Actuators in Robotics

DASE7503 Robotic Systems Integration

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Introduction

- Be a device that converts energy into physical motions like rotary or linear motion.
- Most common types of robotic actuators, including electric and pneumatic.
- Electric actuators use an electric current and magnets.
- Pneumatic actuators use compressed air to achieve motions.
- Electric actuators can use either direct current (DC) or alternating current (AC) power.



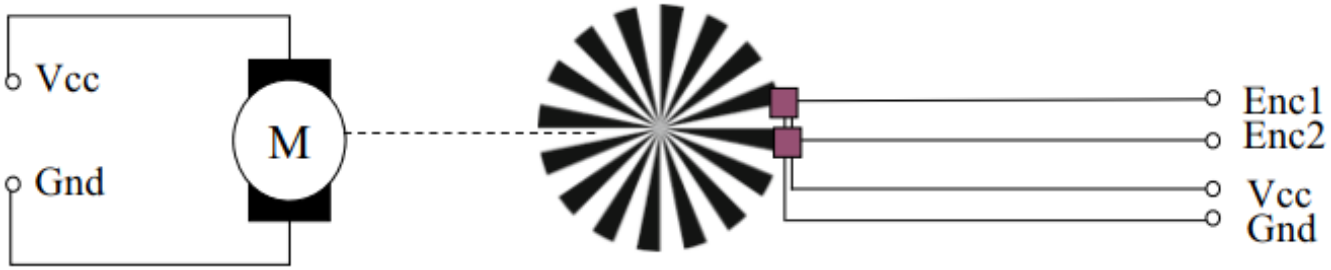


DC Motors

- Electric motors can be:
  - AC or DC motors
  - Brushed or brushless
  - Single-phase or three-phase
  - Special motors, such as stepper motors or servos
- **Single-phase DC electric motors** are arguably the most commonly used method for locomotion in **mobile robots**.
- DC motors are clean, quiet and can produce sufficient power for a variety of tasks.
- Electric motors are much easier to control than **pneumatic actuators**, which are frequently used when high torques are required and an umbilical cord for an external compressor pump is possible .

DC Motors

- **Standard DC motors** revolve **continuously** and therefore require a feedback mechanism using shaft encoders as shown in the following Figure.
- **Stepper motors** also move **continuously**, but only advance a fixed step angle (e.g., 2°) forward or backward at a time.
- **Servos** do not have a continuous movement, instead they can only rotate back and forth about a limited angular range (e.g., ±90°). In addition to power, they have a PWM signal input that tells them the desired angular position.



Motor–encoder combination

DC Motors

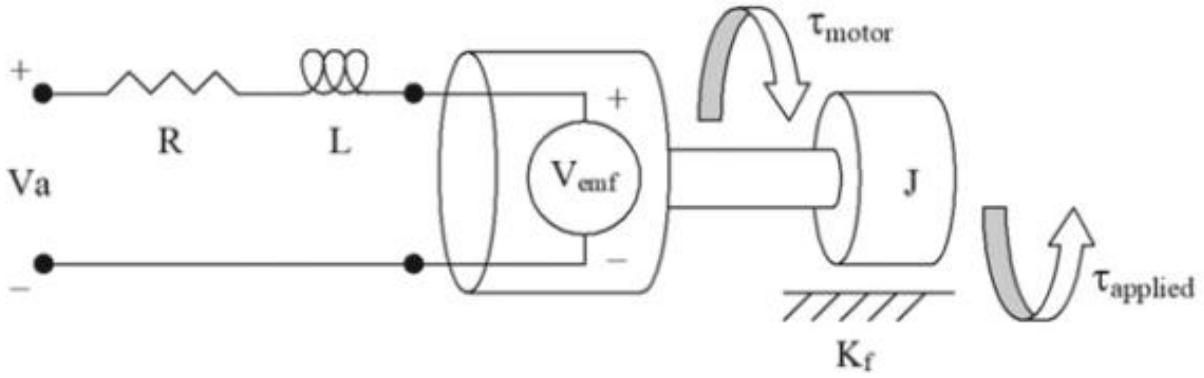
- To select the appropriate motor system for building robot hardware
- The best choice is an **encapsulated motor combination** comprising:
  - DC motor
  - Gearbox
  - Optical or magnetic encoder (dual phase-shifted encoders for detection of speed and direction).
- **The encapsulated motor systems** has the advantages to be
  - much smaller than that using separate modules
  - dust-proof and shielded against stray light, which is required for optical encoders.
- **The encapsulated motor systems** use a fixed assembly like this is that the gear ratio may only be changed with difficulty, or not at all.

DC Motors

Motor Model

- A voltage V_a is applied to the terminals of the motor, which generates a current i in the motor armature.
- The torque τ_m produced by the motor is proportional to the current, and K_m is the motor's torque constant:

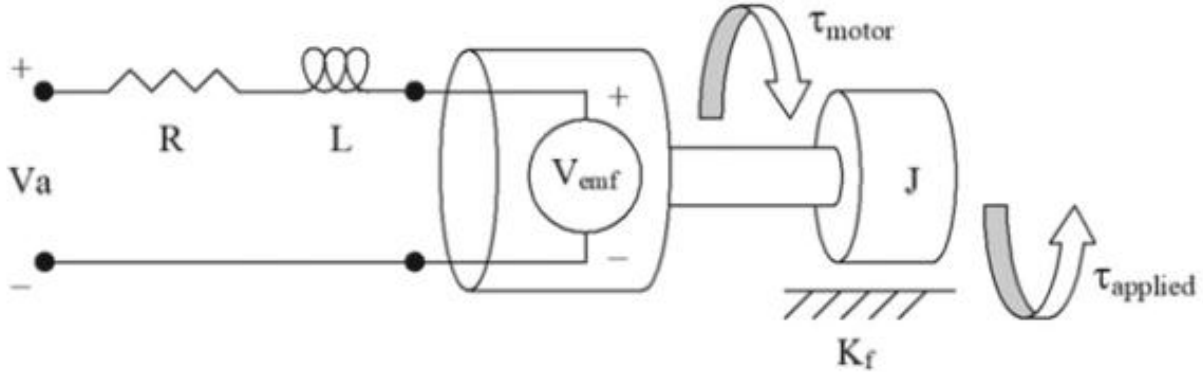
$$\tau_m = K_m \cdot i$$



θ	Angular position of shaft [rad]	R	Nominal terminal resistance [Ω]
ω	Angular shaft velocity [rad/s]	L	Rotor inductance [H]
α	Angular shaft accel. [rad/s^2]	J	Rotor inertia [kg·m^2]
i	Current through armature [A]	K_f	Frictional const. [N·m·s/rad]
V_a	Applied terminal voltage [V]	K_m	Torque constant [N·m/A]
V_e	Back *emf* voltage [V]	K_e	Back *emf* constant [V·s/rad]
τ_m	Motor torque [N·m]	K_s	Speed constant [rad/(V·s)]
τ_a	Applied torque (load) [N·m]	K_r	Regulation constant [(V·s)/rad]

DC motor variables and constant values

DC Motors



Motor Model

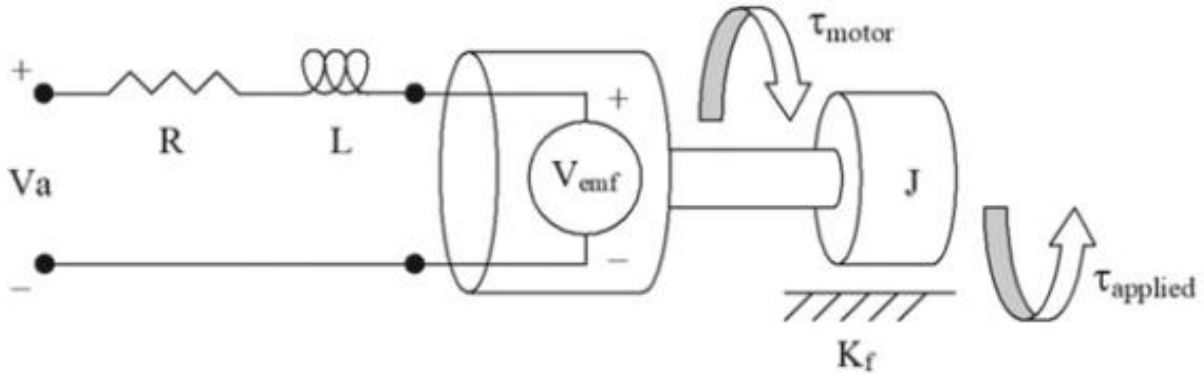
- It is important to select a motor with the right output power for a desired task. The **output power P_o** is defined as the rate of work, which for a rotational DC motor equates to the angular velocity of the shaft ω multiplied by the applied torque (the torque of the load):

$$P_o = \tau_a \cdot \omega$$

- The **input power P_i**, supplied to the motor is equal to the applied voltage multiplied by the current through the motor:

$$P_i = V_a \cdot i$$

DC Motors

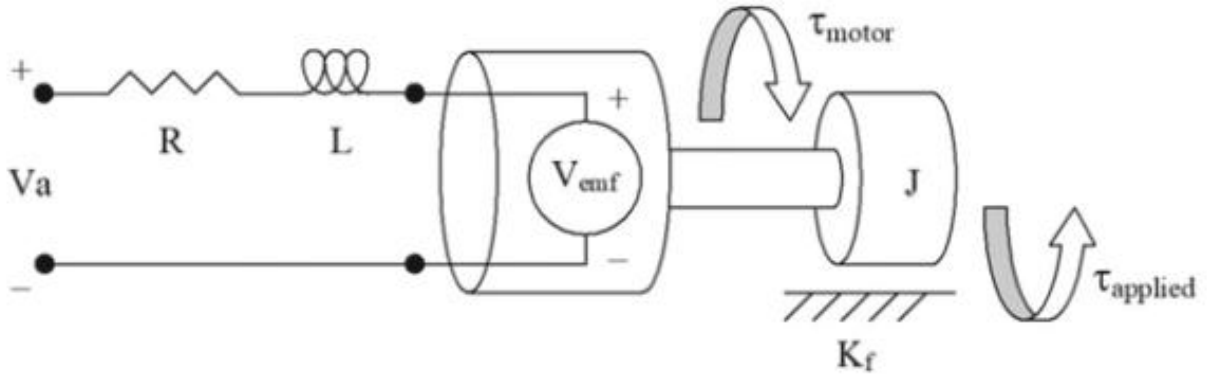


Motor Model

- The motor also generates heat as an effect of the current flowing through the armature. The **power lost to thermal effects P_t** is equivalent to:
  $$P_t = R \cdot i^2$$

- The **efficiency η of the motor** is a measure of how well electrical energy is converted to mechanical energy. This can be defined as the output power produced by the motor divided by the input power required by the motor:
  $$\eta = P_o / P_i = (\tau_a \cdot \omega)/(V_a \cdot i)$$

DC Motors

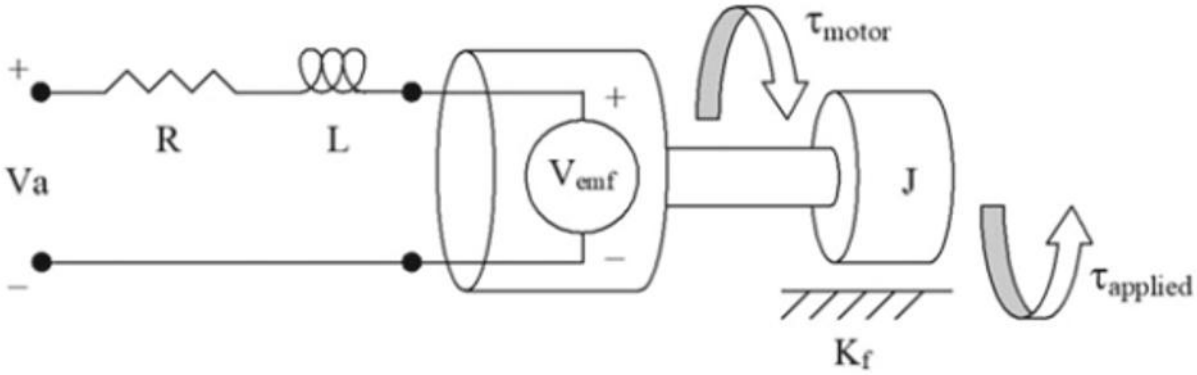


Motor Model

- The efficiency is **not constant for all speeds**, which needs to be kept in mind if the application requires **operation at different speed ranges**.
- The electric system of the motor can be modeled by a **resistor–inductor pair** in series with a voltage V_{emf}, which corresponds to the **back electromotive force** (see Figure).
- This voltage is produced because **the coils of the motor are moving through a magnetic field**, which is the same principle that allows an electric generator to function.
- The voltage produced can be approximated as a linear function of the shaft velocity; K_e is referred to as **the back emf constant**:

$$V_e = Ke \cdot \omega$$

DC Motors



Simplified Motor Model

- In the simplified DC motor model, **motor inductance** and **motor friction** are negligible and set to zero, and the rotor inertia is denoted by J. The formulas for current and angular acceleration can therefore be approximated by:

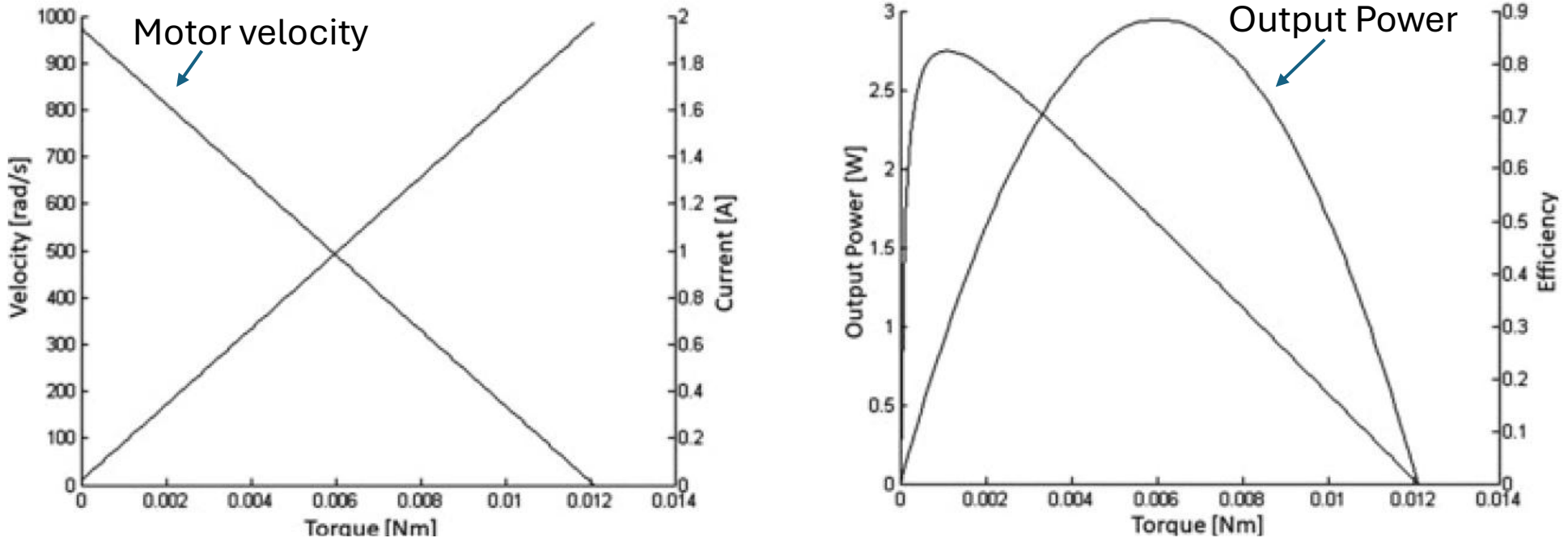
$$i = -\omega \cdot K_e/R + V_a/R$$

$$d\omega/dt = (K_m \cdot i - \tau_a)/J$$

DC Motors

Simplified Motor Model

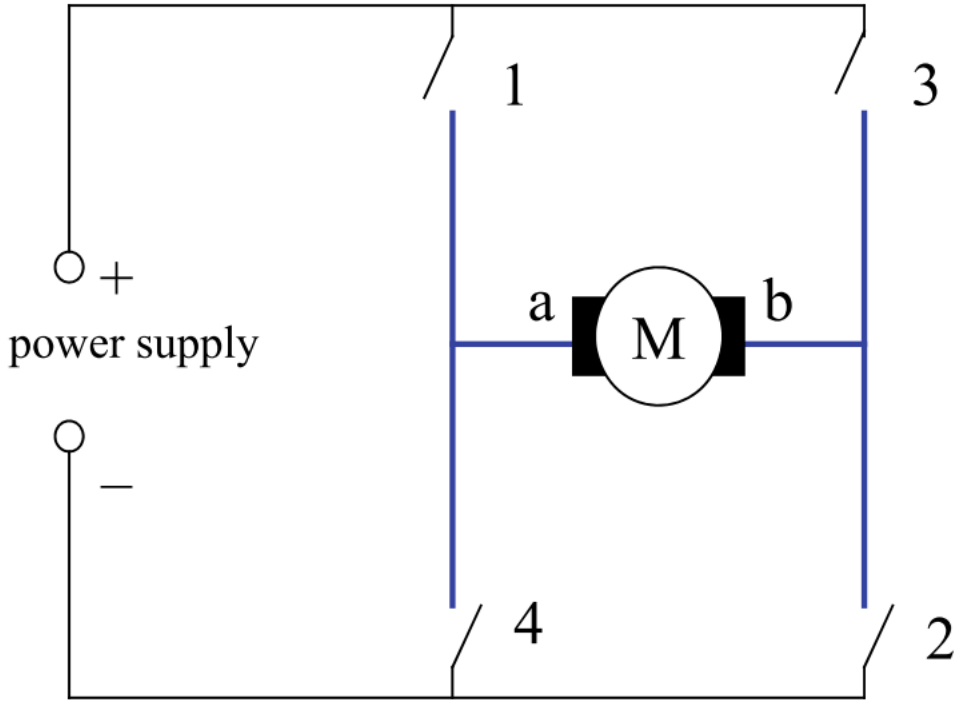
- With increasing **torque**, the motor **velocity** is reduced linearly, while the **current** increases linearly. Maximum **output power** is achieved at a **medium torque level**, while the **highest efficiency** is reached for relatively **low torque values**.



Ideal DC motor performance curves

H-Bridge

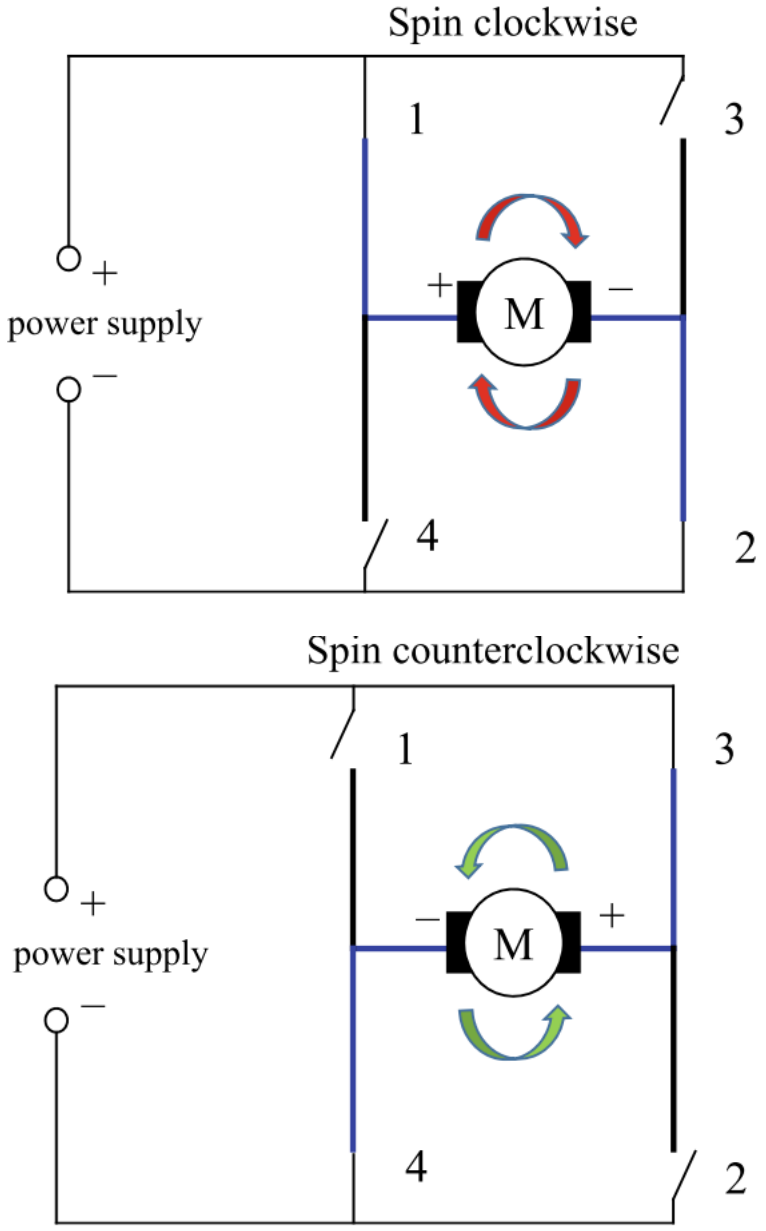
- For most applications, we want to be able to do two things with a motor:
  - Run it in forward and backward directions.
  - Modify its speed.
- In order to change polarity of the supply voltage on the motor, we need a so-called **H-bridge**. This will enable a motor to spin forward or backward at a fixed speed.
- Have a motor with two terminals a and b and a power supply with '+' and '–' .



H-bridge Setup

H-Bridge

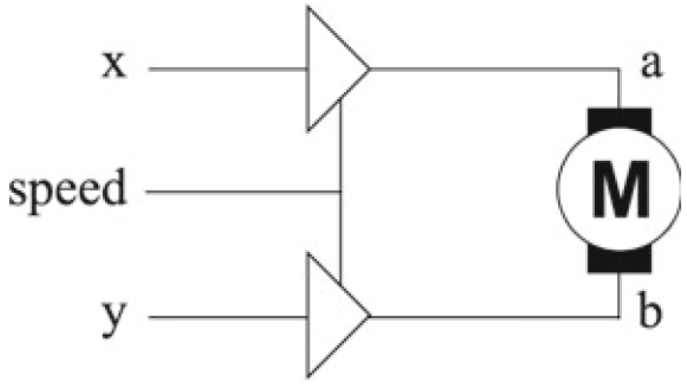
- Closing switches 1 and 2 will connect a with '+' and b with '–': The motor runs forward.
- In the same way (after opening 1 and 2 again), closing switches 3 and 4 instead will connect a with '–' and b with '+': The motor runs backward.
- The way to implement an H-bridge when using a **microcontroller** is to use **a power amplifier chip** in combination with the **digital output pins** of the controller or **an additional latch**. This is required because the digital outputs of a microcontroller have very severe output power restrictions.
- They can only be used to drive other logic chips, but **never a motor directly**.



H-bridge and operation

H-Bridge

- A motor can draw a lot of power (e.g., 1A or more), connecting digital outputs directly to a motor can destroy the microcontroller.
- A typical **power amplifier chip** containing two separate amplifiers is L293D from ST SGS-Thomson.
- The two inputs x and y are needed to switch the input voltage, so one of them has to be '+', the other has to be '–'.
- Since they are electrically decoupled from the motor, x and y can be directly linked to digital outputs of the microcontroller.
- So **the direction of the motor** can then be **specified by software**, for example setting **output x to logic 1 and output y to logic 0**.
- Since x and y are always the opposite of each other, they can also be substituted by a single output port and a negator.
- There are two principal ways of **stopping the motor**:
  - set both x and y to logic 0 (or both to logic 1) or
  - set speed to 0 (by Pulse Width Modulation)



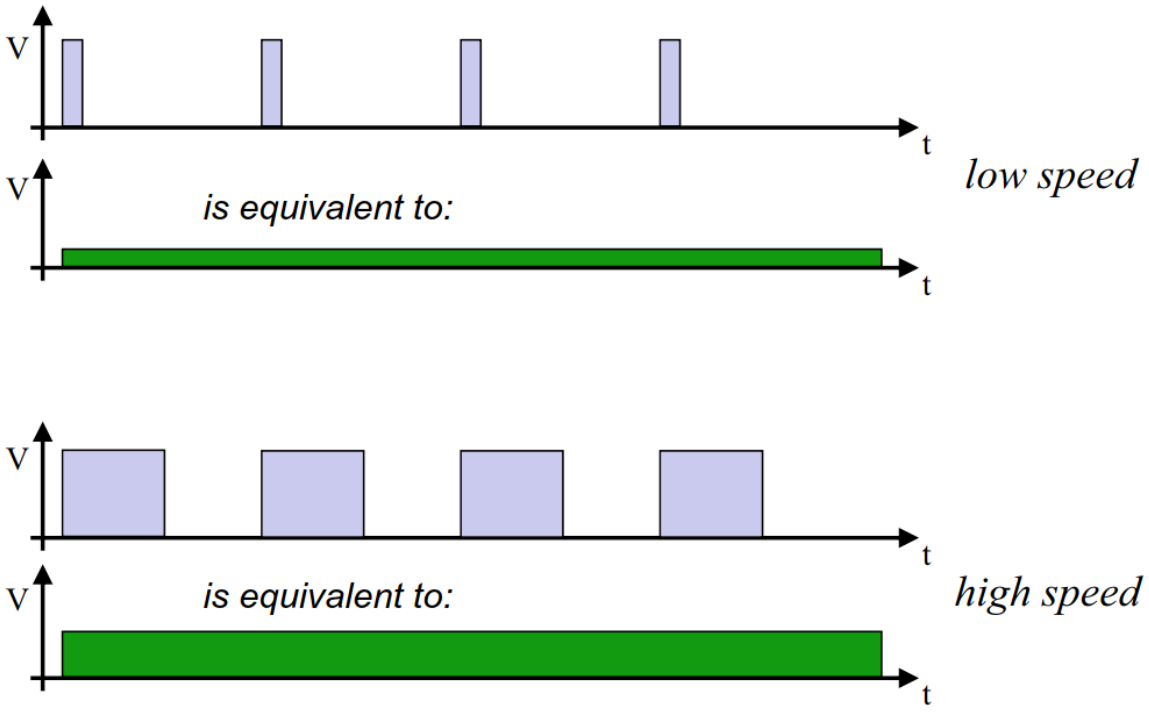
Power amplifier as motor driver

Pulse Width Modulation

- PWM for short is a smart method for avoiding **analog power circuitry** by utilizing the fact that mechanical systems have a relatively high latency.
- Instead of generating an analog output signal with a voltage proportional to the desired motor speed, it is sufficient to generate **digital pulses** at the full system voltage level (e.g., 5 V).
- These **pulses** are generated at a **fixed frequency**, for example 20 kHz, so they are beyond the human hearing range.

Pulse Width Modulation

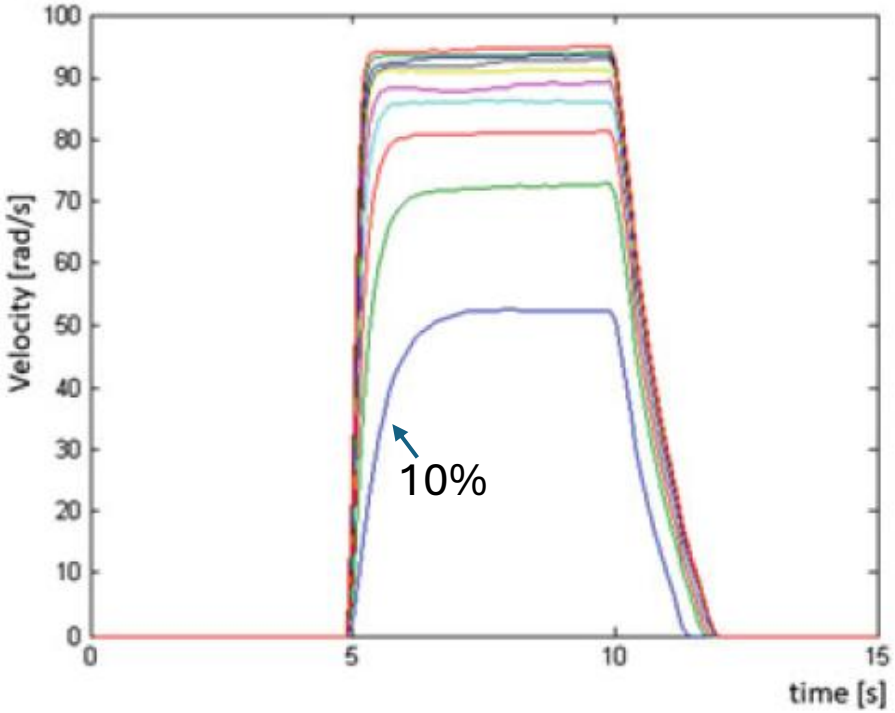
- By varying the pulse width in software, as shown in Figure, top versus bottom), we also change the equivalent or effective analog motor signal and therefore control the motor speed.
- One could say that the motor system behaves like an integrator of the digital input impulses over the cycle time. The quotient t_{on}/t_{period} is called the **pulse width ratio** or **duty cycle**.



Pulse Width Modulation

- The PWM signal can be generated by **software**, and many microcontrollers have already special modes and output ports built in to support this operation.
- The digital output port for the PWM signal is then connected to the speed pin of the **power amplifier**.

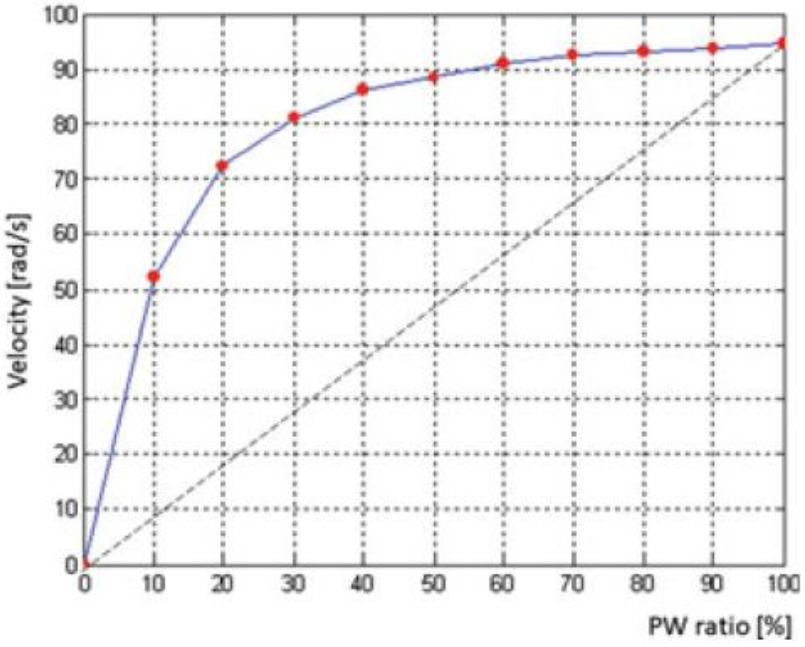
- The right Figure shows **the motor speed over time** for **PWM settings** of 10%, 20%, …, 100%.
- In each case, the PWM signal is issued at time t = 5 s (On). The motor then reaches the desired velocity with only a small delay and stays constant until the signal is shut down at t = 10 s (Off).
- After that, the motor speed drops off somewhat slower due to its **internal inertia**. This type of behavior is called a **step response**, since the motor input signal jumps in a step function from zero to the desired PWM value.



Measured motor step response

Pulse Width Modulation

- The generated motor speed is **normally not a linear function of the PWM signal ratio**, as can be seen when comparing the measurement of a Faulhaber 2230 motor in right Figure, to the dashed diagonal line.
- Note that these measurements have been done for **an idling motor without any load**. Depending on load, these curves will change significantly.



Speed versus pulse width ratio

Pulse Width Modulation

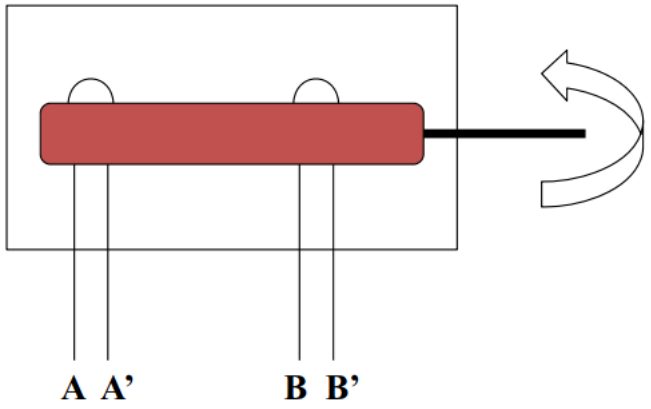
- Motor calibration can be done by measuring the motor speed at various settings between 0 and 100, and then entering the PW ratio required to achieve the desired actual speed in a motor calibration table of the HDT (hardware description table).
- **Motor calibration** is especially important for **robots with differential drive**, because in these configurations, normally one motor runs forward and one backward, in order to drive the overall robot forward.
- Many DC motors exhibit some differences in **speed versus PW ratio** between forward and backward direction. This can be eliminated by using **motor calibration**.
- That the actual motor speed does depend not only on the PWM signal supplied, but also on external factors such as the load applied (e.g., the weight of a vehicle or the steepness of its driving area). What we have achieved so far is called **open-loop control**.

Stepper Motors

- Differ from standard DC motors in such a way that they have two **independent coils** which can be independently controlled. As a result, stepper motors can be moved by pulses to proceed exactly a **single step forward** or **backward**, instead of a smooth continuous motion in a standard DC motor.
- A typical number of steps per revolution is **200**, resulting in a step size of 1.8°. Some stepper motors allow half steps, resulting in an even finer step size.
- There is also a maximum number of steps per second, depending on load, which limits a stepper motor's speed.

Stepper Motors

- Two coils are independently controlled by two H-bridges (here marked A, A' and B, B'). Each four-step cycle advances the motor's rotor by a single step if executed in order 1–4.
- Executing the sequence in **reverse order** will **move the rotor one step back**. Note that the switching sequence pattern resembles a gray code, only a single bit changes at each transition.



Switching Sequence:

Step	A	B
1	ON	ON
2	ON	OFF
3	OFF	OFF
4	OFF	ON

Stepper motor schematics

Stepper Motors

- Stepper motors seem to be a simple choice for building mobile robots, considering the effort required for **velocity control** and **position control** of standard DC motors.
- However, stepper motors are rarely used for **driving mobile robots**, since they **lack any feedback on load and actual speed** (e.g., a missed step execution).
- In addition to requiring double the power electronics, stepper motors also have a worse weight/performance ratio than DC motors.

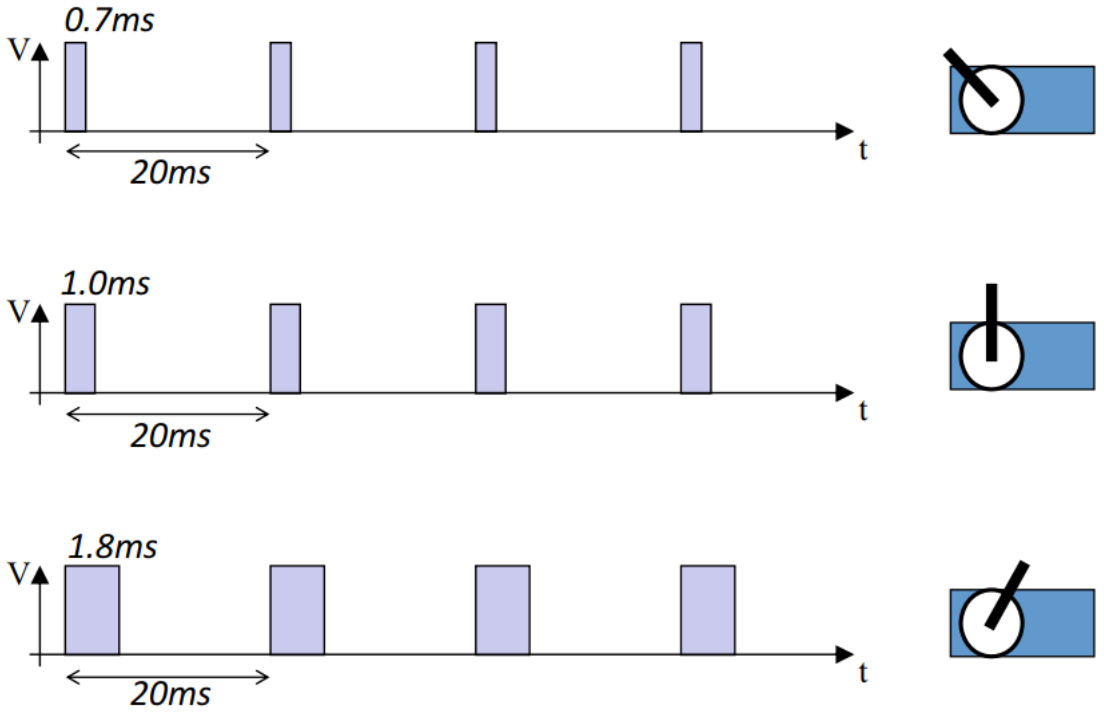
Servos

- A servo, on the contrary, is a DC motor with **encapsulated electronics** for PWM control and is mainly used for hobbyist purposes, as in model airplanes, cars, or boats.
- A servo has three wires: V_{CC}, ground and the PWM input control signal.
- Unlike PWM for DC motors, the input pulse signal for servos is **not transformed into a velocity**.
- Instead, it is an analog timing control input to specify the desired position of the servo's rotating disk head.
- A servo's disk **cannot perform a continuous rotation** like a DC motor. It only has **a range**, depending on the model, of about ±120° from its middle position.
- Internally, a servo combines a DC motor with a simple feedback circuit, often using a potentiometer sensing the servo head's current position.



Servos

- The **PWM signal** used for servos always has **a frequency of 50 Hz**, so pulses are generated every 20 ms.
- The width of each pulse specifies the desired position of the servo's disk.
- For example, a width of 0.7 ms will rotate the disk to the leftmost position (+120°), and a width of 1.8 ms will rotate the disk to the rightmost position (−120°), as shown in right Figure.
- Exact values of pulse duration and angle depend on the servo brand and model.



Servos

- Like stepper motors, servos seem to be a good and simple solution for robotics tasks.
- However, servos have the same drawback as stepper motors:
  - They do not provide any feedback to the outside.
- When applying a certain PWM signal to a servo, we do not know when the servo will reach the desired position or whether it will reach it at all, e.g., because of a too high load or because of an obstruction.