DEVELOPMENT AND FEASIBILITY OF OPEN-SOURCE HARDWARE AND SOFTWARE IN CONTROL THEORY APPLICATION

by

DEREK J. BLACK

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Major Professor
Dr. Dale Schinstock

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DEREK J. BLACK

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Abstract

Control theory is a methodology investigated by many mechanical and electrical engineering students throughout most universities in the world. Because of control theory?s broad and interdisciplinary nature, it necessitates further study by application through laboratory practice. Typically the hardware used to connect the theoretical aspects of controls to the practical can be expensive, big, and time consuming to the students and instructors teaching on the equipment. This is due to the fact that connecting various hardware components such as sensors, encoders, amplifiers, and motors can lead to data that does not fit perfectly the theoretical mold developed in the controls classroom, further dissuading students of the idea that there exists a connection between developed theoretical models and what is seen in practice.

There is a recent trend in universities wishing to develop open-source, inexpensive hardware for various applications. This thesis will investigate and conduct a multitude of experiments on an apparatus known as the Motorlab to determine the feasibility of such equipment in the field of control theory application. The results will be compared against time-tested hardware to demonstrate the practicality of open-source, inexpensive hardware.

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Acronyms

ARM   Advanced RISC Machine

DAEC   Dynamic Angle Error Compensation

MPU   Microprocessor Unit

BLDC   Brushless DC

GUI   Graphical User Interface

NERMLAB New Earth Robotics Motor Lab

back-emf back electromotive force

RPM   Rotations Per Minute

Acknowledgments

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Chapter 1

Introduction

Current research indicates a growing need for laboratory components for introductory control theory classes. However, many hurdles like budget, class size, and space limitations arise when laboratories are added to lecture components in universities [1]. This thesis will address the issues, like budget of laboratory hardware, class sizes, and space limitations, and try to assess the feasibility of utilizing low budget, smaller, and portable laboratory hardware for introductory control classes. The introduction of this thesis will be broken up into sections to address these issues individually. It's important to note, that while this thesis does recognize the importance of having laboratory components to control theory lectures, it will not be the main focus, rather importance will be given to addressing the feasibility of low budget portable hardware, more specifically the Motorlab, for control applications. This chapter serves more as a background to why lower budget, portable hardware is important to control classes, and in turn demonstrates a need for these low budget devices.

1.1   Hardware and Software Budget

1.2   Space Limitations

Chapter 2

Apparatus

Two pieces of apparatus were used to conduct the experiments in this thesis. This chapter will detail the purpose, design and recreation of the equipment. Section 2.1 will cover the new Motorlab, including the hardware implementation, design of components, and basic functionality. Section 2.1.3 will detail how a new type of position sensor works that is used for the position measurements of the Motorlab. Then, the older Motorlab will be discussed and compared to the new Motorlab in section 2.2.

2.1   New Motorlab

The new Motorlab is a reimplementation of older laboratory hardware created by Dr. Schinstock and Dr. White for Control of Mechanical Systems I at Kansas State University. The Motorlab allows users to connect the theoretical ideas of control theory with those in practice. (Maybe include applications of the motorlab and its use in the laboratory).

2.1.1   Hardware

The new Motorlab consists of several key pieces of hardware, namely a Microprocessor Unit (MPU), motor driver, and a Brushless DC (BLDC) motor. The main MPU of the Motorlab is the STM32 Nucleo, which allows Arduino attachment shields and other STM boards to

be attached for added functionality. For the purposes of the Motorlab, a motor driver was required to drive a brushless DC motor, namely a RCTIMER GBM2804. An X-Nucleo-IHM07M1 (a three-phase brushless DC motor driver) was selected to be the primary driver for the Motorlab.

2.1.2 Position Sensor

The main purpose of the Motorlab is to conduct control laboratory experiments, as a result, feedback via sensor readings is necessary to do such control. The typical way to do position and speed control of mechanical systems and motors is to use position feedback via an encoder. An encoder is a device that converts angular position of a motor shaft to an analog or digital signal that can be processed by an MPU. In the case of the Motorlab, an on-axis magnetic encoder is used to do position feedback. Special equipment had to be designed in order to use this type of encoder, and will be detailed in section 2.1.3.

The encoder that is being used on the Motorlab consists of 14-bit on-axis magnetic rotary position sensor chip, specifically the AS5047D by AMS [1]. The position sensor chip provides high resolution absolute angle measurements through a full 360 degree range [2]. In addition to the fast absolute angle measurement system that the position sensor provides, it also has Dynamic Angle Error Compensation (DAEC) that provides position control systems with near 0 latency [2].

The AS5047D chip is a magnetic sensor that utilizes the Hall-effect. The chip works by taking the Hall sensors and converting the perpendicular magnetic field on the surface of the chip to a voltage. The voltage signals are filtered and amplified in order to calculate the angle of the magnetic vector. In order for position measurements to be taken, a small diametrically opposed magnet must be placed on the shaft of the equipment being measured. The magnet and AS5047D are contactless, meaning there is a small air gap between the chip and magnet. As the magnet rotates above the chip (Figure 2.1), angle measurements are calculate and

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[1] AMS is an Austrian analog sensor and semi-conductor manufacturer

[2] These chips typically provide a maximum resolution of 2000 steps/revolution in decimal mode and 2048 steps/revolution in binary mode

transmitted through the chip [2]. The Motorlab uses the AS5047D chip primarily as a position and speed control system.
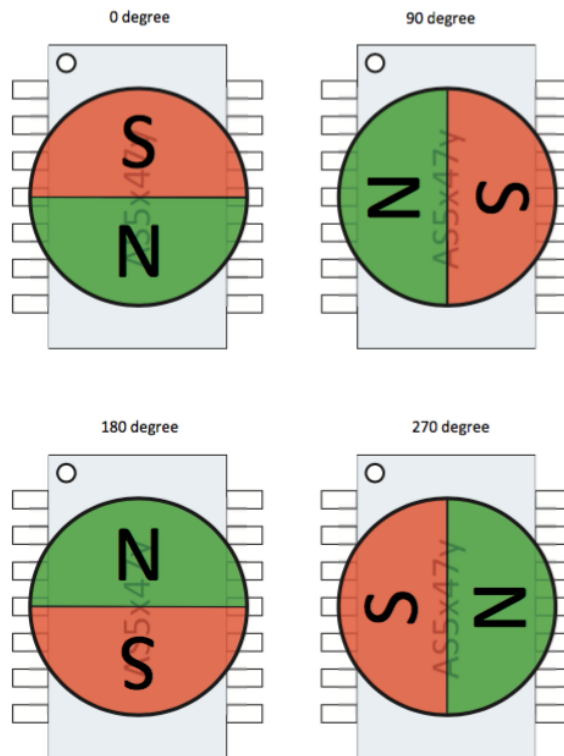

Figure 2.1: *Magnet and AS5047D [2]*

2.1.3 Motorlab Parts

Along with the hardware mentioned in section 2.1.1, three components were needed to be developed in order to bring the Motorlab to fruition: a printed circuit board that houses the on-axis magnetic rotary position sensor, a spacer to put distance between the circuit board and the motor, and a magnet holder, which holds one diametrically opposed magnet [3]. Both the spacer and magnet holder which can be seen in figure 2.2 had to be 3D printed in order to achieve the required specifications of the apparatus setup. Detailed drawings of these two parts can be found in (appendix) if reproduction is desired. Along with the two 3D

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[3]Diametrically opposed meaning the north and south poles of the magnet are in-plane as opposed to top/bottom poles. Reference figure 2.1 for further clarification

printed parts, a printed circuit board had to be designed by Eric Patterson of Kansas State University to allow the position sensor to communicate with the rest of the hardware.

Because of variability in resolution of current 3D printers, care was given to the design of the magnet holder [4]. A spline was used for both the shaft of the magnet holder and the section that holds the magnet itself. The spline allowed for greater tolerances in the parts, meaning the magnet holder could be easier to press fit into the motor, and likewise allowed easier removal of the diametrically opposed magnet.
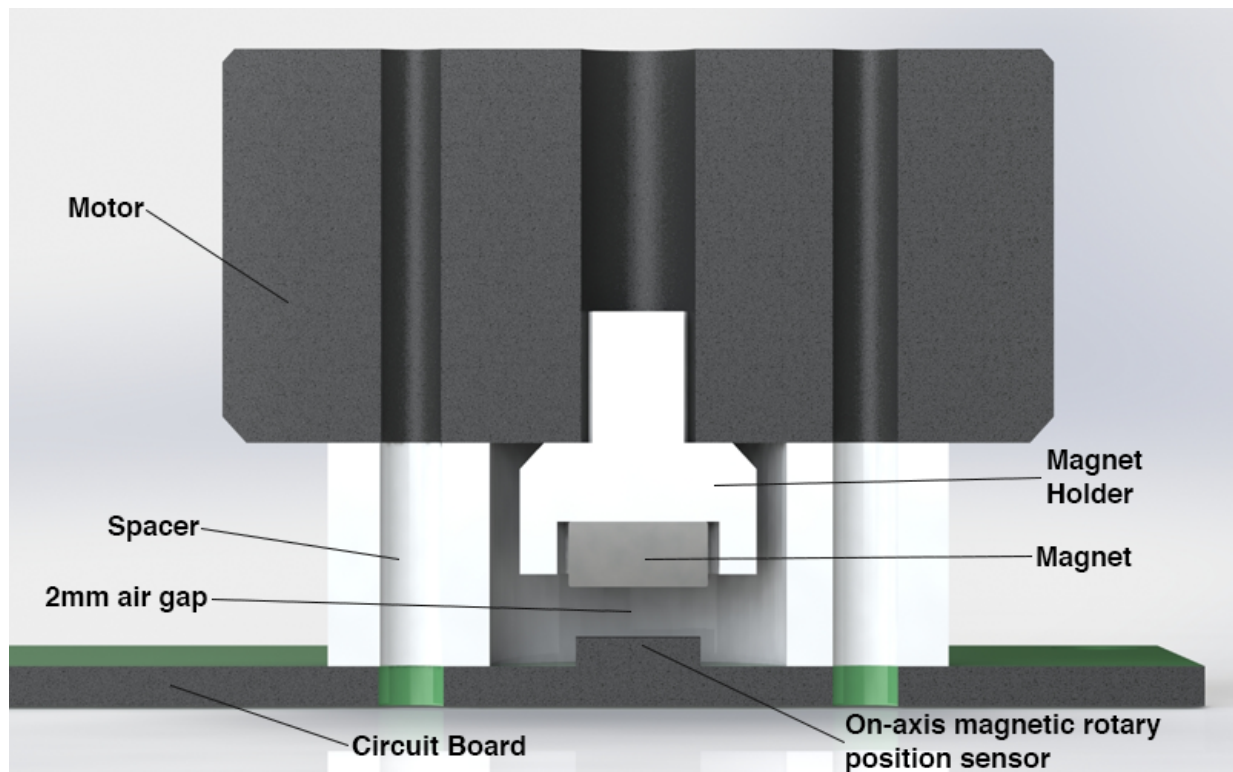
Figure 2.2: *Section View of Motorlab Assembly*

2.1.4 Motorlab Cost

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[4]Because of this variability in resolution, the magnet holder was printed in iterations, varying the diameter of the spline to insure a tight fit in the motor shaft

Table 2.1: *Motorlab expenditure report*

Component	Brand/Manufacture	Cost
BLDC Motor	RCTIMER GBM2804	11.94 USD
Position Sensor	AS5047D AMS	4.21 USD
ST32 Nucleo	STMicroelectronics	10.12 USD
X-Nucleo-IHM07M1	STMicroelectronics	9.80 USD
Magnet	Unknown	3.00 USD
Printed Circuit Board	Eric Patterson	– USD
	TOTAL COST	**39.07 USD**

2.1.5   Motorlab GUI
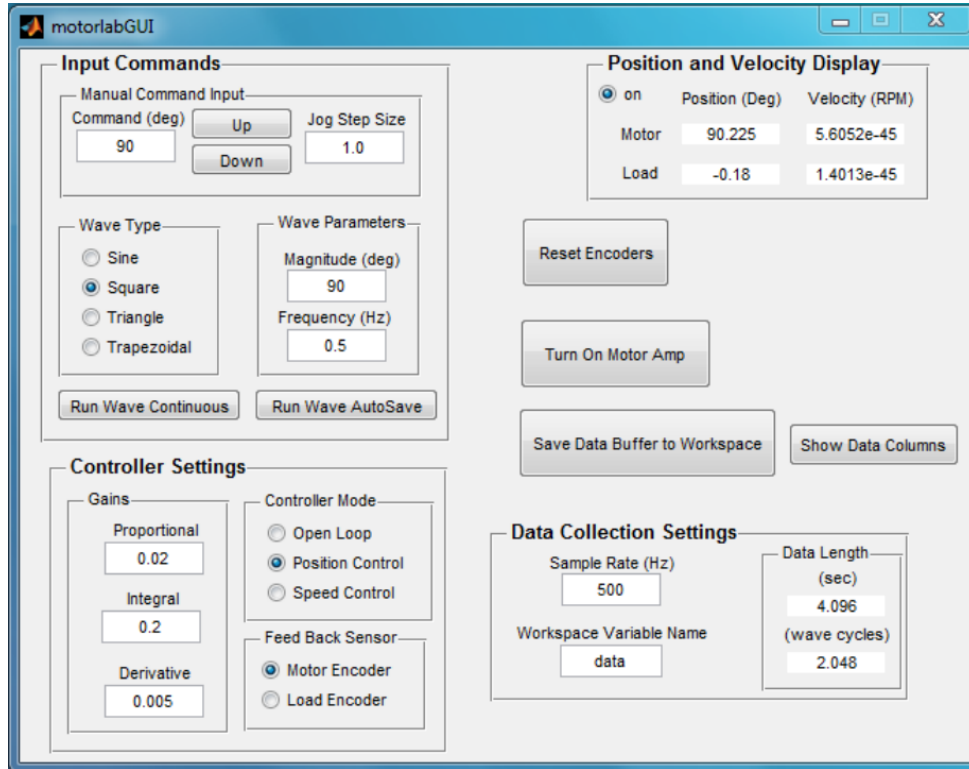
Figure 2.3: *Motorlab GUI in MATLAB*

The Motorlab interfaces with a Graphical User Interface (GUI) coded in MATLAB to allow users to run various laboratory experiments on the hardware. It allows the selection of various wave types, frequency, controller gains, and sample rate that get sent to the Motorlab. After the parameters of the experiment are setup, the GUI can run the Motorlab,

which in turn sends the experimental data to the workspace of MATLAB in the form of a matrix. The MATLAB GUI can be seen in figure 2.3.

2.2 Motorlab

The Motorlab is a piece of laboratory equipment developed by Dr. Dale Schinstock and Dr. Warren N. White at Kansas State University. It has been in service at the university for over 15 years, and as a result is a time-tested piece of laboratory hardware that has proven to be reliable in terms of providing quality practical control theory application to students enrolled in the class Control of Mechanical Systems I. Because the Motorlab's hardware components were designed and created to insure a very clear translation of laboratory results, in addition to the Motorlab having a much larger operating limit and bandwidth than students use in laboratory practice, this represents to a good base model to compare the results of the apparatus in this thesis too.

Various hardware make up the Motorlab, namely, a high quality BLDC motor, BLDC servo amplifier by Copley Controls Corp., and a ST Discovery board [5]. Typically the Motorlabs run a cost of about 700 USD per lab station [3].

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[5]STMicroelectronics is a Switzerland based micro-controller manufacturer

Chapter 3

Model Development

Chapter 3 will be dedicated to developing the various parameters that make up the NERMLAB such as the motor torque constant, back electromotive force (back-emf), inductance, and max voltage. Each section in Chapter 3 will detail the process of how the various parameters were measured, calculated, and experimentally determined. Nomenclature for various constants and parameters are detailed in the table 3.1.

Table 3.1: *Motor parameters*

Parameter	Description
V	Motor Voltage
k_t	Motor Torque Constant per Phase
k_T	Overall Motor Torque Constant
K_e	Back Electromotive Force Constant per Phase
$K_{e,LL}$	Line-Line Back Electromotive Force Constant
J	Mass Moment of Inertia
L	Motor Inductance
R	Motor Resistance
τ	Time Constant
T	Motor Torque

3.1 Motor Resistance

3.2 Motor Torque Constant and Back EMF

The motor torque constant (k_t) is a common parameter used in BLDC motors. It relates the armature current to the torque produced by a motor: $T = k_T i$. Many methods exist to determine the torque constant, including relating the motor velocity constant k_v which is inversely related to the torque constant by $k_T = \frac{1}{k_v}$, or by measuring the line-line back-emf voltage per phase (K_e). K_e is the peak value of the back-emf per angular velocity measured from line-neutral. However since line-neutral is typically unavailable on most BLDC motors, the back-emf constant is often represented as a line measurement, $K_{e,LL}$. The overall torque constant can then be related to the line measurement back-emf for sinusoidal type outputs by equation — [4].

$$k_T = \frac{\sqrt{3}}{2} K_{e,LL}$$

Because $K_{e,LL}$ can be experimentally determined, it is possible to find the overall motor torque constant for a BLDC motor. One simply needs to measure the line-line sinusoidal[1] back-emf voltage at various speeds to get a good estimate of $K_{e,LL}$, then in conjunction with equation — k_T can then be determined.

3.2.1 Procedure

Outline of the experimental procedure done to measure Kt.

$$K_E = \frac{V}{\omega_m}$$

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[1]Note in the case of trapezoidal waveforms the relationship between k_T and $K_{e,LL}$ are proportional, i.e. $k_T = K_{e,LL}$

3.3 Mass Moment of Inertia Estimation

Mass moment of inertia J is the equivalent to mass in a rotational system (commonly referred to as angular mass). More formally is it defined as $J = \int r^2 dm$, where r is the distance to some mass from an axis of rotation.

The angular mass of the NERMLAB will be determined in two ways: experimentally determining J through software modeling, and approximating J through mathematical formulation. For both setups the mass of the rotating inertia had to be measured.

3.3.1 Software Modeling of Mass Moment of Inertia

3.3.2 Mathematical Approximation of Mass Moment of Inertia

To simplify the mathematical analysis of the mass moment of inertia calculation of the angular mass of the NERMLAB, an engineering assumption will be made that the angular mass is a rotating ring mass. This assumption is valid for the particular motor used in this thesis due to the fact that most of the mass is concentrated around the outside parameter of the motor. The outside ring mass of the motor contributes the most to the inertial load, so the mathematical formulation would result in the following equation:

$$J_z = \frac{m}{2}(r_1^2 + r_2^2) = mr_2^2(1 - t + \frac{t^2}{2})$$
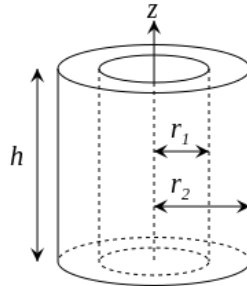
Figure 3.1: *Thick Walled Cylinder (J)*

3.4   Motor Inductance

$$L = R\tau$$

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Appendix A

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Appendix B

Title for This Appendix

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