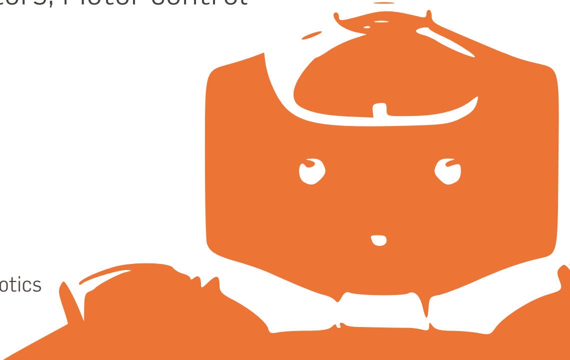
You can download the sources of this presentation here:
github.com/severin-lemaignan/module-mobile-and-humanoid-robots

ROBOTICS WITH PLYMOUTH UNIVERSITY

ROCO222
Intro to Sensors and Actuators
Magnets, Brushless Motors, Motor control

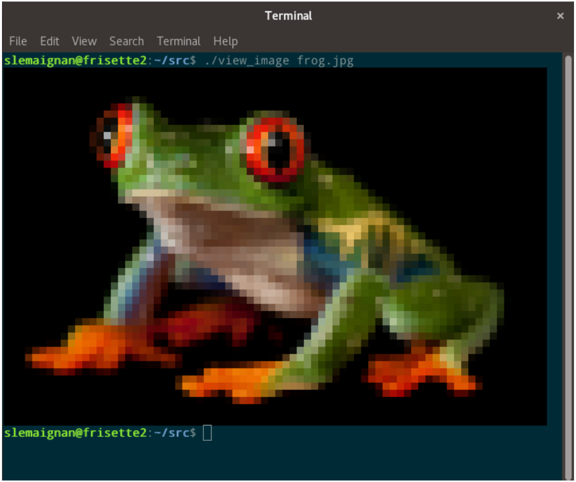


Séverin Lemaignan

Centre for Neural Systems and Robotics
Plymouth University

LAST WEEK'S PROGRAMMING CHALLENGE

Console-based image viewer



```python
# -*- coding: utf-8 -*-

import sys
from PIL import Image

im = Image.open(sys.argv[1])
im.thumbnail((80,80))
w, h = im.size

def print2pixels(col1, col2):
    R,G,B=col1
    r,g,b=col2

    return "\033[38;2;%d;%d;%dm" \
           "\033[48;2;%d;%d;%dm" % (R,G,B,r,g,b)


ascii_img = ""

for y in range(0,h,2):
    for x in range(w):
        ascii_img += print2pixels(im.getpixel((x, y)),
                                  im.getpixel((x, y + 1)))
    ascii_img += "\n"

print ascii_img
```

TODAY'S OBJECTIVES

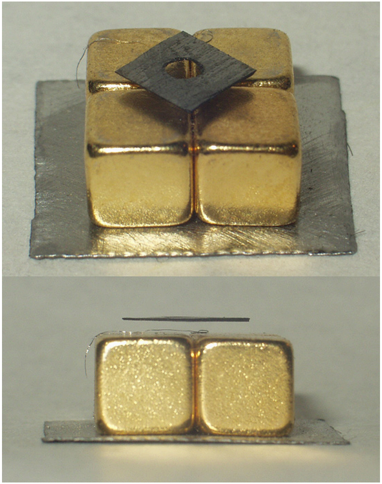
- Know a bit more about **permanent magnets**, and in particular, about **hysteresis curves**
- Undertand the working principle of a **brushless motor** and how it compares to brushed DC motors
- Know what **PWM** and **H-bridge** stand for, how a H-bridge is built, and how to control it,
- Understand the difference between **open-loop and closed-loop control**.

MAGNETISM & MAGNETS

TYPES OF MAGNETISM: DIAMAGNETISM

Diamagnetism

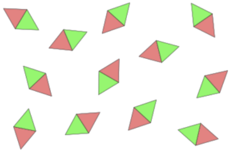
- Induced magnetic field in a direction opposite to an externally applied magnetic field
- Tend to oppose applied field



- Pyrolytic graphite will levitate over a permanent magnet array

TYPES OF MAGNETISM: PARAMAGNETISM

- Paramagnetism
  - Have a small positive susceptibility to magnetic fields
  - Tendency of magnetic dipoles to align with an external magnetic field
  - Magnetization is proportional to the applied magnetic field



Dipoles - field absent

TYPES OF MAGNETISM: PARAMAGNETISM

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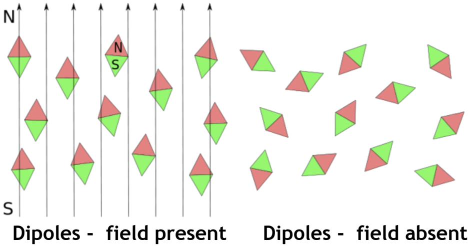
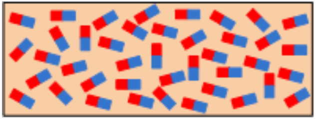


TYPES OF MAGNETISM: FERROMAGNETISM

- Ferromagnetism
  - Unpaired electron spins to line up parallel with each other in a region called a domain
  - Mechanism by which ferromagnetic materials form permanent magnets
  - This is the type of magnetics useful for actuation



Loose and Random Magnetic Domains

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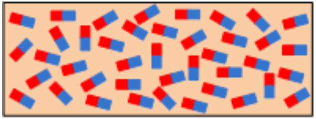
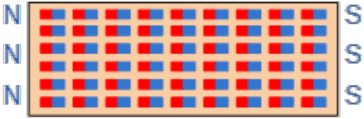


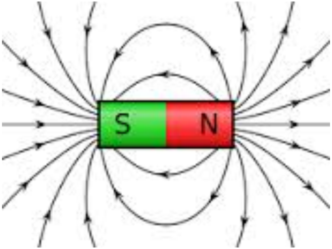
Loose and Random
Magnetic Domains



Effect of Magnetization
Domains Lined-up in Series

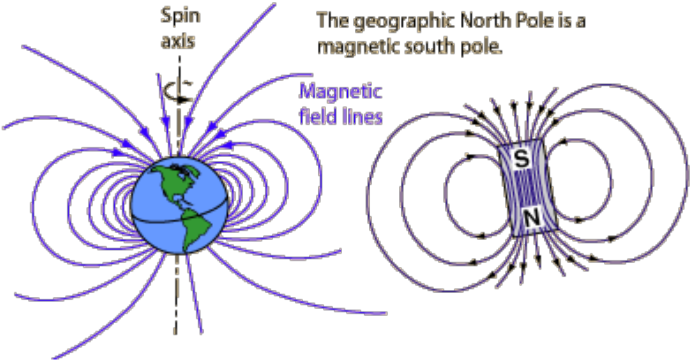
PERMANENT SOURCES OF MAGNETISM

- Lodestone occurs naturally
- Permanent magnets – rare earth, alnico, etc.



EARTH'S MAGNETIC FIELD

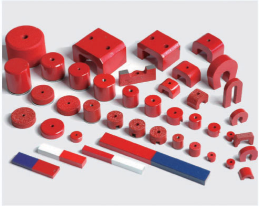
- The earth also generates an magnetic field



FERRITE MAGNETS

- Used in applications where cost needs to be as low as possible
- Dark graphite grey color
- Reasonable resistance to demagnetization
- Operate at temperatures up to 180 degrees C.
- Considerably weaker than Neodymium magnet

ALINICO (ALNICO)



- Made from aluminium, nickel and cobalt
- Less brittle than most rare-earth magnets
- Largely been replaced by stronger rare-earth magnets
- Still commonly used in the manufacturing of sensors, guitar pickups, loudspeakers

SAMARIUM COBALT (SMCO)

- First types of rare-earth magnets
- Commercially available for almost 30 years
- Operate in high temperatures –
- Good for industrial manufacturing
- Superior resistance to corrosion.
- Brittle and can be chipped and cracked easily
- Unsuitable for applications that require repetitive direct impact to the surface of the magnet.
- Should be recessed into a hole or groove to protect the magnet from impact

NEODYMIUM MAGNETS (NDFEB)

- Developed in the mid 1980s
- Most powerful of all permanent magnets
- Used where the strongest magnetic force is required in smallest volume
- Capable of lifting in excess of 1,000 times their own weight
- Emit deep magnetic fields
- Hard and brittle
- Protective plating needed to avoid rusting

NEODYMIUM MAGNETS ARE VERY POWERFUL

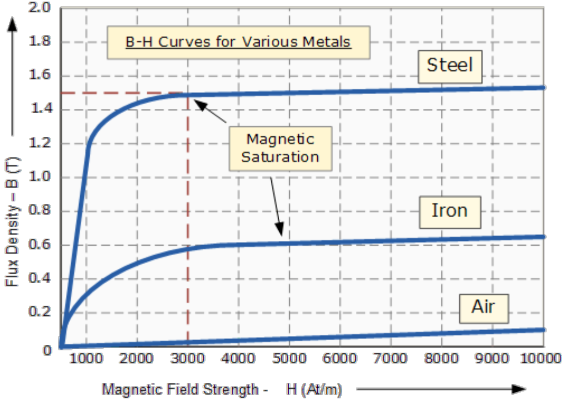
- Large magnets can be dangerous
- May shatter if two allowed to slam together
- Handle with care

$$d = 0.012\,\text{meters}$$

$$B = 0.5\ \text{Tesla}$$

$$h = 0.019\,\text{meters}$$

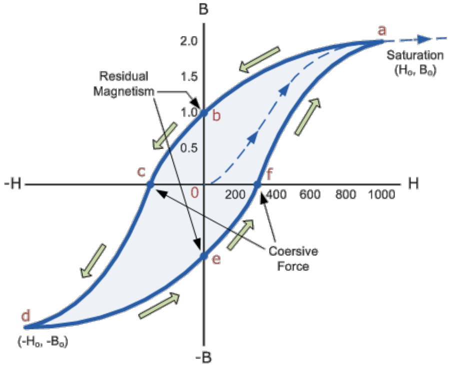
MAGNETIZATION CURVE OF FERROMAGNETIC MATERIALS



MAGNETIC HYSTERESIS LOOP

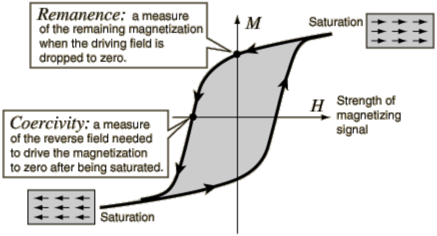
- When magnetic field H is applied to magnetic material the value of the magnetic flux density B does not follow linearly, but rather depends on the part history of the applied field H.
- Initial application of H will magnetize the material and the path starts at the origin. Thereafter reducing H will cause a reduction of B but along a higher path and when H reaches zero B will represent the remnant magnetism

- It will be then necessary to apply a negative field H to achieve a zero value of B.
- Therefore as B is plotted against H that goes up down and then changes sign, the characteristic does not consist of a straight-line passing through the origin but rather takes the form of a loop. The larger the area of the loop the larger the hysteresis of the magnetic material.



IMPORTANT CHARACTERISTIC OF PERMANENT MAGNETS

- Coercivity– determines how easy to demagnetize by applying an magnetic field
- Remanence – the value of B remaining after the magnetization process
- Energy product BH – relates to how much material requires to generate required flux density B



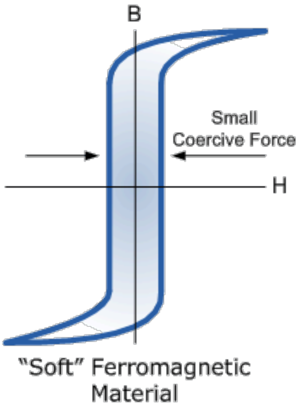
- Operating temperature – at which the magnet can operate satisfactorily
- Direction of magnetization – the location of the North and South poles
- Demagnetization temperature – determined by Curie temperature
- Mechanical robustness – how brittle or tough material is (cf Neodymium versus AlNiCo)
- Chemical stability in environment – sometimes need plating or epoxy coating
- Mechanical dimensions and geometry – bar, rod, square, arc, etc. Choose appropriately for the application

HARD AND SOFT MAGNETIC MATERIALS

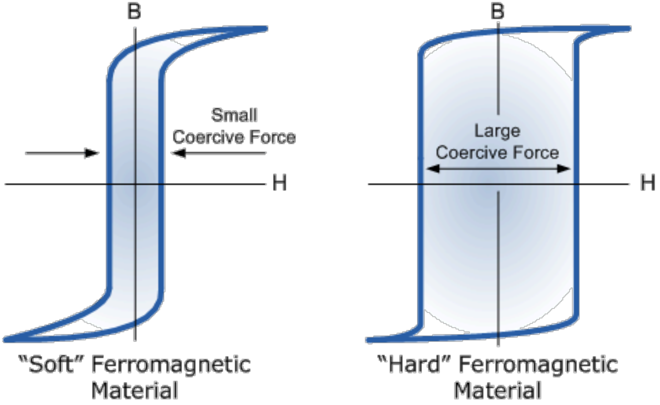
- An example of a hard magnetic material is AlNiCo.
- Exhibit high hysteresis and therefore retain their magnetism after being magnetized
- Can be used to make permanent magnets.
- An application could be the magnet for a loudspeaker.

- Soft iron is soft magnetic material. Is has a high relative permeability so it increases the flux density from a coil wrapped around it.
- Low magnetic hysteresis and therefore does not remain magnetism when the magnetic field it removed.
- Good choice form the core of a lifting electromagnet that can be switched on and off

MAGNETIC HYSTERESIS LOOPS FOR SOFT AND HARD MATERIALS



MAGNETIC HYSTERESIS LOOPS FOR SOFT AND HARD MATERIALS



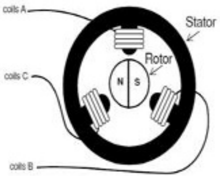
BRUSHLESS DC MOTORS

PROBLEMS OF MECHANICAL COMMUTATION

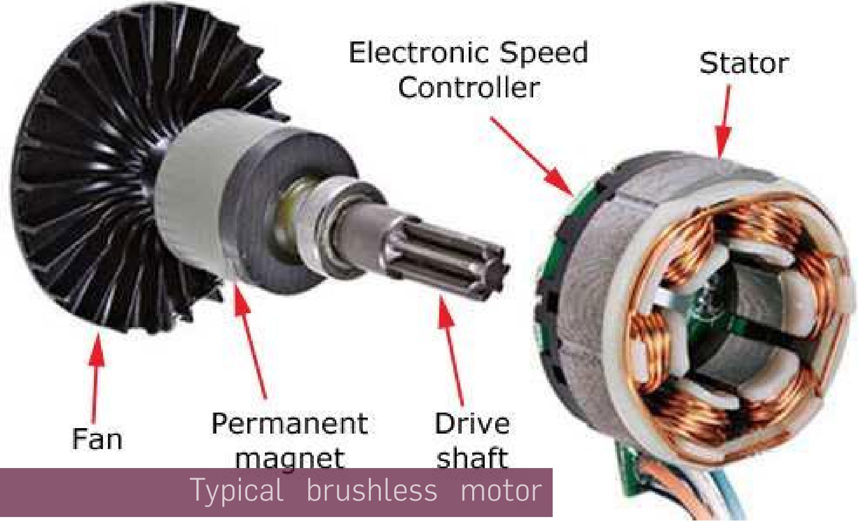
- Can get potential difference across commutator segments
- Commutation shorts out the commutator segments
- Arcing and sparkling at the brushes
- Brushless electronic switching solves this issue

BRUSHLESS DC MOTOR

- looks like DC brushed motor turned inside out
- commutation is performed electronically to eliminate brushes → **electronic commutation, EC**
- the stator generally consists of several coils
- current flow in the stator coils creates magnetic field
- this forces the permanent magnet rotor to spin
- continuous rotation by switching on current in the stator → **sequenced magnetic field**
- brushless motors **require a controller** that perform the commutation



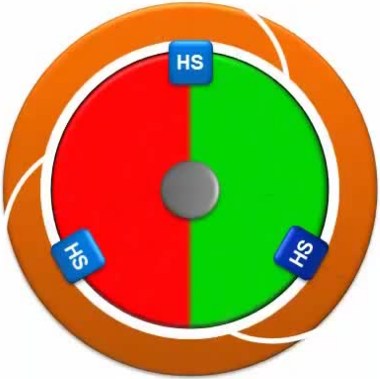
1 pair of poles



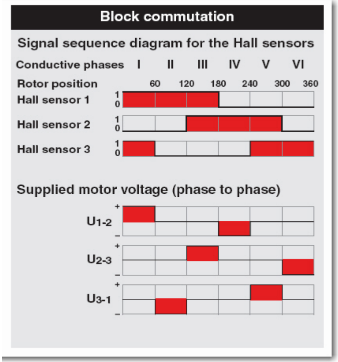
Typical brushless motor

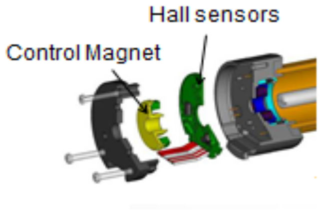
This animation shows the block commutation sequence of a brushless DC motor.

On the right there is a schematic cross section of a maxon EC motor.



HOW DO BRUSHLESS MOTORS WORK?



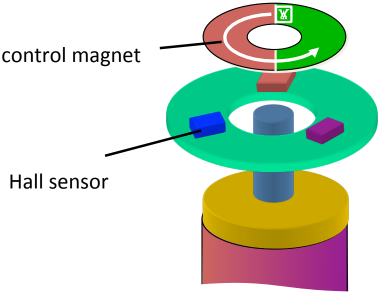


- Electronic commutation is used to switch current in the stator could so that the rotor is forced to rotate

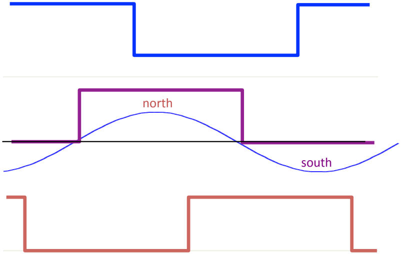
- There is often a control magnet is in line with the poles of the large magnet in the motor to identify rotor angle so that the controller can switch current into the appropriate coils
- As it turns Hall sensors are stimulated by the magnetic flux.
- The Hall sensors are used to tell the controller what the orientation is of the magnet with respect to the three winding phases.
- Current in the stator coils is turned on and off in sequence creating motion from pole to pole.

BLOCK COMMUTATION

Rotor position from Hall sensor signals



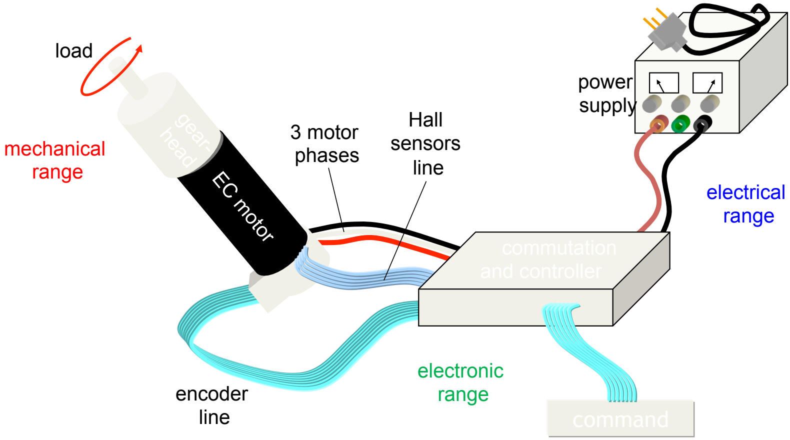
EC-max and EC flat:
Power magnet is probed directly



1	1	0	0	0	1	1
0	1	1	1	0	0	0
0	0	0	1	1	1	0
0°	60°	120°	180°	240°	300°	360°

rotation angle

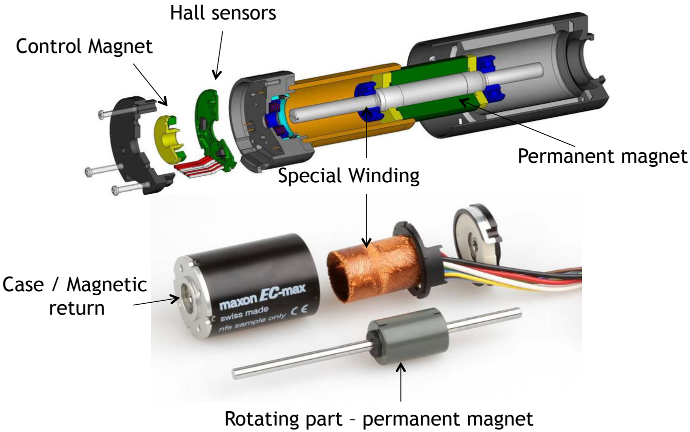
COMPONENTS OF AN EC DRIVE SYSTEM



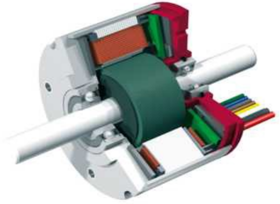
BRUSHLESS MOTOR FOR RC AIRCRAFT

- Product Name : Brushless Motor;Model : A2212-6;KV : 2200RPM/V
- Fit for Battery : 2-3 Li-Poly;Fit for ESC : 30A;Shaft Size : 3 x 12mm/ 0.1" x 0.5"(D*L)
- Motor Part Size : 25 x 28mm/ 1" x 1.1"(L*D);Mounted Screw Hole Diameter : 2.5mm/0.1";Screw Hole Centre Distance : 13 x 13mm/0.5" x 0.5"(L*W)
- Cable Length : 55mm / 2.2";Material : Metal, Electronic Parts;Color : Silver Tone, Brass Tone
- Weight : 59g;Package Content : 1 x Brushless Motor w Prop Adapter

CONSTRUCTION OF A EC BRUSHLESS MOTOR



MAXON EC FLAT BRUSHLESS MOTOR



Multi pole motor

Flat design gives more torque as the flux is acting further from the centre of rotation

ADVANTAGES AND DISADVANTAGES OF EC

Brushed DC motors

- Mechanical commutation
- Need periodic brush maintenance
- Power losses in brushes
- Sparking
- Can have noisy operation
- Linear torque characteristic at lower speeds
- Change direction by changing voltage polarity
- Controller not always needed

EC motors

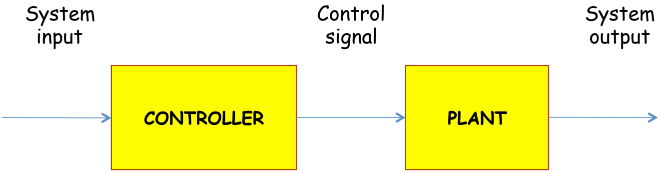
- Electronic commutation
- Low or no maintenance
- Less power loss
- No sparking
- Quieter operation
- More linear torque characteristic
- Change direction by changing switching sequence
- Always needs drive controller circuitry
- Requires sensors
- Higher reliability & efficiency
- Stator on outside – better for heat dissipation
- Longer life
- More expensive

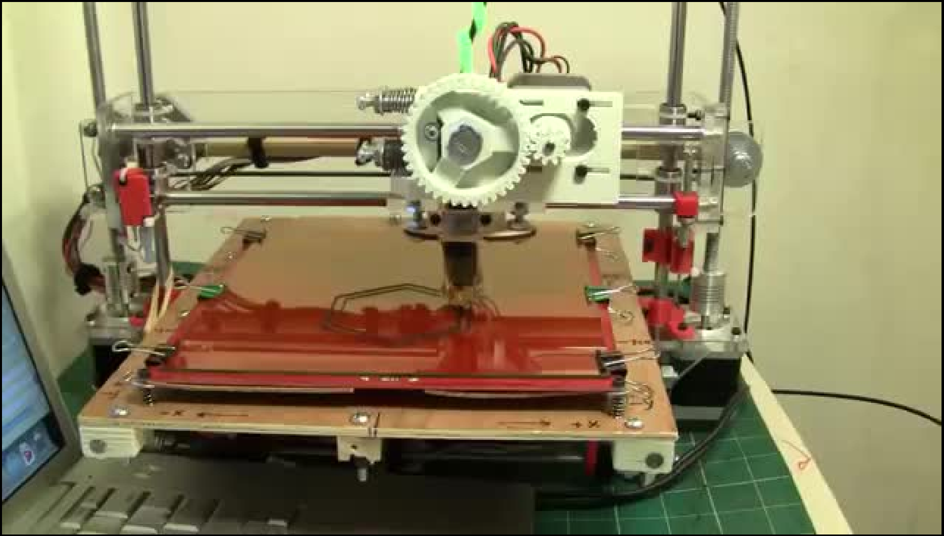
10 min break

MOTOR CONTROL

OPEN LOOP CONTROL SYSTEMS

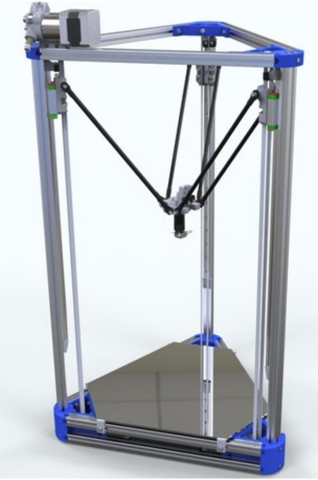
- In open-loop control systems the output has no effect on the control action
- The output is neither measured nor fed back for comparison with the input
- Open loop system can work well if the controller is appropriate and the plant properties don't change over time and there are no disturbances to the system



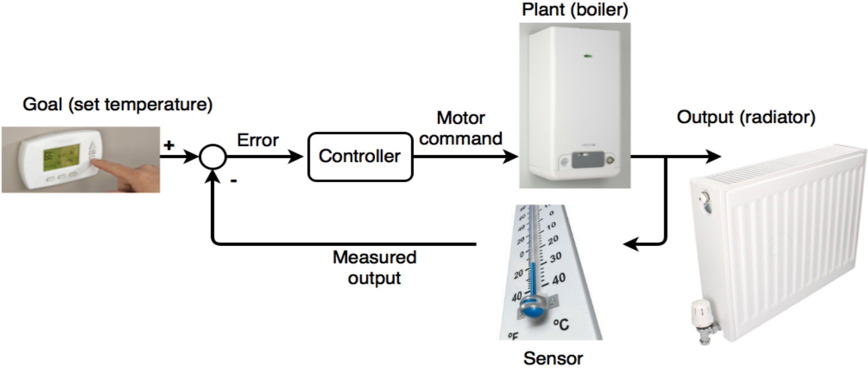


OPEN LOOP CONTROL SYSTEMS

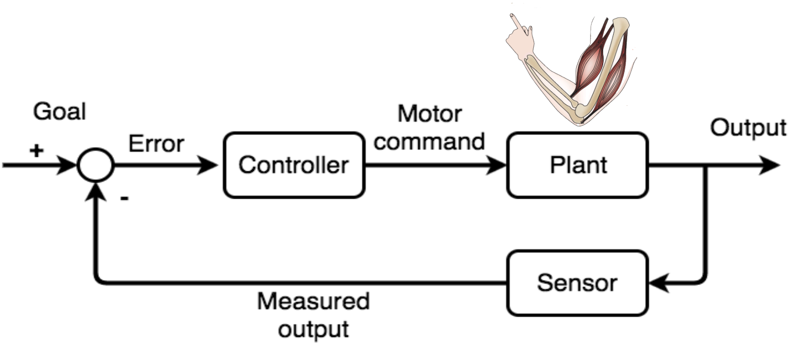
- The accuracy of the system depends on calibration.
- Example: Stepper motor control used in 3D printers
- BUT: In the presence of disturbances, an open-loop system will not perform the desired task!
- E.g., if stepper looses pulses then calibration lost
- This is why feedback can be useful



CLOSED-LOOP CONTROL



CLOSED-LOOP CONTROL

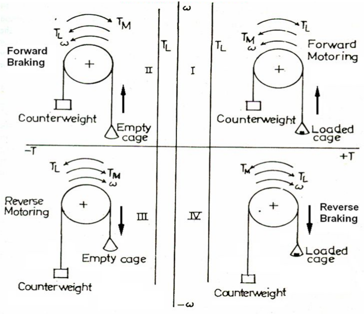


- In closed-loop systems feedback control makes use of a measurement of output to modify input to the controller
- feedback control can improve performance. It involves
- Specify target goal
- Comparing sensory feedback with goal to calculate error
- Feeding the error via a controller to generate plant commands
- The causes the system output to move to goal

THE MODES OF OPERATION OF A DC MOTOR – HOIST EXAMPLE

Forward movement, motor torque opposite from direction of rotation

Forward movement, motor torque in direction of rotation

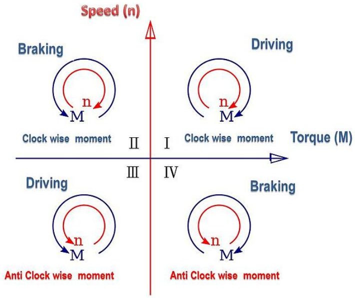


Backward movement, motor torque in direction of rotation

Backward movement, motor torque opposite from direction of rotation

$\Rightarrow$ four quadrant

MOTOR SPEED-TORQUE CHART

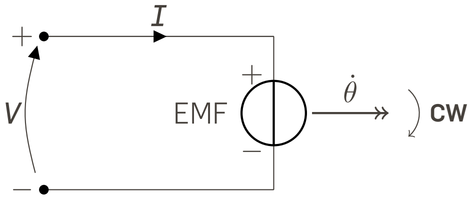


Source: ElectronicsHub (check the link for more details)

- **Quadrant I** – Driving forward with positive speed and positive torque
- **Quadrant II** – Generating or braking with positive speed and negative torque
- **Quadrant III** – Driving with negative speed and negative torque
- **Quadrant IV** – Generating or braking with negative speed and positive torque

ANALYSIS OF THE FOUR QUADRANTS

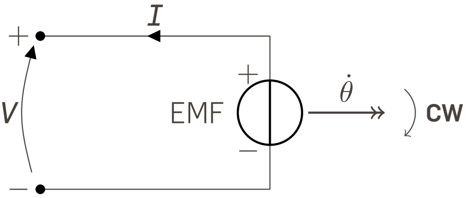
Quadrant I: Forward motoring



$$\left.\begin{array}{l} V > EMF \Rightarrow I > 0 \Rightarrow \tau > 0 \\ \dot{\theta} > 0 \end{array}\right\} P_{el} > 0, P_{mech} > 0$$

ANALYSIS OF THE FOUR QUADRANTS

Quadrant II: Forward bracking



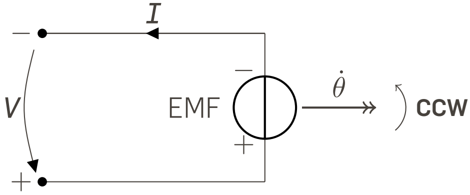
Supply voltage reduced:

$$\left.\begin{array}{l} V < EMF \Rightarrow I < 0 \Rightarrow \tau < 0 \\ \dot{\theta} > 0 \end{array}\right\} P_{el} < 0, P_{mech} < 0$$

$\Rightarrow$ power is provided back to the generator: **regenerative braking**

ANALYSIS OF THE FOUR QUADRANTS

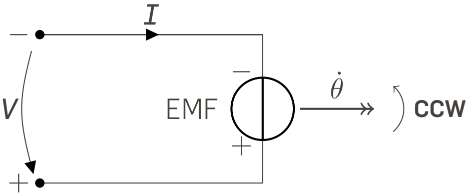
Quadrant III: Reverse motoring



$$\left.\begin{array}{l} V < 0 \text{ and } |V| > |EMF| \Rightarrow I < 0 \Rightarrow \tau < 0 \\ \dot{\theta} < 0 \end{array}\right\} P_{el} > 0, P_{mech} > 0$$

ANALYSIS OF THE FOUR QUADRANTS

Quadrant IV: Backward braking



Again, reduced supply voltage:

$$\left.\begin{array}{l} V < 0 \text{ and } |V| < |EMF| \Rightarrow I > 0 \Rightarrow \tau > 0 \\ \dot{\theta} < 0 \end{array}\right\} P_{el} < 0, P_{mech} < 0$$

$\Rightarrow$ power is provided back to the generator: **regenerative braking**

Example of four quadrant operation application

ONE AND TWO QUADRANT OPERATION

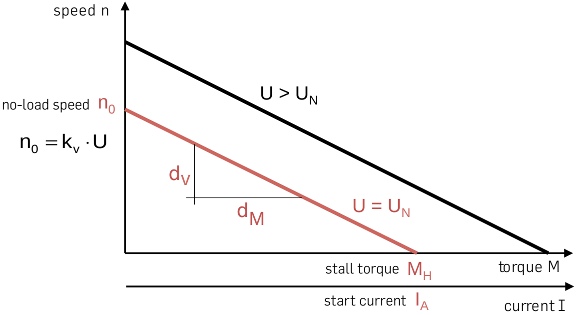
One quadrant operation

- Motoring with +ve speed and +ve torque
- Lots of simple applications of motors involve single-quadrant loads operating in quadrant I
- E.g., fan blowing air forwards
- Torque always in the same direction as speed
- Can drive fan in a single direction but not slow down under its own power

Two quadrant operation

- Motoring with +ve speed and +ve torque OR -ve speed and -ve torque
- Switch to change direction
- E.g., fan that can blow air forwards or backwards
- Torque always in the same direction as speed
- Can drive fan in a both directions but not slow down under own power

RELATION TO THE SPEED-TORQUE CHARACTERISTIC



Remember:

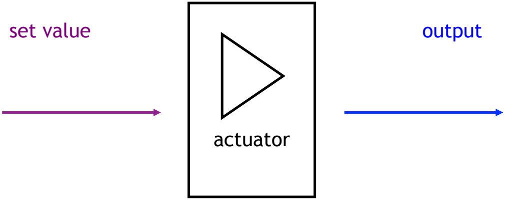
$$\dot{\theta} = \frac{V}{K} - R \cdot \frac{\tau}{K^2}$$

$$\tau = K \cdot I$$

Not the same thing! The speed-torque characteristic related the speed to the torque (and to a lesser extend, to the voltage). It is essentially orthogonal to the modes of operation.

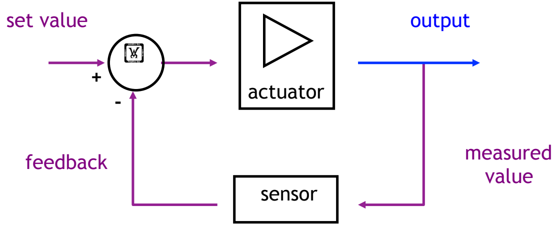
OPEN-LOOP MOTOR CONTROL

OPEN LOOP CONTROL



- Set value is adjusted to specify target output
- No feedback feedforward opertion
- Output is not measured and not use to change input to the plant
- There is an „open loop“

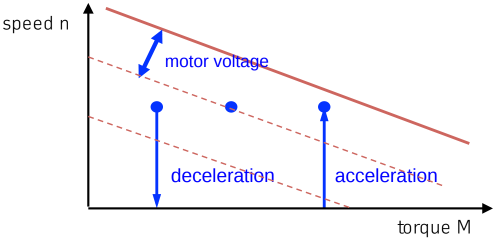
CLOSED LOOP CONTROL



- Set value is adjusted to specify target output
- Output value is measured
- Feedback from output is used to change the input to the plant
- There is a „closed loop“

MOTOR OPERATING POINT VOLTAGE DEPENDENT

- Load operating points are defined by the applications. They are characterised by a load speed n_L at a given load torque M_L
- Motor operating points lie on the speed-torque line

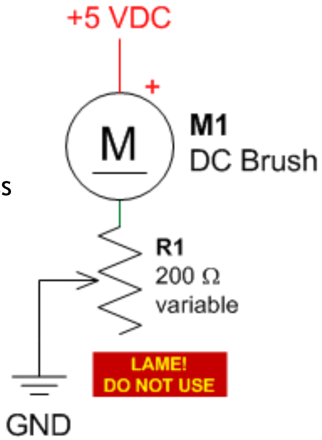


$$\dot{\theta} = \frac{V}{K} - R \cdot \frac{\tau}{K^2}$$
$$\tau = K \cdot I$$

For a given load, we can use the motor voltage to control the motor speed

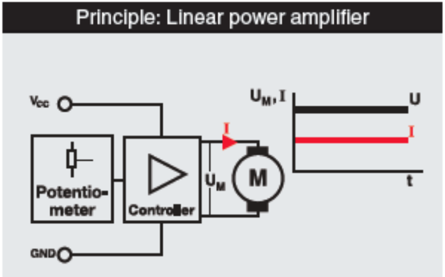
SIMPLE MOTOR SPEED CONTROL

- Example simple methods of motor speed control
- Using rheostat (or voltage drop across a transistor) in series with motor to limit applied voltage will realize a primitive kind of open loop control
- This will realize a primitive kind of open loop control



LINEAR POWER STAGE

- Linear power amplifier to control motor
- Operating voltage is divided between the motor and amplifier.
- Voltage drop across amplifier output stage causes power dissipation
- High currents and low motor voltages cause significant power dissipation
- Simple and favorably priced design of the power amplifier



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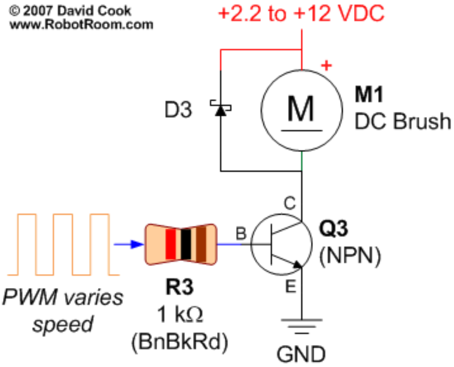
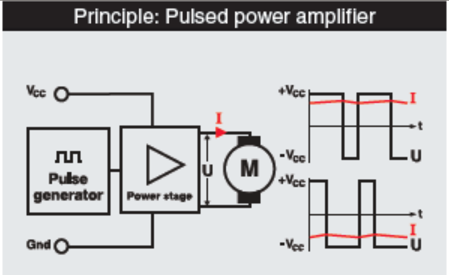
BETTER MOTOR SPEED CONTROL



- Speed of the motor can be controlled by the duty cycle of the square wave
- Transistor either fully on or fully off
- Therefore little power dissipation in control circuitry
- This can achieve high efficiently motor control

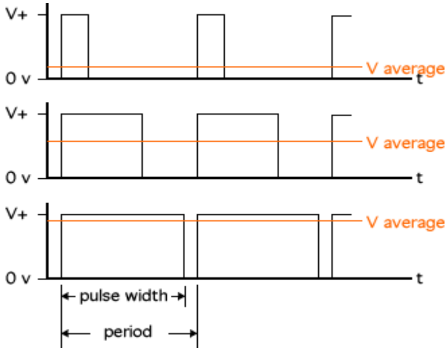
PULSED POWER STAGE (PWM)



- In PWM the controller switches the motor on and off in short intervals (pulses/cycles)
- Average value of voltage changes in relation to the on-to-off time.
- If the off intervals longer, the motor drips in speed.
- Therefore little energy is converted into heat.
- Was more expensive than linear control (at least until recently)

PULSE WIDTH MODULATION WAVEFORMS

- The output of most controllers are almost entirely PWM
- Output square wave is manipulated by the controller into shorter and longer pulses
- The average of the wave gives the effective applied voltage to the motor
- This way the controller has precise control of the voltage supplied to the motor



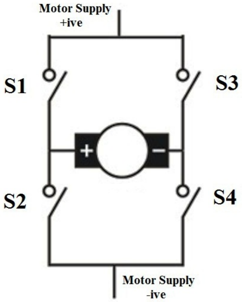
REVERSING THE ROTATION

We now know how to control the speed.

What about the rotation direction?

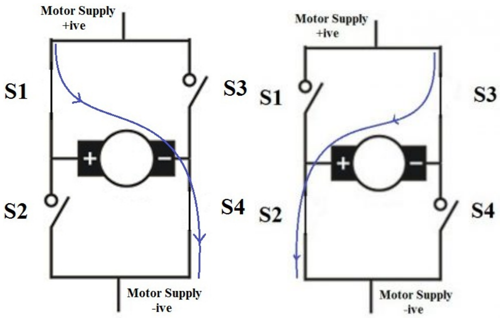
H-BRIDGE

H-BRIDGE CONTROL MOTOR DIRECTION



- The H-bridge is an electronic switching circuit
- Enables a voltage to be applied across a motor (or anything else) in either direction

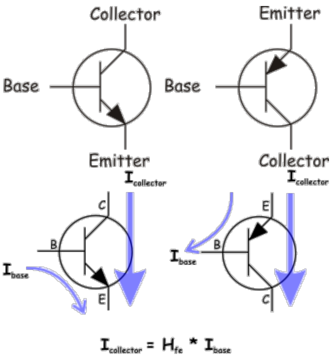
H-BRIDGE CONTROL MOTOR DIRECTION



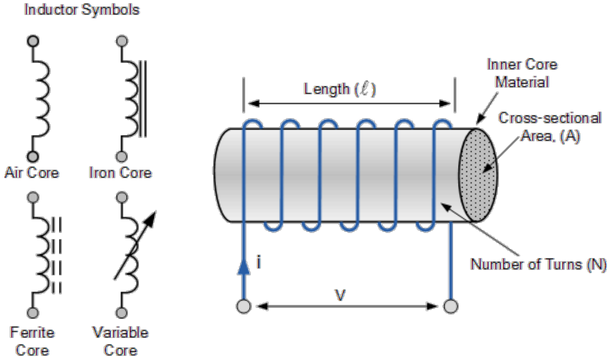
- When switches S1 and S4 are switched on, motor runs in, say, clockwise direction
- When S2 and S3 are switched on, motor runs in anticlockwise direction

USING JUNCTION TRANSISTORS AS SWITCHES

- In practice the switched are realized using transistors
- Either BJTs (***bipolar junction transistors***) or FETs (***field effect transistors***)

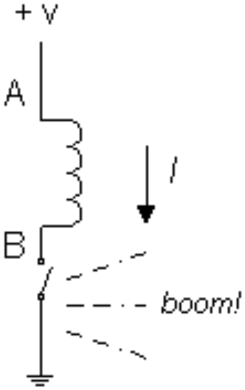


MOTOR INDUCTANCE

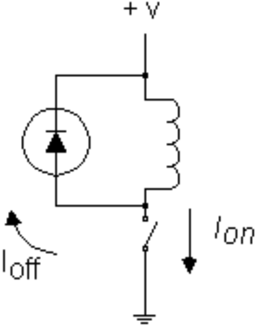


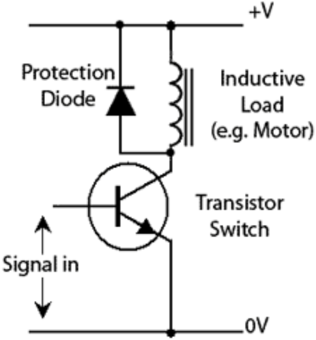
BACK EMF CHEN CURRENT ABRUPTLY SWITCHED OFF

- We must take care switching inductive loads – such as those arising from the coils in motors
- If we have inductance present then:
  V = L di/dt
- If a current i is flowing flows through an induction we abruptly switch it off, di/dt will be large
- Therefore we will experience a large back induced voltage



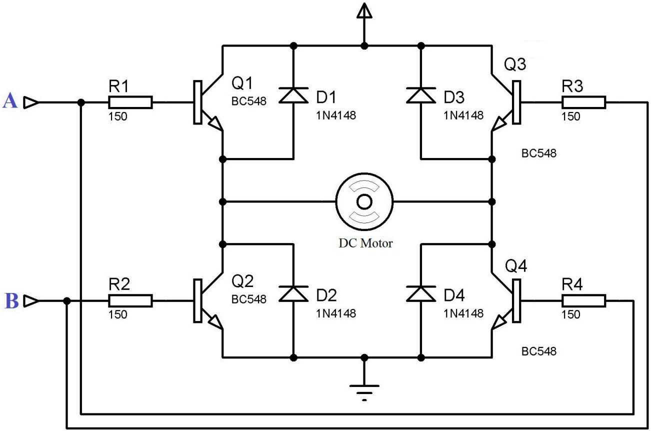
DIODE PROTECTION AGAINST BACK EMF





- Need to protect the drive circuit using a diode across the inductive load
- This shorts out the coil when we which it off and keeps the reverse voltage across the coil to a low and safe value

SIMPLE TRANSISTOR H-BRIDGE

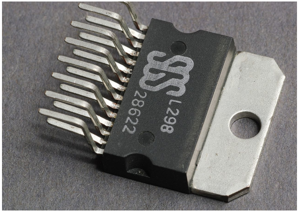


H-BRIDGES ARE AVAILABLE OFF-THE-SHELF

- You don't need to build your own circuits from transistors etc.
- There are many commercially available hobby motor driver controller

- These are suitable for microcontrollers such as Arduino

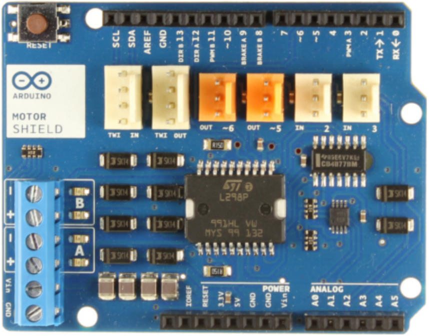
- This H-bridge uses the L298 dual H-bridge motor driver



MOTOR CONTROL WITH ARDUINO

ARDUINO MOTOR SHIELD

- Based on the L298 dual full-bridge driver
- designed to drive inductive loads
- Relays
- Solenoids
- DC and stepping motors.
- Drives two DC motors
- Controlling speed
- Direction of each
- Can measure motor current



http://arduino.cc/en/Main/ArduinoMotorShieldR3

ARDUINO MOTOR SHIELD SPECS

• Motor controller	L298P
• Operating Voltage	5V to 12V
• Max current	2A per channel 4A max (with external power supply)

- Current sensing 1.65V/A

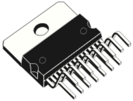
- Drives 2 DC motors or 1 stepper motor
- Free running stop and brake function

L298 DUAL FULL-BRIDGE DRIVER

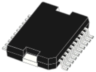
L298

DUAL FULL-BRIDGE DRIVER

- OPERATING SUPPLY VOLTAGE UP TO 46 V
- TOTAL DC CURRENT UP TO 4 A
- LOW SATURATION VOLTAGE
- OVERTEMPERATURE PROTECTION
- LOGICAL "0" INPUT VOLTAGE UP TO 1.5 V (HIGH NOISE IMMUNITY)



Multiwatt15



PowerSO20

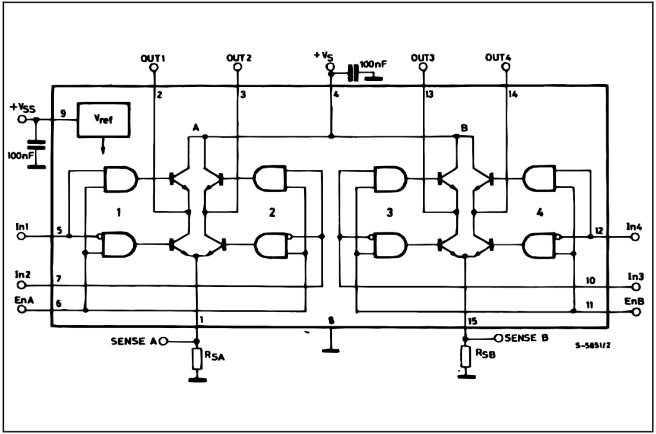
ORDERING NUMBERS : L298N (Multiwatt Vert.)
L298HN (Multiwatt Horiz.)
L298P (PowerSO20)

DESCRIPTION

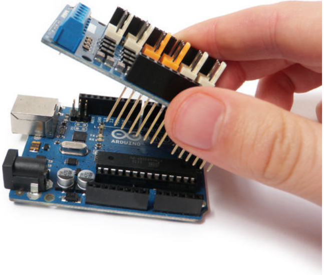
The L298 is an integrated monolithic circuit in a 15-lead Multiwatt and PowerSO20 packages. It is a high voltage, high current dual full-bridge driver designed to accept standard TTL logic levels and drive inductive loads such as relays, solenoids, DC and stepping motors. Two enable inputs are provided to enable or disable the device independently of the input signals. The emitters of the lower transistors of each bridge are connected together and the corresponding external terminal can be used for the connection of an external sensing resistor. An additional supply input is provided so that the logic works at a lower voltage. 2

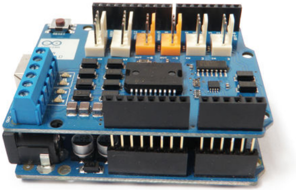
L298 DUAL FULL-BRIDGE DRIVER

BLOCK DIAGRAM



INSTALL THE ARDUINO MOTOR SHIELD





ARDUINO MOTOR SHIELD OUTPUT CHANNELS

- The motor shield has 2 separate channels: A and B
- Each use 4 of the Arduino pins to drive or sense the motor

- Use each channel separately to drive two DC motors
- Combine them to drive one stepper motor

- Has 6 headers for the attachment of Tinkerkit inputs, outputs, and communication lines.

- With an external power supply, the motor shield can safely supply up to 12V and 2A per motor channel (or 4A to a single channel).

PINS ALWAYS IN USE BY THE MOTOR SHIELD

Function	**Channel A**	**Channel B**
Direction	Digital 12	Digital 13
Speed (PWM)	Digital 3	Digital 11
Brake	Digital 9	Digital 8
Current Sensing	Analog 0	Analog 1

By addressing these pins, you can:

- select a motor channel to initiate
- specify the motor direction (polarity)
- set the motor speed (PWM)
- stop and start the motor (with or without braking)
- monitor the current of each channel (torque)

DC MOTOR CONNECTIONS

- Drive two Brushed DC motors by connecting the two wires of each one in the (+) and (-) screw terminals for each channel A and B
- Control direction by setting HIGH or LOW the DIR A and DIR B pins
- Control the speed by varying the PWM A and PWM B duty cycle values
- Brake A and Brake B pins set HIGH will brake the DC motors
- Measure DC motor current reading the SNS0 and SNS1 pins
- voltage proportional to the measured current, which can be read as a normal analog input, through the function analogRead() on the analog input A0 and A1.

MOTOR SHIELD 1-CHANNEL DC MOTOR DEMO

Plug the motor's positive (red) wire into Channel A's + terminal on the motor shield

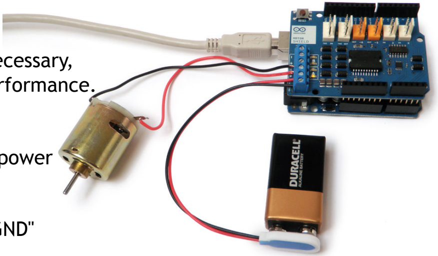
Plug the motor's ground (black) wire into Channel A's - terminal on the shield

An external power supply is not always necessary, but it drastically improves the motor's performance.

To connect your external power supply:
Connect the positive (red) wire from the power supply to the "Vin" terminal

Connect the ground (black) wire to the "GND" terminal.

Upload the code to control the Motor Shield from Arduino.



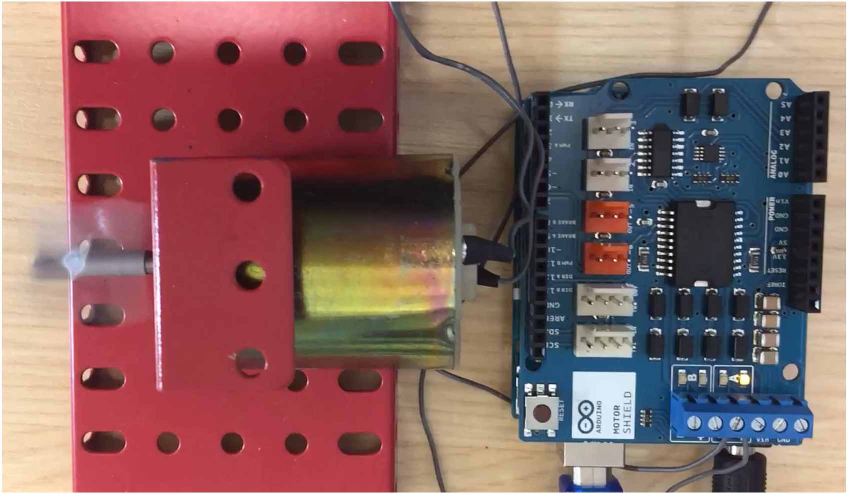
MOTOR SHIELD 1-CHANNEL DC MOTOR DEMO

```
/*************************************************************
Motor Shield 1-Channel DC Motor Demo
by Randy Sarafan
For more information see:
www.instructables.com/id/Arduino-Motor-Shield-Tutorial
*************************************************************/
void setup() {
//Setup Channel A
pinMode(12, OUTPUT); //Initiates Motor Channel A pin
pinMode(9, OUTPUT); //Initiates Brake Channel A pin
}
```

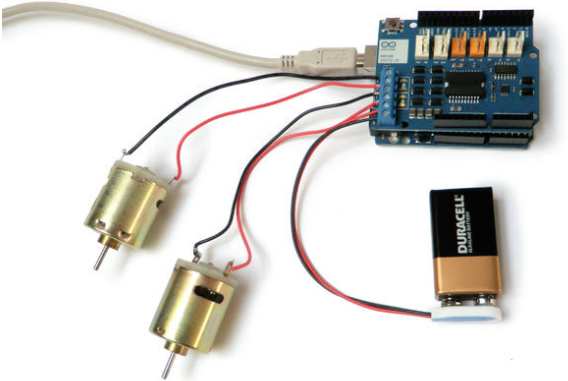
MOTOR SHIELD 1-CHANNEL DC MOTOR DEMO

```
void loop(){
  //forward @ full speed
  digitalWrite(12, HIGH); //Establishes forward direction of Channel A
  digitalWrite(9, LOW); //Disengage the Brake for Channel A
  analogWrite(3, 255); //Spins the motor on Channel A at full speed
  delay(3000);
  digitalWrite(9, HIGH); //Engage the Brake for Channel A
  delay(1000);
  //backward @ half speed
  digitalWrite(12, LOW); //Establishes backward direction of Channel A
  digitalWrite(9, LOW); //Disengage the Brake for Channel A
  analogWrite(3, 128); //Spins the motor on Channel A at half speed
  delay(3000);
  digitalWrite(9, HIGH); //Engage the Brake for Channel A
  delay(1000);
}
```

DC MOTOR RUNNING



MOTOR SHIELD 2-CHANNELS DC MOTOR DEMO



MOTOR SHIELD 2-CHANNELS DC MOTOR DEMO

```
/*************************************************************
Motor Shield 2-Channel DC Motor Demo
by Randy Sarafan

For more information see:
www.instructables.com/id/Arduino-Motor-Shield-Tutorial
*************************************************************/


void  setup()
{
  //Setup Channel A
  pinMode(12, OUTPUT);  //Initiates  Motor  Channel  A  pin
  pinMode(9,  OUTPUT);  //Initiates  Brake  Channel  A  pin

  //Setup  Channel  B
  pinMode(13,  OUTPUT);  //Initiates  Motor  Channel  B  pin
  pinMode(8,  OUTPUT);    //Initiates  Brake  Channel  B  pin
}
```

MOTOR SHIELD 2-CHANNELS DC MOTOR DEMO

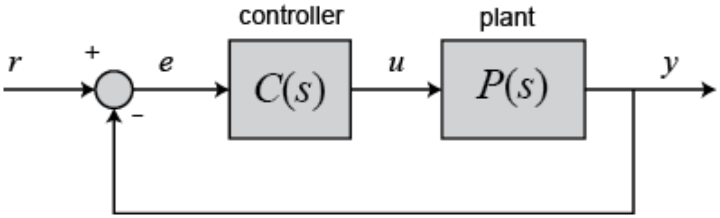
```
void loop(){
  //Motor A forward @ full speed
  digitalWrite(12, HIGH); //Establishes forward direction of Channel A
  digitalWrite(9, LOW); //Disengage the Brake for Channel A
  analogWrite(3, 255); //Spins the motor on Channel A at full speed

  //Motor B backward @ half speed
  digitalWrite(13, LOW); //Establishes backward direction of Channel B
  digitalWrite(8, LOW); //Disengage the Brake for Channel B
  analogWrite(11, 128); //Spins the motor on Channel B at half speed
  delay(3000);

  digitalWrite(9, HIGH); //Engage the Brake for Channel A
  digitalWrite(9, HIGH); //Engage the Brake for Channel B
  delay(1000);
}
```

CLOSING THE LOOP

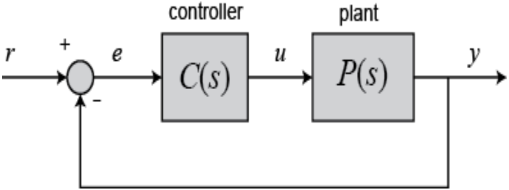
SIMPLE FEEDBACK CONTROLLER



- Plant characteristics are often fixed
- We need to design the controller to achieve required plant performance
- Have to be careful because feedback system can go unstable!
- So what should the controller be?

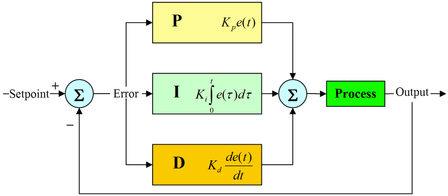
ADDING A PID CONTROLLER

- Place a PID controller C(s) in series with the plant P(s) and make use of negative feedback



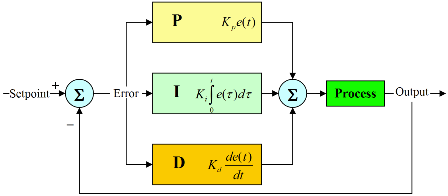
- A well-designed control system will ensure
  - We reach a target value quickly
  - Without overshoot
  - With low steady state error.

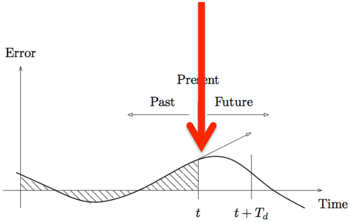
PID PARALLEL PATHWAYS



- PID is a mathematical algorithm that the controller uses to compensate for load fluctuations and changes in set point.
- These operations are executed on the error between the set point and the actual value.
- They determine ow the plant will react to change
- A PID controller consists of 3 parallel elements that are located in the forward path in a feedback controller scheme located before the plant
- The plant to be controller received the sum of these three processed signals as its input
- The 3 PID elements have different effects

PROPORTIONAL TERM

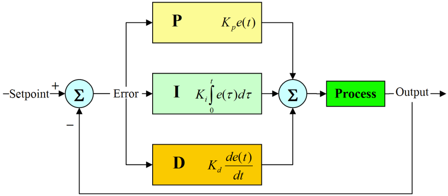


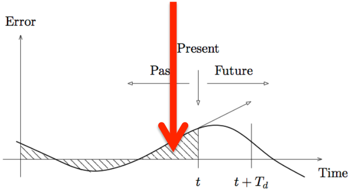


The proportional term directly relates to the error value at the present moment in time

- The proportional gain is given as K_p
- Proportional gain can improve rise time
- If K_p too high the system can become unstable

INTEGRAL TERM



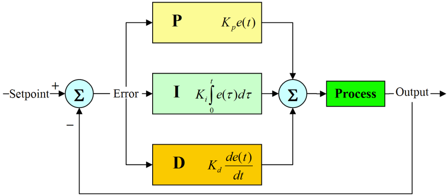


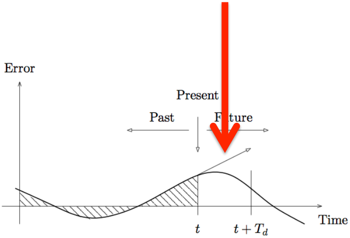
The integral term relates to a past values of the error up to the present point in time

It is proportional to both the magnitude of the past error and its duration

- The integrator gain is given as K_i
- Integral term eliminates residual steady-state error

DERIVATIVE TERM

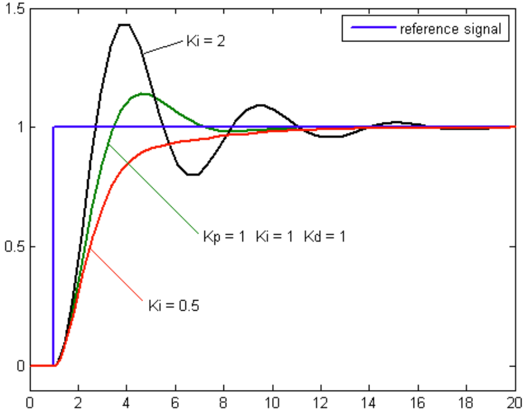




The derivative term that is proportional to the slope of the error over time and relates to a prediction of what the error will be like in the future

- The differentiator gain is given as K_d
- Derivative term improves settling time and stability of the system

CHANGING PID CONTROLLER CHARACTERISTICS



Tuning PID parameters strongly affects controller performance

READING THE ENCODER

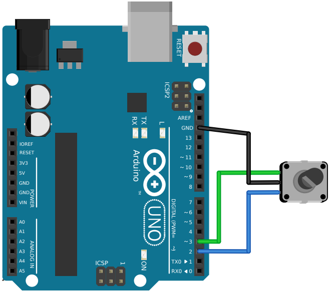
```
const int PERIOD = 1000; //ms
const byte interruptPin = 2;
int pulses = 0;

void setup() {
  pinMode(interruptPin, INPUT);

  // set the interrupt call-back
  attachInterrupt(
        digitalPinToInterrupt(interruptPin),
        count_pulses, RISING);
}

void loop() {
    delay(PERIOD); // idle for PERIOD
    // assuming one pulse per revolution
    double rpm = pulses * (1000./PERIOD) * 60
    pulses = 0;
}

void count_pulses() {
  pulses++;
}
```



USING THE ARDUINO'S PID LIBRARY

```
#include <PID_v1.h>
#define PWM_PIN 3

// our setpoint is our target speed
double setpoint = 2000; //rpm

// our input is our encoder reading
double input = 0;

// our output is the PWM value
double output = 0;

double Kp=1, Ki=1, Kd=1;
PID myPID(&input, &output,
          &setpoint,
          Kp, Ki, Kd, DIRECT);
```

```
void setup()
{
  // [...encoder initialization...]

  //turn the PID on
  myPID.SetMode(AUTOMATIC);
}

void loop()
{
  input = ...; // calculate speed
  myPID.Compute();
  analogWrite(PWM_PIN, output);
}
```

That's all, folks!

Questions:
Portland Square B316 or **severin.lemaignan@plymouth.ac.uk**

Slides:
github.com/severin-lemaignan/module-introduction-sensors-actuators