Lecture 16: Actuators and Output

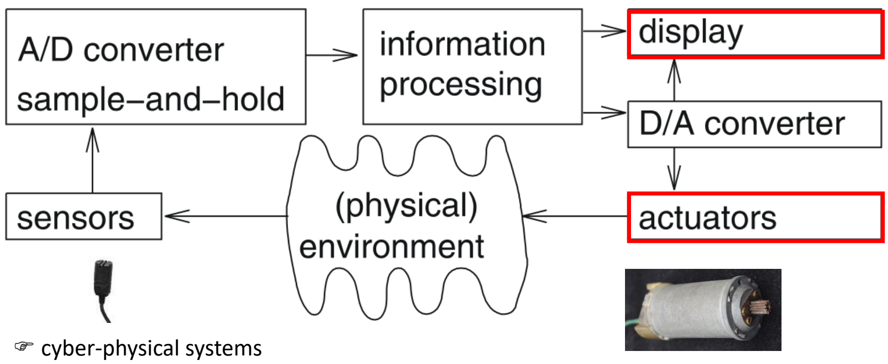
Seyed-Hosein Attarzadeh-Niaki

Review

Photodiodes	Temperature sensors	Humidity sensors	Ultrasonic sensors
Digital IR sensors	Gas sensors	Hall sensors	Color Sensors
Digital tilt	Accelerometer sensor	Analog sound sensor	Capacitive touch sensor

CPS & ES Hardware

- Embedded system hardware is frequently used in a loop (***"hardware in a loop"***):



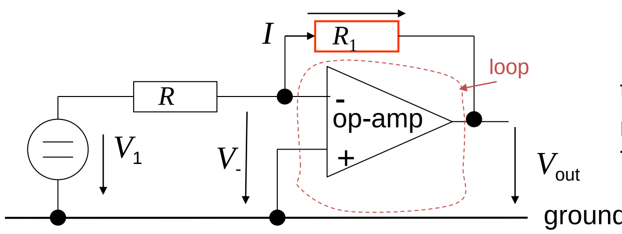
☞ cyber-physical systems

Driving Actuators

- Most actuators cannot be driven directly using IO pins of a processor
  - Analog actuators
  - Limited current source/sink capability
  - Exceptions: LEDs
- Be careful using DACs: limited DAC output current
  - Use power amplifiers: linearity problem
  - Use PWM

Op-Amps with feedback

- In circuits, negative feedback is used to define the actual gain.



Due to the feedback to the *inverted* input, R_1 reduces voltage V_-. To which level?

$V_{out} = - g \cdot V_-$ (op-amp feature)

$I \cdot R_1 + V_{out} - V_- = 0$ (loop rule)

$\Rightarrow I \cdot R_1 + - g \cdot V_- - V_- = 0$

$\Rightarrow (1+g) \cdot V_- = I \cdot R_1$

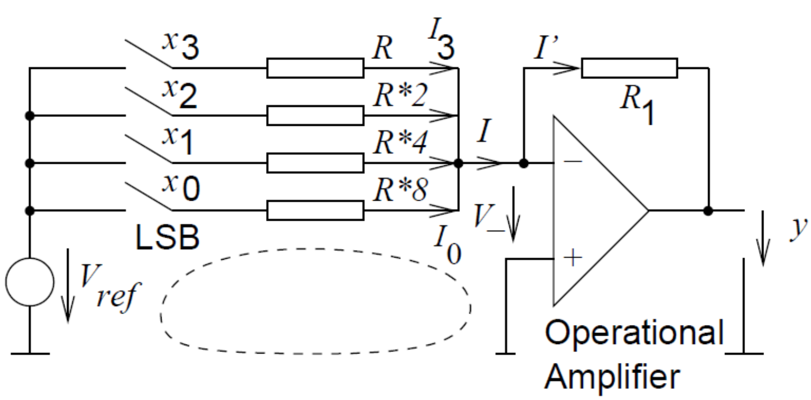
$$\Rightarrow V_- = \frac{I \cdot R_1}{1+g}$$

$$\boxed{V_{-,ideal} = \lim_{g \to \infty} \frac{I \cdot R_1}{1+g} = 0}$$

V_- is called **virtual ground**: the voltage is 0, but the terminal may not be connected to ground

Digital-to-Analog (D/A) Converters

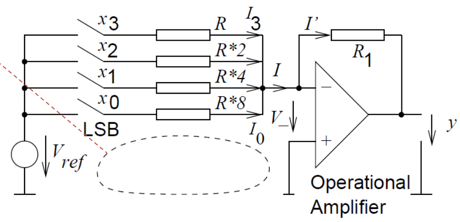
Various types, can be quite simple, e.g.:



Current I proportional to the number represented by x

Loop rule:

$$x_0 \cdot I_0 \cdot 8 \cdot R + V_- - V_{ref} = 0$$



☞ $$I_0 = x_0 \times \frac{V_{ref}}{8 \times R}$$

In general: $$I_i = x_i \times \frac{V_{ref}}{2^{3-i} \times R}$$

Junction rule: $$I = \sum_i I_i$$

☞ $$I = x_3 \times \frac{V_{ref}}{R} + x_2 \times \frac{V_{ref}}{2 \times R} + x_1 \times \frac{V_{ref}}{4 \times R} + x_0 \times \frac{V_{ref}}{8 \times R} = \frac{V_{ref}}{8 \times R} \times \sum_{i=0}^{3} x_i \times 2^i$$

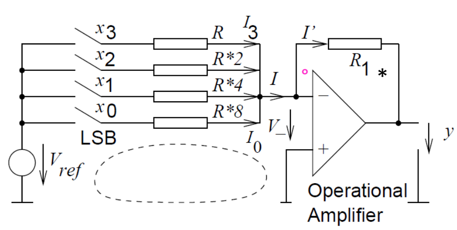
$I \sim nat(x)$, where $nat(x)$: natural number represented by x;

Current I proportional to the number represented by x

Loop rule*: $$y + R_1 \times I' = 0$$

Junction rule°: $$I = I'$$

☞ $$y + R_1 \times I = 0$$



From the previous slide

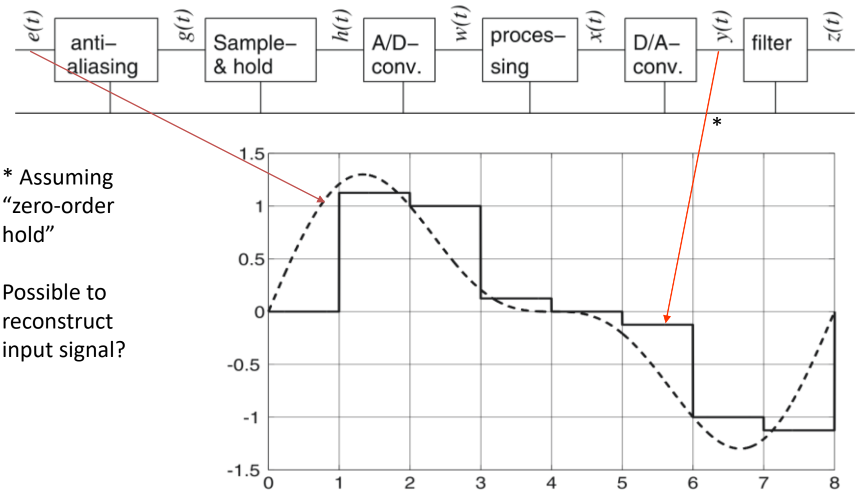
$$I = \frac{V_{ref}}{8 \times R} \times \sum_{i=0}^{3} x_i \times 2^i$$

Hence:

$$y = -V_{ref} \times \frac{R_1}{8 \times R} \sum_{i=0}^{3} x_i \times 2^i = -V_{ref} \times \frac{R_1}{8 \times R} \times nat(x)$$

Op-amp turns current $I \sim nat(x)$ into a voltage $\sim nat(x)$

Output generated from signal $e_3(t)$

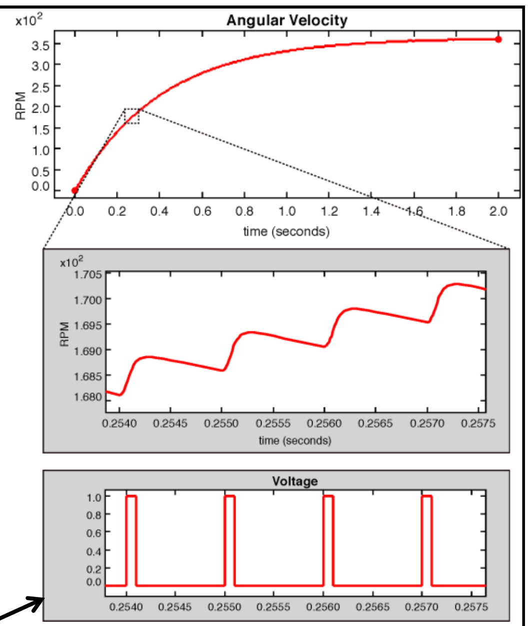


* Assuming "zero-order hold"

Possible to reconstruct input signal?

Pulse-Width Modulation (PWM)

Delivering power to actuators can be challenging. If the device tolerates rapid on-off controls ("bang-bang" control), then delivering power becomes much easier.



Duty cycle around 10%

DC motor

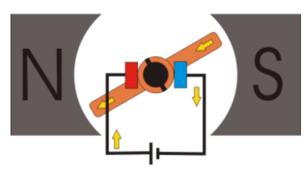
Electro-mechanical Control

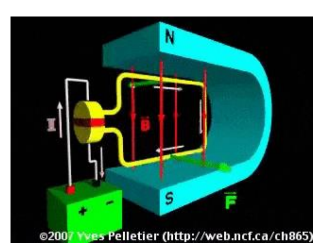
Servo motor

Stepper motor

DC Motors

- Increasingly common in a variety of motor applications
  - Examples: fans, pumps, appliances, automation, and automotive drive
- Reasons to use
  - Better speed versus torque characteristics
  - High efficiency
  - Long operating life
  - Noiseless operation
  - Ratio of torque delivered to size of the motor is higher





DC Motor Model

$$v(t) = Ri(t) + L\frac{di(t)}{dt} + k_b\omega(t)$$

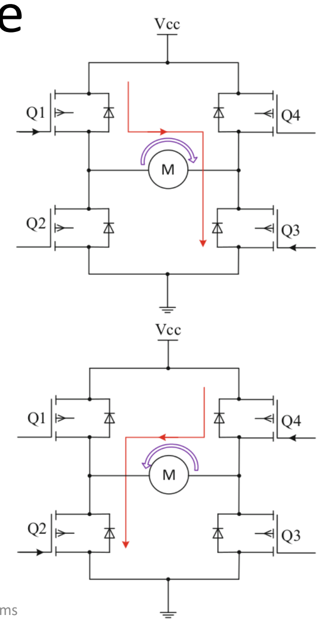
- R is the resistance and L the inductance of the coils in the motor
- When a coil rotates in a magnetic field, it generates a current causing a back electromagnetic force $k_b\omega(t)$

$$I\frac{d\omega(t)}{dt} = k_T i(t) - \eta\omega(t) - \tau(t)$$

- k_T an empirically determined motor torque constant
- η is the kinetic friction of the motor
- τ is the torque applied by the load

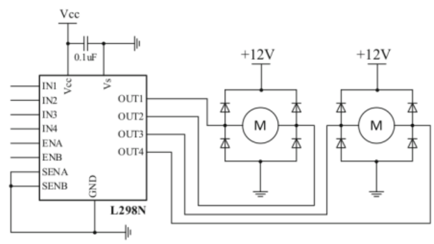
H-Bridge

- A DC motor runs by supplying a voltage difference across its leads
- To control the direction of the spin of DC motors, without changing the way that the leads are connected, an H-Bridge is commonly used
- Q1&Q3 or Q2&Q4



L298N DC Motor Driver

- Dual motor controller
- Two protected driver circuits capable of delivering up to 2A of continuous current to each motor at up to 36VDC
- Accepts standard 0–5 V input
- Use a PWM signal on each enable pin (ENA and ENB) to set the speed of each motor

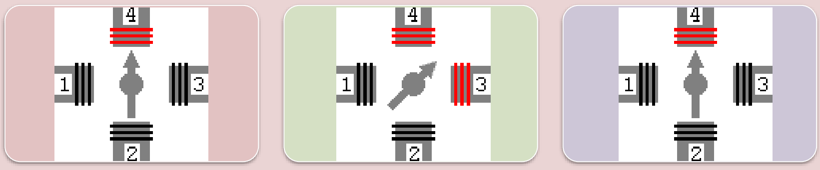


IN1	IN2	Action
LOW	LOW	Motor breaks and stops
HIGH	LOW	Motor turns forward
LOW	HIGH	Motor turns backward
HIGH	HIGH	Motor breaks and stops

Stepper Motor

- A stepper motor is a brushless, synchronous electric motor
- Converts digital pulses into mechanical shaft rotations
- Each rotation of a stepper motor is divided into a set of number of steps
  - The stepper motor controller must send a separate pulse for each step
- Can precisely control the position of the stepper motor *without any feedback* mechanism (Open-loop)
- The stepping movement converts into a continuous rotation with high frequency pulses

Stepper Motor Basics

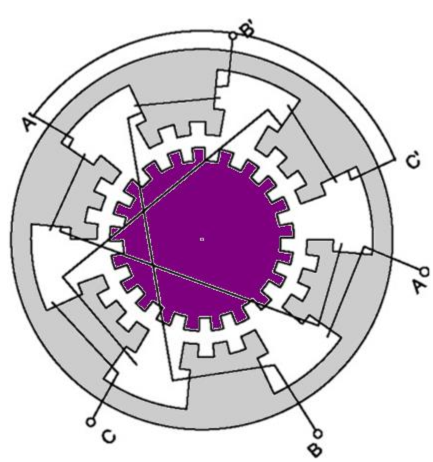


Single-Coil Excitation	Two-Coil Excitation	Half-Step Excitation

http://cs.pitt.edu/FORTS/jim/stepmtr.htm

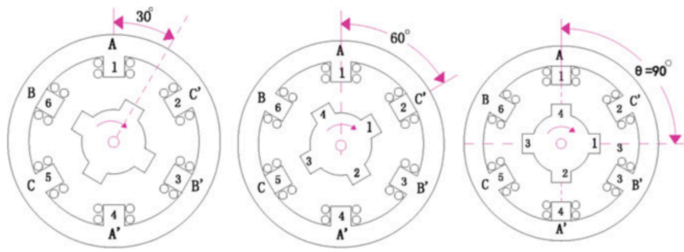
Working Principle of Stepper Motor

- Constructed from ferromagnetic material with salient poles
  - Each wound with an excitation coil
- Example: six stator coils connected in two-coil groups to form three separate circuits called *phases*
  - Each phase has its own independent switch
- Opposite pairs of stator coils are connected in series
  - One S-pole, the other N-pole



Working Principle of Stepper Motor I

- The step angle of this three-phase, four-rotor teeth motor: $\beta = \frac{360}{4\times 3} = 30^{\circ}$
- **One-phase-ON**: energizing stator phases in sequence A-B-C-A (or C-B-A-C) causes the rotor to rotate clockwise (counter-clockwise) in 30 steps



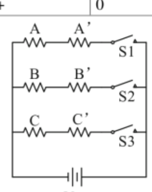
A	B	C	
+	0	0	0
0	+	0	30
0	0	+	60
+	0	0	90

Working Principle of Stepper Motor II

Two-phase-ON

- If stator phases are switched in the sequence AB-BC-CA-AB the motor will take full steps of 30° each

A	B	C	
+	+	0	15°
0	+	+	45°
+	0	+	75°
+	+	0	105°

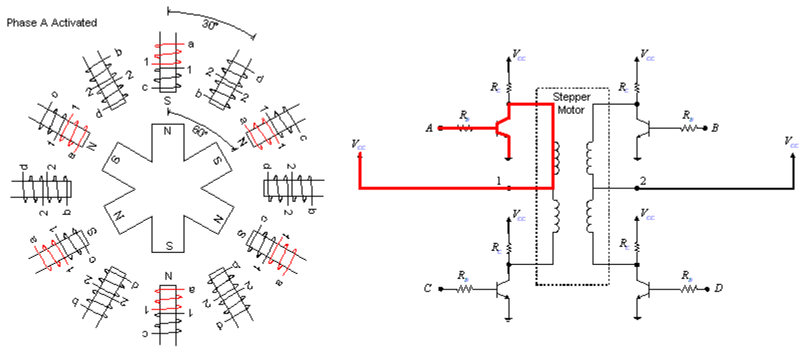


Half-step operation

- If stator phases are excited in the sequence A-AB-B-BC-C-CA-A it causes the rotor to advance in steps of 15°

	A	B	C	
A	+	0	0	0°
AB	+	+	0	15°
B	0	+	0	30°
BC	0	+	+	45°
C	0	0	+	60°
CA	+	0	+	75°
A	+	0	0	90°

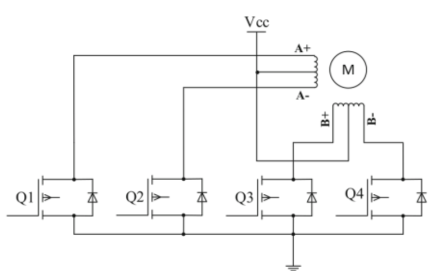
All Phases of Driving A Stepper Motor

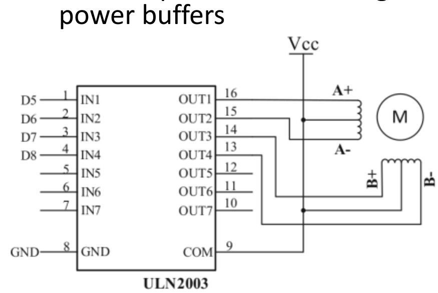


http://educypedia.karadimov.info/library/StepperMotorConstructionAllPhases1.gif

Driving Principle Unipolar Stepper Motors

- One winding with a center tap per phase
- A magnetic pole can be reversed without switching the direction of the current
- ULN2003/2004 internally employs high-voltage, high-current Darlington arrays
- Useful for driving solenoids, relays, DC motors, LED displays, filament lamps, thermal printheads, and high-power buffers

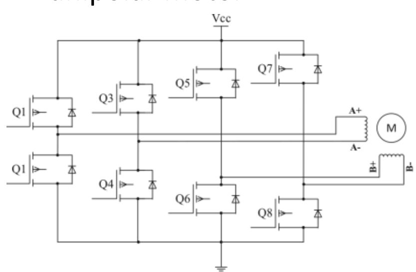


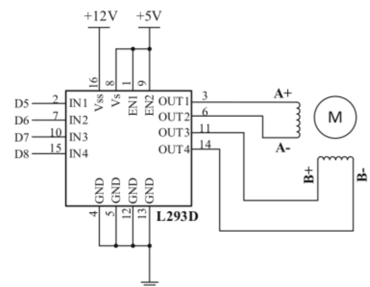


Driving Principle
Bipolar Stepper Motors

- A single winding per phase
- The current in a winding needs to be reversed in order to reverse a magnetic pole (H-bridge)
- More powerful than a unipolar motor

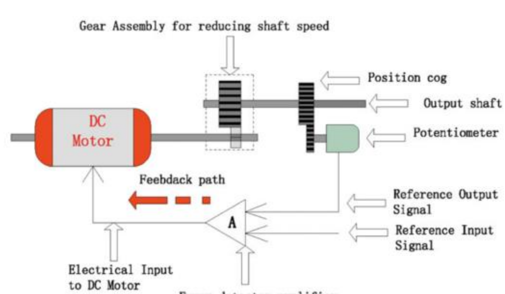
- L293D contains two H-bridges for driving stepper motors
- Pins 2, 7, 10, 15 Control signals





Servo Motor

- Popular with hobbyists
- Controlling them with microcontrollers is universal for all models
- Receive PWM signals to determine how to move
- consist of the motor and gearbox, a position sensor, an error amplifier and motor driver, and a circuit to decode the requested position
- Based on feedback



Comparison

Servo Motors

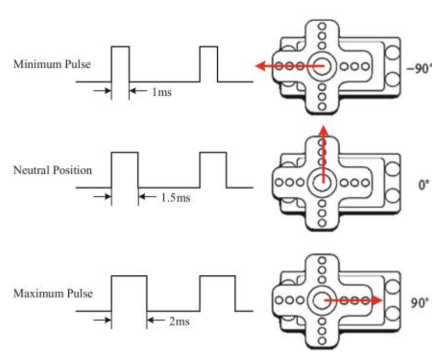
- Operate in a closed loop
  - Have an internal feedback
- RC Servo motors are limited to 0°–180° of movement
- Price: more expensive
- Do not lose torque in high rotational speeds

Stepper Motors

- Operate in a open loop
  - More error-prone
- Stepper motors do not need modifications to move 360°
- Price: cheaper
- Lose torque in high rotational speeds

Driver Circuit for Servo Motors

- Controlled through a control line
  - usually yellow in color
- Pulse width on this line determines how the motor will move
  - Pulse proportional modulation (PPM)
- 1–2 ms out of a 20 ms time period
  - 1.5 ms pulse -> 90°
  - Shorter -> closer to 0°
  - Longer -> closer to 180°



Next Lecture

- Multitasking