in the Zumo/Arduino kit. - User Pushbutton: Arduino pin header 12 which is an optional pushbutton
Physical Components	- Front expansion area: There are, included with the Zumo robot, spaces for other pin headers and added sensors - The Pololu Zumo v1.3 is designed to directly connect to the Arduino Uno microcontroller board o Exact measurements: 8.31 centimeters (about 3.27 in) width, 6.6 centimeters (about 2.6 in) length, and width of microcontroller board: 0.157 centimeters (about 0.06 in), total height of 0.8 centimeters (about 0.31 in) including external connections. - Arduino libraries, online libraries, and other external resources are available to be downloaded from these websites and ported to the Zumo robot itself.

Testing and Interfacing with the Zumo Robot

When testing and connecting the Zumo robot, the Arduino IDE (Integrated Development Environment) is used to implement C code that collects sensor data from the Zumo robot and sends command signals to the motors. The sensor data is viewed on the Serial Monitor. External libraries for the Zumo robot, developed by a joint development team consisting of Pololu employees and external developers [17], are used to quickly communicate with the peripherals. Once communication is set up and familiarity with the Zumo libraries is gained, the system identification and controller implementation portions of the laboratory development can be completed.

For this laboratory experiment, the trajectory goal is to travel in a straight line. This is achieved by using the gyroscope Z-axis sensor. The sensor provides rotational information about the vehicle's orientation. When gathering data from the Zumo robot, the data can either be captured through the Arduino IDE serial monitor or an external terminal program such as PuTTY. Due to limitations of exporting the data from the Arduino IDE serial monitor, PuTTY is used as the software program of choice for data collection. To collect data, the C code is deployed onto the Arduino, and PuTTY is then configured to communicate with the Arduino via the serial port. From here, the program prints out the accelerometer, gyroscope, and compass X, Y, and Z values. These printouts are saved as a Comma Separated Values (csv) file, which can be imported into MATLAB. After the collection of sensor data is established, controller implementation begins. A progression through proportional, integral, and derivative control techniques is implemented. This included the tuning of controller gains for these various implementations, as well as using the presence of disturbances (tapping the robot off course with a pen or pencil) to test the implemented controller.

Design Process of the Laboratory Assignment

This feasibility study for the Zumo robot laboratory design and implementation began as a question proposed to the student research team member on this paper as, "Can a control systems laboratory assignment be developed using a small-scale robot as an alternative application to the current laboratory system within the scope of either the required control systems course or the elective course?" The Pololu Zumo robot was chosen as a potential product that could be used to answer this question. The Zumo robot is a compact system included of two motor treads, four geared wheels, the robot chassis, frontal shield, and microelectronic components. Onboard, the Zumo shield holds all sensors that are needed for this experiment, which includes a 3-axis accelerometer, gyroscope, and compass.

The goal of the project is to develop a laboratory experiment for students to use within either or both ECE control systems courses (ELE 3701 or ELE 4701). This laboratory is aimed at helping expand the applications of control systems beyond the stationary DC motor. There are two outcomes of this proposed laboratory: 1. How can this system be modeled? (System identification) and 2. What are the contributions of each of the different classical controller techniques (P, PI, PD, and PID) on the system's behavior in the presence of a disturbance?

The Arduino Uno board connects on top of the Zumo robot and is used to explicitly implement C code to deploy the controller using digital control techniques. In all existing laboratory experiments in both ELE 3701 and ELE 4701, MATLAB Simulink is used as the control system implementation platform. The switch from MATLAB Simulink to directly writing the C code to implement the designs is new for the students in either of these courses. Up to this point, students use MATLAB Simulink to build block diagram models, but now the students use C code in the Arduino IDE to carry out the tasks of the laboratory experiment. To reduce the ramp-up time, the Zumo libraries are utilized and students import these libraries from GitHub [17] into their Arduino project. From these libraries, students use the built-in methods to command the motors, access the Zumo robot sensor data, and display the data onto the console of the IDE. From here, a terminal program, such as PuTTY, is used to collect sensor data. That data can then be exported via copying and pasting into a csv file. This csv file is imported into the MATLAB workspace for plotting to provide a graphical visualization of the system response.

After students confirm they can collect data from the sensors, they provide a constant spin command to the motors to effectively produce a step input. They will collect the gyroscope Z sensor data via the process described above to obtain the step response. The plot of this data is the step response and is one of the key deliverables for the lab. Students use this plot to extract key data points to derive the transfer function for their robotic system.

For the second deliverable of the lab, the main goal and focus of this section is for students to implement a controller that will allow the system to be robust against rotational disturbances, while achieving a trajectory goal of driving in a straight line, and investigate how these disturbances can throw a system off of its equilibrium when the disturbances are too large. Using the controller techniques introduced in the control systems course, students are tasked with applying these ideas in C code. The first draft of the laboratory experiment will provide students with skeleton C code, which they will need to apply their knowledge and understanding of the control design by inputting proper parameters and implementing the control system design on the Zumo robot Arduino system. At the end of this process, students will show the instructor the results of their PID Controller implementation. Throughout this controller's development, the students will also show at least 2 of the other controllers (P, PI, or PD) in the presence of the disturbances to discuss how each part of the PID contributes to the overall response.

Conclusion and Future Work

This work-in-progress study investigates the feasibility of using the Zumo robot platform within laboratory experiments in an ECE control systems course. To include the Zumo robot within the required control systems course at MSOE, more existing laboratory experiments than originally anticipated would need to be removed. It was decided that the existing experiments in that course effectively support the learning goals. With this conclusion, the authors propose the use of the Zumo robot for in-class demonstrations within an introduction to control systems course to provide students with an added system without the requirement of fully learning the system integration side.

The work provided here also considers the implementation of a laboratory experiment within an advanced control systems applications course. It was decided that a two-part experiment would be necessary and would provide students with a third system application to control, broadening their experience in this field.

The authors plan to implement the laboratory experiment described in this paper during the next offering of the control systems applications course, ELE 4701. After the first implementation, the authors will reflect on the learning outcomes and refine the laboratory experiment. In the meantime, the authors will work on developing in-class laboratory demonstrations for both ELE 3701 and ELE 4701.

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