Lab Exercise 08 Brushed DC Motors

Lab 08.1   Introduction

In this lab, we will use a brushed DC motor to drive a rotational mechanical system with a myRIO microcontroller; measure the motor's voltage, current, and angular velocity; and characterize the motor. The electromechanical systems are shown in Figure 08.1.

The objectives of this lab exercise are for students:

1. to characterize the performance of a motor,
2. to apply motor driving,
3. to apply PWM,
4. to apply H-bridge circuits,
5. to apply quadrature encoders, and
6. to estimate electromechanical system parameters such as the motor constant.

Lab 08.2   Materials

The following materials are required for each lab station:

☐ 1. a PC with LabVIEW installed;[1]
☐ 2. a myRIO configured with LabVIEW;[2];
☐ 3. one ECL apparatus (see Figure 08.1) with encoder and most motor driver connections pre-connected as in Figure 08.7, *except C-channel connections*, which are left for the students;
☐ 4. a multimeter;
☐ 5. a breadboard;
☐ 6. jumper wires; and
☐ 7. two 330 kΩ resistors R_1 and R_2 (or similar).

Lab 08.3   Motor driving

A DC motor requires DC electrical power provided by a circuit called the "driving" circuit. For industrial motors at least, these circuits must provide significant power, and for this reason a separate (from the control circuit) power supply is often used. There is a quick-and-dirty way to drive a DC motor at variable speed: since its angular velocity is reliably

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[1]See Resource 2 for more details on the LabVIEW software configuration.
[2]See Resource 3 for more details on the myRIO software configuration.

proportional to its voltage, place a potentiometer in series with the power supply and motor. However, this has disadvantages that include the power being limited and dissipated at high potentiometer resistance (low speed). For most applications, we will need either a current (or power) amplifier or a microcontroller and an integrated circuit to produce a pulse-width modulation driving signal. The latter is usually more cost-effective, but the former is advantageous in certain applications.

Lab 08.4   Pulse-width modulation

Pulse-width modulation (PWM) is a technique used to deliver an effectively variable signal to a load (in our case a motor) without a truly variable power source. A pulse of full source amplitude is repeated at a high frequency (e.g. 20 kHz), delivering a signal that is effectively averaged by the load dynamics such that its effects on the load are nearly continuous. The fraction of the period T that the signal is high (on) is called the *duty cycle* δ. Figure 08.2 shows a PWM signal $v(t)$ and its average $\bar{v}(t)$ with a few parameter definitions.

The mean of any periodic signal with period T can be computed with the integral

$$\bar{v}(t) = \frac{1}{T} \int_0^T v(t),$$

which is easily evaluated for a PWM signal:

$$\bar{v}(t) = \frac{Aw}{T} = A\delta.$$

This result shows that if a PWM signal is delivered to a load, such as a DC motor, that is relatively unaffected by high-frequency signals, the effective signal will be simply the product of the source amplitude A and the duty cycle δ. The duty cycle can have values from 0 to 1, so the effective DC signal produced varies linearly with δ from 0 to A.

Lab 08.5   Motor driving with PWM

A microcontroller such as the myRIO or Arduino can easily produce a PWM signal; however, this signal is typically *low-power* and cannot drive even small DC motors. Therefore it is common to include a special kind of integrated circuit (IC) that uses the microcontroller's low-power PWM signal to gate a high-power DC source signal for delivery to the motor.
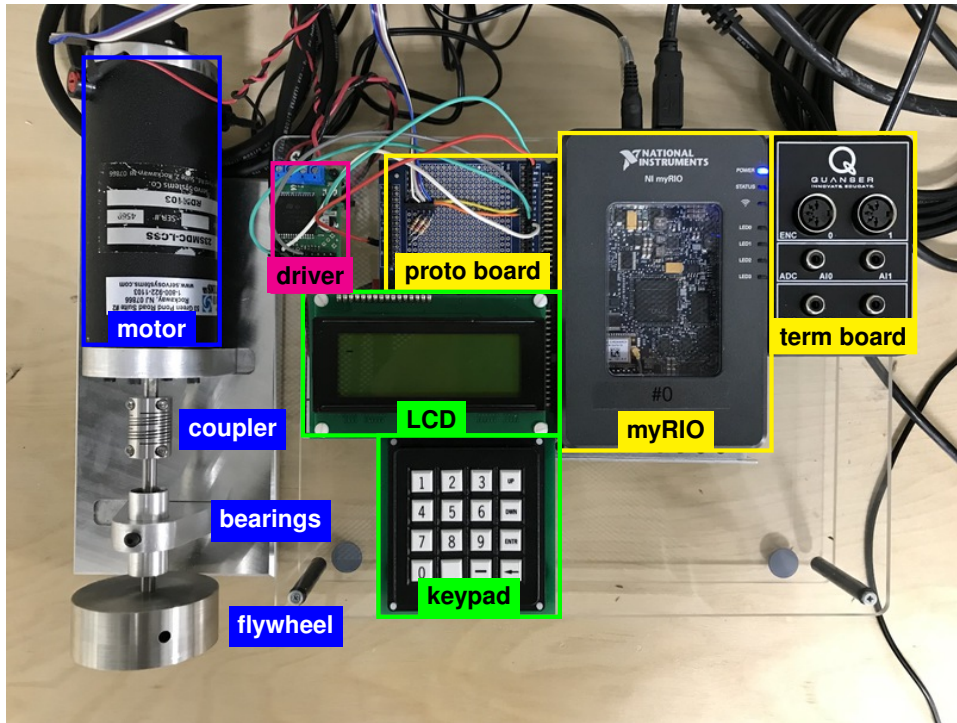
(a) top view of most of the ECL apparatus.

(b) front view of most of the ECL apparatus.

Figure 08.1: the electromechanical system from the Embedded Computing Laboratory (ECL) used in this lab exercise.

These are called *motor drivers*. They deliver power from a high-power **motor drivers** source in accordance with a PWM signal, and they often include many additional features such as

1. compact forms;
2. forward- and reverse-driving (see Lab 08.6)
3. protection against reverse voltage, overcurrent, and overheating; and
4. output pins that monitor delivered current and voltage.

Lab 08.6   H-bridge circuits

We want to drive DC motors at different effective voltages *and* different directions. An H-bridge circuit allows us to reverse the direction of the PWM signal delivered to the motor. Figure 08.3 is a diagram of the H-bridge circuit.

The switches S1-S4 are typically instantiated with MOSFET transistors. As shown in the figure below, during the high duration of the PWM pulse, either S1 and S4 (Figure 08.3(b)) or S2 and S3 (Figure 08.3(c)) are closed and the others are open.

Recall that the electronics side of a DC motor can be modeled as a resistor and inductor in series with an electro-mechanical transformer. The inductance of the windings make it an "inductive" load, which presents the following challenge. We can't rapidly change the current flow through an inductor without a huge spike in voltage, and the switches do just that, leading to switch damage. Therefore, during the low or "off" duration of the PWM signal, S1-S4 cannot all be simply opened. There are actually a few options for switch positions that allow the current to continue to flow without inductive "kickback."
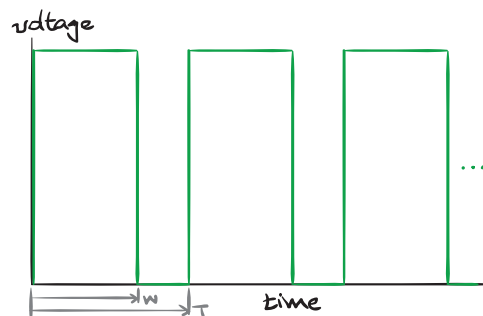

Figure 08.2: a pulse-width modulation (PWM) signal.

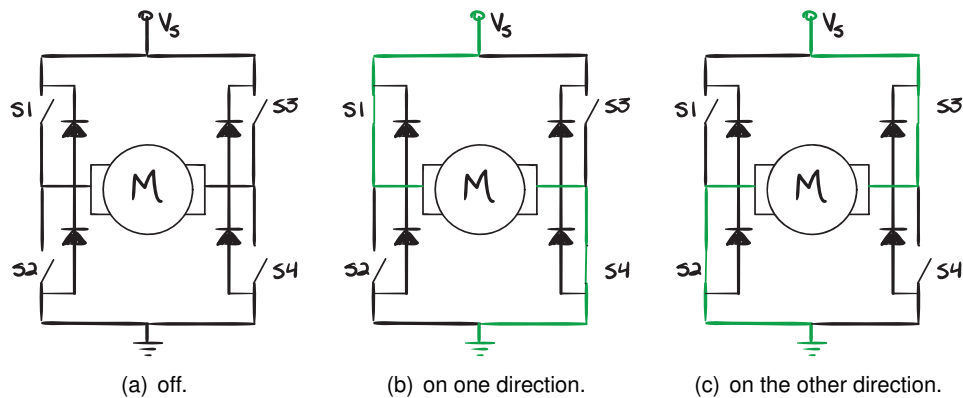(a) off.　　　　(b) on one direction.　　　　(c) on the other direction.

Figure 08.3: H-bridge operation.

What's up with the diodes? Technically, they could be used to deal with the kickback. But since the diodes dissipate power, the proper switching is the primary kickback mitigation technique. However, the diodes ease the transition between switch flips, which are never quite simultaneous.

Lab 08.7　The ECL instantiation

We use a connectorized printed circuit board (PCB, e.g. a PC motherboard)—the Pololu motor driver carrier:

<div align="center">

pololu.com/product/1451

ricopic.one/resources/pololu_VNH5019.pdf (manual)

</div>

This includes an STMicroelectronics VNH5019 H-bridge motor driver integrated circuit:

<div align="center">

ricopic.one/resources/vnh5019.pdf

</div>

Lab 08.8　Voltage dividing

The myRIO's C-connector has analog differential inputs that accept voltages in the interval $[-10, +10]$ V. However, the DC power supply used can deliver more than (but we will not exceed) 20 V, which is the
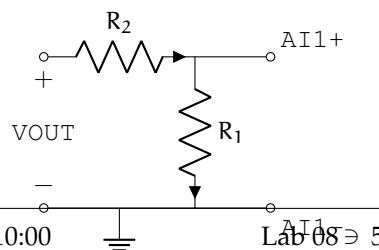

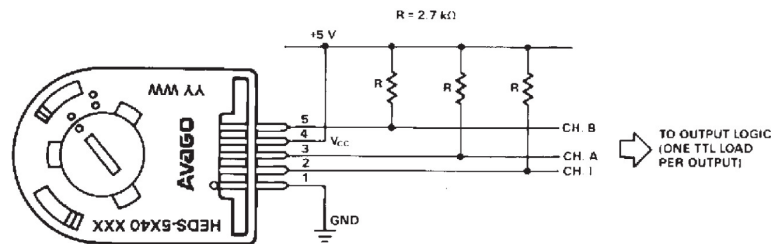**Figure 08.4:** voltage divider for measurement of VOUT.

Figure 08.5: the encoder used (source: HEDM-55xx/560x & HEDS-55xx/56xx Data Sheet).

maximum we expect to measure at the motor via pin `VOUT`. This is a common situation, that the analog inputs will not contain the voltage range that we would like to measure. The easiest method to mitigate this challenge is to use a simple voltage divider circuit with known resistances R_1 and R_2. We do not want to saturate the myRIO input, nor do we want the input to be so small that we lose resolution, so we choose our resistance ratio accordingly—in this case, two nominally 330 kΩ resistors will work just fine, dividing the signal in two.

Lab 08.9   Measuring motor speed

Motor position and angular velocity are best measured by rotational quadrature encoders. Rotational encoders are made from a wheel with alternating dark and light stripes. The encoder we have affixed to the rear shaft—the HP HEDS-5640-A06 with manual

ricopic.one/resources/encoder_manual.pdf

—has black stripes on clear plastic. A light source either reflects differently off the stripes or, as in our case, passes the light through the clear plastic wheel into a photodiode or is blocked by the black stripes. Each time a stripe passes by, the photodiode detects a "blink," which is passed on to the myRIO via digital channels of the myRIO configured for detecting encoder outputs.

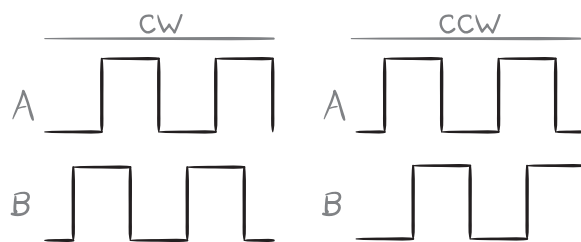The encoder pinout is shown in Figure 08.5, from the manual.

Figure 08.6: quadrature encoding with channels A and B.

Lab 08.10 Quadrature encoders

The only issue remaining is that a given "blink" doesn't give one important piece of information: which direction the encoder is rotating. However, a clever technique called *quadrature encoding* can be used to determine direction. The idea is that if we double the number of stripes, but offset the second set by half of a stripe width, then measure both "channels" A and B, then the direction can be determined by which channel "leads" the other. For instance, in Figure 08.6, the encoder output is high when light is detected and low when it is blocked by a stripe. Channel A leads B when the encoder is rotating clockwise (CW) and B leads A when it is rotating counter-clockwise (CCW).

Lab 08.11 Step response measurements

In this laboratory, a step voltage input will be supplied to the motor until the flywheel has reached steady-state speed. Then, the step voltage will be removed and the flywheel will slow to a stop. With a single continuous measurement in time, this step input and free response will be repeated several times, such that the step responses can be averaged in post-processing.

These step responses characterize both transient *and* steady-state for the system. The Mechatronics lecture course shows how such data can be used to estimate, as we will here, both the dominant time constant τ_1 and the motor constant (transformer ratio) TF (with estimates $\tilde{\tau}_1$ and $\tilde{TF}$).

Lab 08.12 Measurement setup

Check to make sure the PC, myRIO, proto board, motor driver, and motor are properly connected before proceeding with the final measurement setup steps, below.
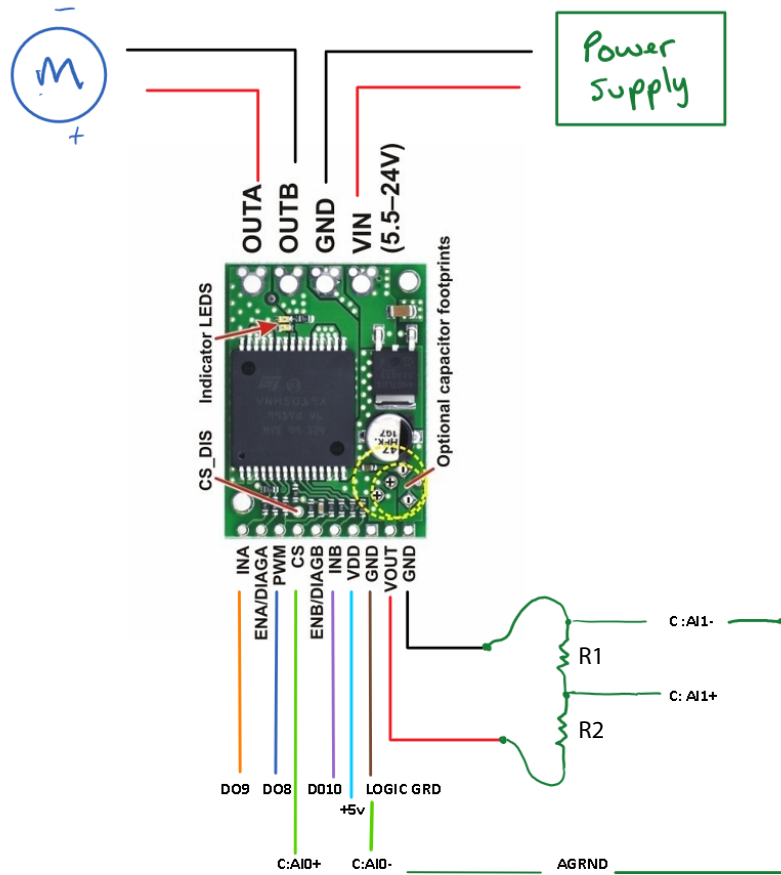
Figure 08.7: the motor driver with labeled pinout connections to the myRIO, power supply, and motor. The motor driver pinout is from pololu.com.

☐ 1. Unplug the myRIO power supply and the motor power supply (large yellow, cylindrical plug).
☐ 2. Measure and record the actual resistances of R_1 and R_2 with a multimeter.

	R_1 (kΩ)	R_2 (kΩ)
nominal		
measured		

☐ 3. Using a breadboard and two 330 kΩ resistors, build a voltage divider to divide the motor driver voltage VOUT across resistors R_1 and R_2.
☐ 4. Use Figure 08.7 to make the remaining connections of the motor driver carrier to the myRIO C-connector, with the voltage measurement across R_1.
☐ 5. Plug in the myRIO power supply and the motor power supply.

Lab 08.13   Measurement procedure

☐ 1. Open the lab 08 VI downloaded as part of the lab stubs in lab 02.
☐ 2. Once the VI is open, navigate to the front panel and enter the measured values for the voltage divider resistors R_1 and R_2.
☐ 3. Zero the duty cycle control slider and run the VI.
☐ 4. Play around with the motor speed by sliding the duty cycle control.

> **Box 08.1   Caution**
>
> The direction toggle switch should only be used when the duty cycle has been set to zero! Failure to observe this safety precaution can cause damage to the apparatus and excessive negligence may result in disciplinary action.

☐ 5. After everyone has had a chance to change the motor speed, set the duty cycle to zero.
☐ 6. Use the `execute` button to run at least 6 cycles with the default parameters, such as 40% duty cycle. The motor should speed up to a steady speed, then slow to a stop, each cycle. If the motor does not slow to a complete stop in each cycle, consider increasing the interval divisor and running it again.
☐ 7. Press the `stop` button to save your data. Use Matlab to verify your data before you leave the lab.

Lab 08.14   Report requirements

Write a detailed report of your experimental results, as outlined in the report template. Pay special attention to the following.

☐ 1. Estimate the nonzero steady-state value of the angular velocity $\Omega_{J\infty}$. Include a 95% confidence interval.

☐ 2. Use $\Omega_{J\infty}$ to transform the mean step response to decay to zero, take its natural logarithm, and perform a least-squares regression on the resulting data with a linear fit. (If any negative values are input to the natural logarithm, the result will be complex. Mitigate this with the method described in the corresponding Mechatronics lecture. Furthermore, ignore the first five or so of the "fast" time constant τ_2, estimated in the Mechatronics lecture.)

☐ 3. Identify an estimate for the dominant time constant τ_1 from the linear regression. Assign a 95% confidence interval.

☐ 4. From a steady-state analysis of the differential equation (or its solution) governing Ω_J (as described in the corresponding Mechatronics lecture), solve for a transformer ratio estimate $\widetilde{TF}$ in terms of $\Omega_{J\infty}$. Assign a 95% confidence interval.

☐ 5. Plot the sample mean step response with error bars $\pm$ one standard deviation of the means for each point (which is itself a mean). On the same figure, plot the analytic step response (described in a Mechatronics lecture) using all specification sheet parameter values. Also on the same figure, plot the analytic step response using, where appropriate, your estimates $\tilde{\tau}_1$ and $\widetilde{TF}$.

☐ 6. Report all measured parameters (e.g. resistance of resistors).