DC Motor Actuators

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1.0 Learning Outcomes

After studying this ACE-CORE guide, you should be able to demonstrate the Learning Outcomes listed in Table 1. On completion of the guide, revisit Table 1 and confirm whether each Learning Outcome has been achieved.

Table 1: *Learning Outcomes from the DC Motor Actuators Guide*

ID	Learning Outcome	Achieved
1.	Describe the main parts of a DC motor and explain how the applied voltage determines its speed and direction of rotation, including the role of the back emf.	☐
2.	Explain why a motor driver is needed between a microcontroller and a DC motor and describe how an H-bridge controls the direction of rotation, including the danger of shoot-through.	☐
3.	Explain how PWM is used to control the speed of a DC motor and calculate the average motor voltage for a given duty cycle.	☐
4.	Describe the connections and output signals of a quadrature encoder and calculate the angle and speed of a motor shaft from encoder pulse counts.	☐
5.	Explain how the two encoder phases are used to determine the direction of rotation, and how the H-bridge and encoder form the actuator and measurement blocks of a closed-loop motor control system.	☐

2.0 Introduction

A DC motor is one of the most widely used actuators in control systems. It converts electrical energy into rotary motion, and it is found in robotics, electric vehicles, industrial automation, drones and many everyday products. In a control system, the motor is the actuator that turns the controller's output into a physical action, such as turning a wheel at a required speed or moving an arm to a required angle.

The Introduction to the ATmega328P Microcontroller guide showed how a microcontroller produces digital and PWM output signals, and the Microcontroller-Based Measurement guide showed how it reads sensors. This guide brings these together for a DC motor. It explains how a DC motor works, how its direction and speed are controlled using an H-bridge motor driver, and how its angle and speed are measured using an encoder. The mathematical modelling of the motor is covered in the ACE-CORE Engineer guides.

Why are DC Motor Actuators Important?

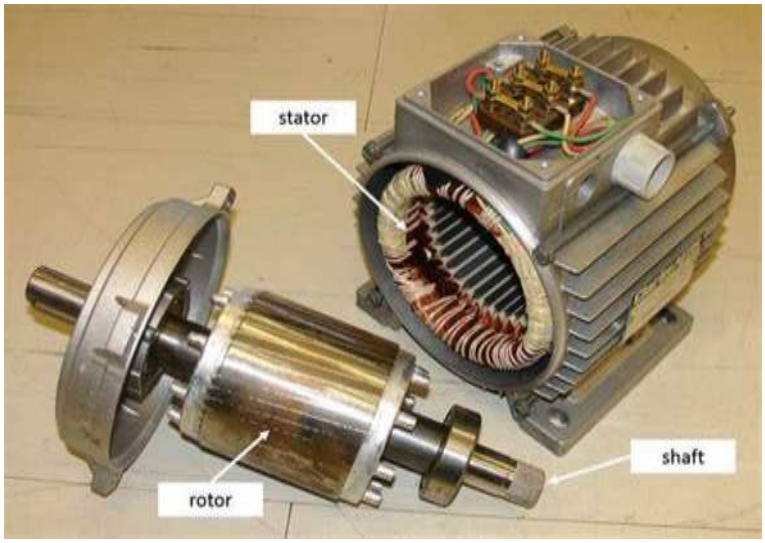
Understanding DC motor actuators is important because:

i. DC motors are the most common actuator in small-scale control systems, so they appear in many practical applications.
ii. A microcontroller cannot drive a motor directly from its pins, so a motor driver, such as an H-bridge, is always needed.
iii. Controlling the speed or position of a motor accurately requires a measurement of what the motor is actually doing, which an encoder provides.
iv. Together, the motor, H-bridge and encoder form the actuator and measurement blocks of a complete closed-loop control system.

3.0 The DC Motor

A typical DC motor is shown in Figure 1(a). The stator is the stationary outer part, which contains the magnets or windings that produce a magnetic field. The rotor (or armature) rotates inside the stator and carries the windings through which the motor current flows. The shaft is connected to the rotor and transfers the rotation to the load, often through gears, pulleys or a wheel.

(a)



(b)

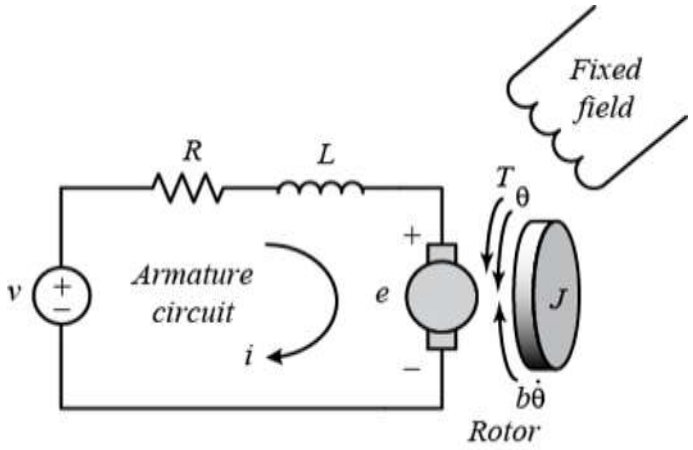


Figure 1: *A Typical DC Motor (a), and its Electrical Circuit and Mechanical Rotor (b)*

Figure 1(b) shows the motor as an electrical circuit connected to a mechanical rotor. Its behaviour can be summarised as follows:

- When a voltage is applied, a current flows through the armature circuit, which has a resistance R and an inductance L.
- The current produces a torque on the rotor, which is proportional to the current. The torque accelerates the rotor and its load, which has an inertia J, against friction.
- As the rotor turns, it acts as a generator and produces a back electromotive force (back emf), e, which opposes the applied voltage and is proportional to the speed.
- The motor speeds up until the back emf and the losses balance the applied voltage. As a result, in steady state the speed is roughly proportional to the applied voltage, and reversing the voltage reverses the direction of rotation.

These two properties, speed set by the size of the voltage and direction set by its polarity, are what the H-bridge exploits.

4.0 Driving a DC Motor with an H-Bridge

A microcontroller pin can only supply a small current (up to about 20mA on the Arduino Uno), whereas even a small motor needs hundreds of milliamps or more. A motor is therefore always connected through a motor driver, which switches a separate, higher-power supply to the motor under the control of low-power signals from the microcontroller. The most common motor driver is the H-bridge.

An H-bridge consists of four switches (usually transistors, Q1 to Q4) arranged with the motor in the middle, as shown in Figure 2(a). The arrangement looks like the letter H, which gives the circuit its name. The diodes D1 to D4 protect the transistors from the voltage spikes produced by the motor's inductance when it is switched off.

- One direction: turning on Q1 and Q4 connects the supply so that current flows through the motor from the 'A' side to the 'B' side, as shown in Figure 2(b).
- The other direction: turning on Q3 and Q2 reverses the current through the motor, from the 'B' side to the 'A' side, as shown in Figure 2(c), and so the motor rotates the other way.
- Stopped: with all four switches off, no current flows and the motor coasts to a stop.

Whether a given current direction gives clockwise or anticlockwise rotation depends on how the motor is wired. The two switches on the same side (Q1 and Q2, or Q3 and Q4) must never be turned on at the same time, because this would short-circuit the supply (known as shoot-through). Motor driver modules, such as the one in Figure 2(d), include logic that prevents this.

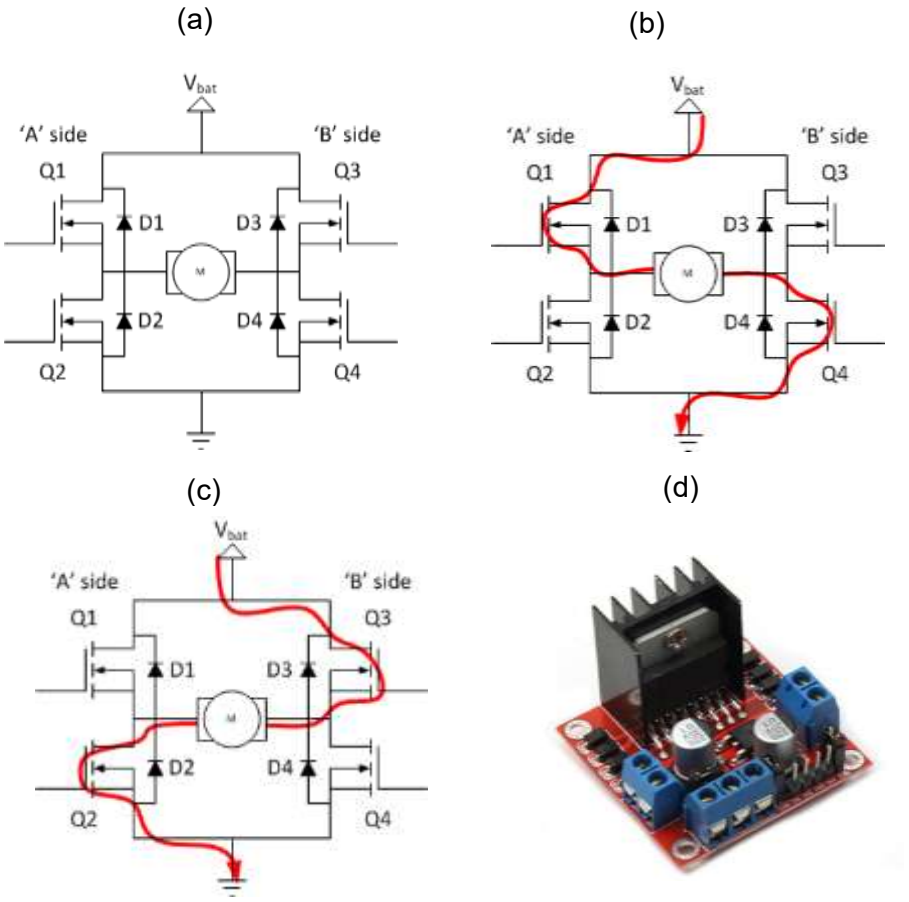


Figure 2: *H-Bridge Circuit (a), Current Path for One Direction of Rotation (b), Current Path for the Other Direction (c), and an H-Bridge Motor Driver Module (d)*

Controlling Speed with PWM

The H-bridge controls the direction of the motor. Its speed is controlled by switching the H-bridge on and off rapidly using pulse-width modulation (PWM), as introduced in the Introduction to the ATmega328P Microcontroller guide. The motor responds to the average voltage, so a duty cycle D applied to a supply voltage V_s gives an average motor voltage of approximately:

$$V_{avg} = D \times V_s \tag{1}$$

For example, with a 12 V motor supply, a PWM value of 128 out of 255 ($D \approx 0.5$) gives an average of about 6 V, and so roughly half of the full speed. A typical connection uses two digital pins from the microcontroller to select the direction, and one PWM pin to set the speed.

This is open-loop speed control: the microcontroller sets the voltage, but it does not know the actual speed. If the load on the motor increases, for example when a vehicle climbs a hill, the speed falls and nothing corrects it. Correcting this requires a measurement of the speed, which an encoder provides.

5.0 Measuring Motor Angle and Speed with an Encoder

An encoder is a sensor mounted on the motor shaft that produces pulses as the shaft rotates. It is a digital sensor of the “digitally encoded” type described in the Microcontroller-Based Measurement guide. A typical DC motor with an encoder has six connections:

- Motor power and motor ground: supply the motor from the H-bridge.
- Encoder power and encoder ground: supply the encoder electronics (usually 3.3 V or 5 V from the microcontroller).
- Encoder phase A: produces a square wave with a fixed number of pulses for each revolution of the shaft.
- Encoder phase B: produces the same square wave, but offset by a quarter of a pulse (90°) from phase A.

Measuring Angle and Speed

The number of pulses produced per revolution, the pulses per revolution (PPR), is given in the encoder datasheet. By counting the pulses from phase A, the microcontroller can calculate how far the shaft has turned. For example, for an encoder with 12 PPR, counting 48 pulses means the shaft has completed $48/12 = 4$ revolutions. In general:

$$\theta = \frac{\textit{pulse count}}{\textit{PPR}} \times 360° \tag{2}$$

The speed is found by counting the pulses, Δn, in a fixed time interval, Δt:

$$\text{speed [RPM]} = \frac{\Delta n}{\text{PPR} \times \Delta t} \times 60 \tag{3}$$

For example, 30 pulses counted in 0.05 s from a 12 PPR encoder gives $30/(12 \times 0.05) \times 60 = 3000$ RPM. If the motor drives its load through a gearbox, and the encoder is on the motor shaft, the output speed is the motor speed divided by the gear ratio.

The resolution of the speed measurement is one pulse per counting interval. With 12 PPR and $\Delta t = 0.05$ s, one pulse corresponds to 100 RPM, so the measured speed changes in steps of 100 RPM. A longer counting interval gives a finer resolution but a slower update, and the measured speed is usually also low-pass filtered, as described in the Microcontroller-Based Measurement guide.

Measuring Direction

Phase B allows the direction of rotation to be determined. As shown in Figure 3, when the shaft turns one way, the edges of phase A occur before those of phase B (A leads B); when it turns the other way, B leads A. By checking the state of phase B at each rising edge of phase A, the microcontroller can tell which way the motor is turning, and count up or down accordingly. Counting the rising and falling edges of both phases (known as quadrature or ×4 decoding) gives four times as many counts per revolution, improving the resolution.

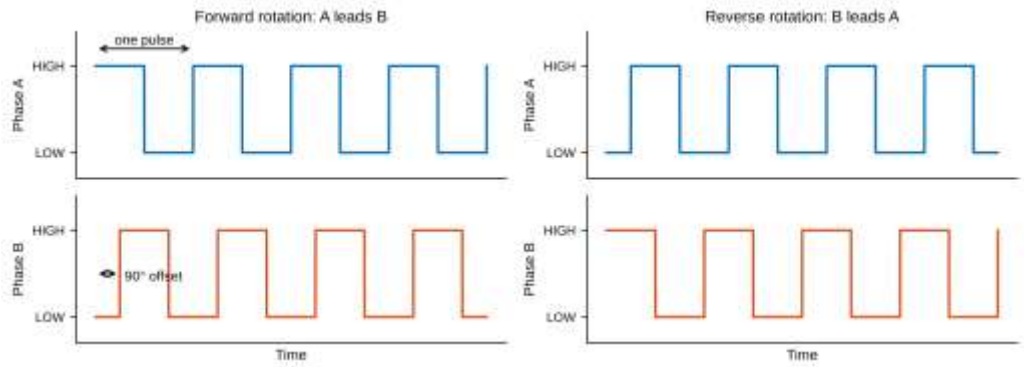


Figure 3: *Encoder Phase A and Phase B Signals for the Two Directions of Rotation*

Towards Closed-Loop Control

With the H-bridge as the actuator and the encoder as the measurement device, the motor can be operated in closed loop: the microcontroller compares the measured speed or angle with the reference and adjusts the PWM output to reduce the error. The measured input voltage and output speed can also be used to build a mathematical model of the motor, which is covered in the ACE-CORE Engineer guides.

6.0 Summary

This guide introduced the DC motor as an actuator in a control system. The speed of a DC motor is roughly proportional to the applied voltage, and its direction is set by the polarity of the voltage. Because a microcontroller pin cannot supply enough current, the motor is driven through an H-bridge, whose four switches reverse the current to change the direction of rotation, while PWM sets the average voltage and so the speed. The two switches on the same side of an H-bridge must never be turned on together.

An encoder provides the measurement needed for closed-loop control. Counting the pulses from phase A gives the angle and speed of the shaft, using the pulses per revolution, and comparing phases A and B gives the direction. Together, the H-bridge and encoder form the actuator and measurement blocks of a closed-loop motor control system.

Recommended Citation

If you have used this guide in your teaching, learning or research, please cite it using the reference below, adapting the format as required by your preferred referencing style.

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