Overview

- Motors
  - Operational Principles
  - Types
    - » DC Motor
    - » RC Servo
    - » Stepper Motor
  - Control
    - » Linear proportional control
    - » Pulse Coded
    - » Pulse Width Modulation
  - Power Electronics
  - Motor Driver
    - » H Bridge

Readings

- **Mobile Robots: Inspiration to Implementation by Flynn, Jones and Seiger**
  - Ultimate Reference on Motors you will need for the course
  - **Pages 193-263 cover:**
    - **How a DC motor works**
    - **DC Motor Modeling, Analysis, Performance curves and Sizing**
    - **Power Electronics -- Bipolar Transistors, MOSFETs**
    - **Interfacing motors -- H Bridges and Power ICs**
    - **Software -- PWM, Feedback control**
- **Micro Mo Application Notes**
  - http://www.micromo.com/03application_notes.asp

Motor and Gearhead Basics

Development of Electromotive Force
- Faraday's Law
- A Single Coil DC Motor
- Motor Constants

Motor Construction
- Sources of the Magnetic Field
- Motor Armature Construction
- Brushes and Commutator
- Shaft Bearings
- Lubrication

Motor Calculations
- Calculating Mechanical Power

Requirements
- Torque - Speed Curves
- Numerical Calculation
- Sample Calculation
- Motor Data Sheet Analysis

Gearhead Construction and Uses
- Spur Gear Type Gearheads
- Direction of Rotation
- Planetary Gears
- Gearhead Data Sheet Analysis

How to Select a DC Micromotor

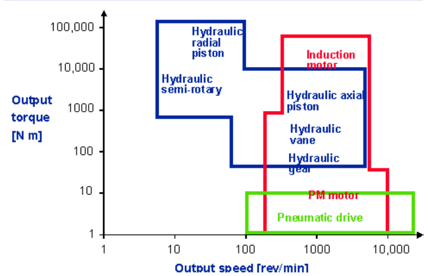
Programmable Motion Control Handbook
This handbook is available in PDF format (500K)

Electromagnetic Actuators

Electromagnetic Actuators

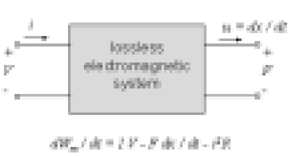
- Linear Actuators
  - Linear Motors
  - Lead Screws
  - Solenoids
- Rotary Actuators
  - DC PM motors ←
  - Stepper motors
    - Unipolar PM stepper
    - Bipolar PM stepper
    - Variable reluctance stepper
  - Wound field motors
  - Brushless motors
  - Induction motors

Actuator Operational Ranges



Conservation of Energy

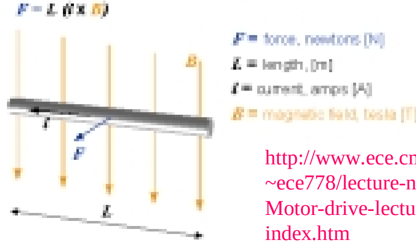
Electric energy input = mechanical work output + stored magnetic energy + heat loss



Lorentz' Law

- Relation of electrical to mechanical energy

$F = L\ (i \times B)$



http://www.ece.cmu.edu/~ece778/lecture-notes/Motor-drive-lecture/index.htm

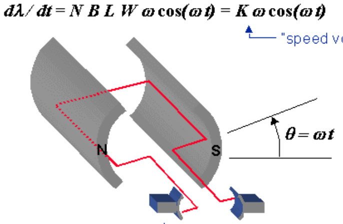
DC Motors

Faraday's Induction Law

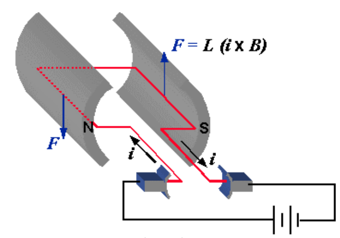
- Relation of mechanical to electrical energy:

λ = magnetic flux $= N\,B\,A = N\,B\,L\,W \sin\,\theta$

$e_a = d\lambda / dt = N\,B\,L\,W\,\omega \cos(\omega t) = K\,\omega \cos(\omega t)$ ← "speed voltage"



Lorentz' Law - Motor Coil

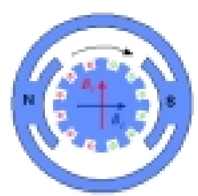


$\tau = N\,A\ (i \times B)$

A = area of coil

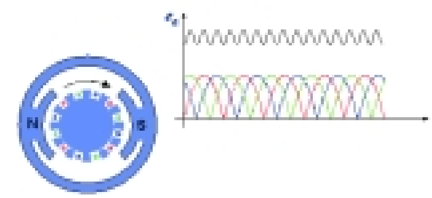
2-Pole DC Motor

- Magnetic field may be generated by stator winding or by permanent magnet (PM)
- Poles is number of N-S pairs



Speed Voltage

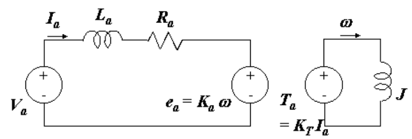
- Generated speed voltages of each coil is staggered in phase
- Result is a nearly d.c. speed voltage



DC Motor Analysis

DC Motor Equivalent Circuit

- Armature (stator) has winding resistance, inductance
- Generated "speed voltage," e_a is in series
- Through conservation of energy, the speed constant, K_a, is found to be equal to the torque constant, K_T
- Motor inertia, J, is modeled as an equivalent inductance



Steady-State Torque-Speed Curve

- Torque is linearly related to speed

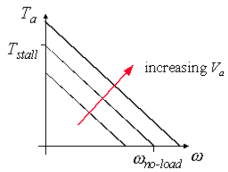
$$T_a = (K_a/R_a)V_a - (K_a^2/R_a)\omega$$
$$\omega = V_a/K_a - (R_a/K_a^2)\,T_a$$

- Both torque and speed increase with applied voltage
- Stall torque,

$$T_{stall} = (K_a/R_a)\,V_a$$

- No-load speed,

$$\omega_{no\text{-}load} = V_a/K_a$$



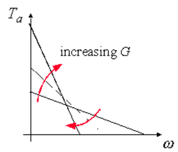
Gear Ratio, G

- Effective motor constant is $K_{eff} = G\,K_a$
- Increases output torque by G

$$T_a = G\,K_a\,I_a$$

- Decreases speed by $1/G$

$$\omega = (V_a - R_a I_a)/(G K_a)$$



http://www.ece.cmu.edu/~ece778/lecture-notes/Motor-lecture/index.htm

DC Motor Analysis

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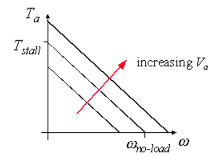


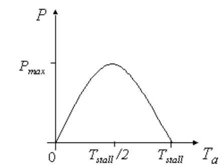
Motor Power

- Mechanical power nonlinear with torque and speed

$$P = T_a\,\omega = (V_a/K_a)\,T_a - (R_a/K_a^2)\,T_a^2$$

- Maximum output power at $T_{stall}/2$

$$P_{max} = T_a\,\omega = 0.25\,V_a^2/R_a = 0.25\,T_{stall}\,\omega_{no\text{-}load}$$



Motor Efficiency

- Efficiency, η = mechanical power out / electrical power in

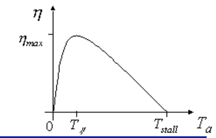
$$\eta = (T_a\,\omega - K_a\,I_o\,\omega)\,/\,(T_a\,\omega + R_a\,I_a^2)$$

where I_o is the no-load current from windage losses

- Maximum efficency at

$$T_\eta = K_a\,sqrt(I_o I_{stall}),$$ where I_{stall} is the stall current

$$\eta_{max} = (1 - sqrt(I_o/I_{stall}))^2$$

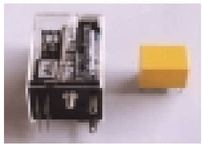


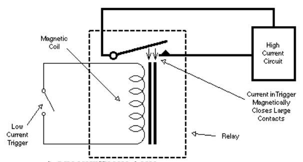
http://www.ece.cmu.edu/~ece778/
lecture-notes/Motor-lecture/index.htm

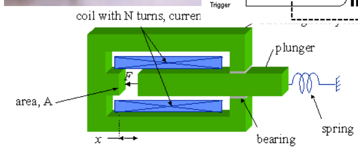
Driving High Currents from Logic

http://www.acroname.com/robotics/info/articles/drivers/drivers.html

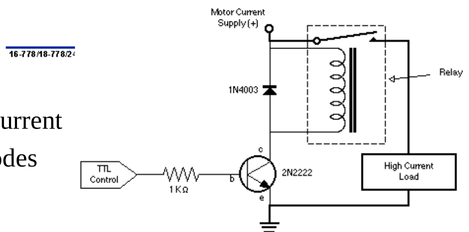
- Relays
  - High current switching using low voltages/currents
  - Arcing/Noise
  - Switching speed (slow) and consume power







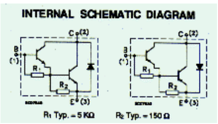
- Transistors
  - Good way to interface a mP
  - Fast switching by altering base current
  - Need to incorporate Flyback Diodes

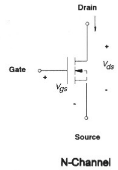


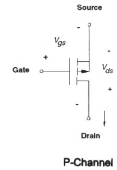
Analyze this circuit

Power Electronics

- 3 Terminal Gate Based Control Devices
  - Low Power -- Power Bipolar (PNP and NPN) Transistors (<0.5 Amps)
    - Current controlled devices
  - Low to Medium Power -- Power Transistors (> 1.0 Amps)
    - Darlington (or Dual Bipolar) -- Max 400 Amps
    - Metal Oxide Semiconducting Field Effect Transistors (MOSFET) -- Max (100 Amps)
      - Useful because gate is ***voltage controlled*** not current controlled
      - Low voltage drop (minimal forward bias voltage)
      - Low power drop

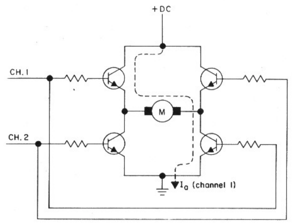




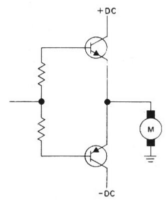


  - High Power
    - Silicon Controlled Rectifier (SCR or Thyristor)
      - » Turned on by a pulse to gate, turned off by stopping the current

Linear Amplifiers (Full vs Half Bridges)



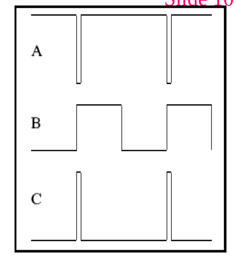
Proportional Control



http://www.cim.mcgill.ca/~buehler/mechatronics/lectures/amplifiers/index.html

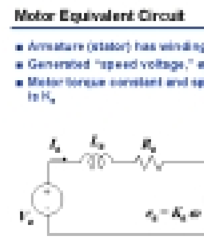
- Full Bridge Linear Amplifiers
  - Unipolar Power supply
  - Voltage and current feedback from motor is difficult
- Half Bridge Amplifiers
  - Need Bipolar Supply
  - Easier to drive and get feedback
  - Commonly used in Linear Amplifiers
- Power Transistors used waste Power = I_M*(Supply - Regulated)

Pulse Width Modulation (PWM)

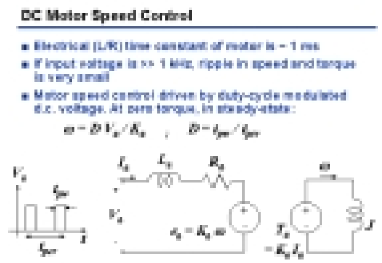


http://www.4qd.co.uk/ccts/pwm.html

- Motor on -- speed up
- Motor off -- coast down
- PWM controller
  - Switches the motor on in a series of pulses.
  - Control the motor speed by modulating the width of the pulses (Duty cycle).
  - 20kHz (inaudible)
  - Fast Enough -- Motor thinks it is being fed from a pure d.c. voltage.
  - Slow enough -- for electronics



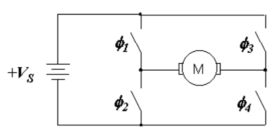
At Constant Load: $V_a = K_a w + R_a I_a$



H-Bridge PWM Basics

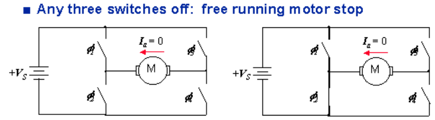
H-Bridge Circuit

- Implements duty-cycle modulation
- Four switches control d.c. voltage applied to motor
- Motor completes "H"
- Switches must handle ~ 2A

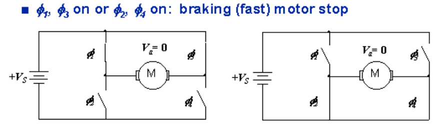


H-Bridge Circuit Operation

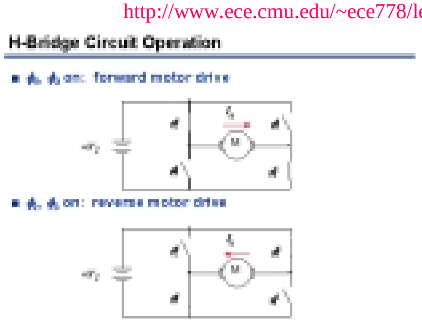
- Any three switches off: free running motor stop

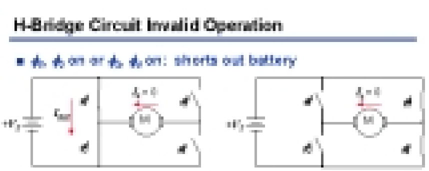


- ϕ_1, ϕ_3 on or ϕ_2, ϕ_4 on: braking (fast) motor stop



http://www.ece.cmu.edu/~ece778/lecture-notes/Motor-drive-lecture/index.htm

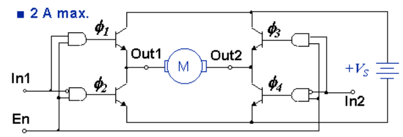




L298 Full Bridge Circuit

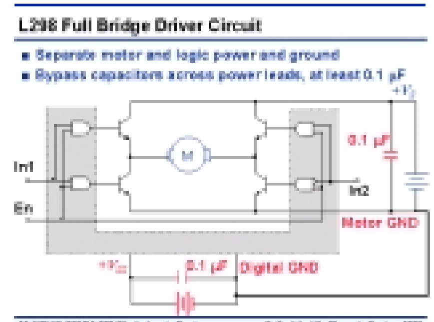
L298 Full Bridge Driver Circuit

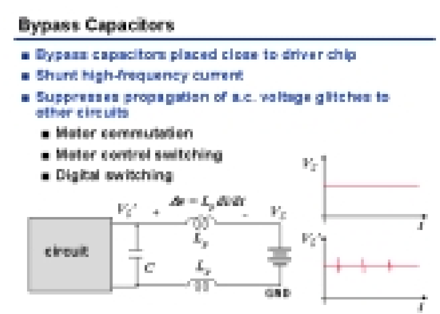
- Bipolar transistors act as high-current switches
- Logic prohibits invalid operation
- 2 A max.



En	In1	In2	
H	H	L	forward
H	L	H	reverse
H	L	L	fast brake
H	H	H	fast brake
L	X	X	free running stop

http://www.ece.cmu.edu/~ece778/lecture-notes/Motor-drive-lecture/index.htm

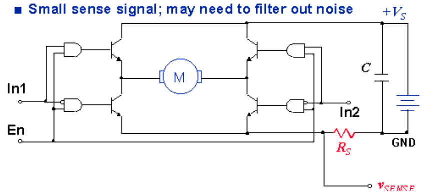




L298 Full Bridge Circuit

Current Sense

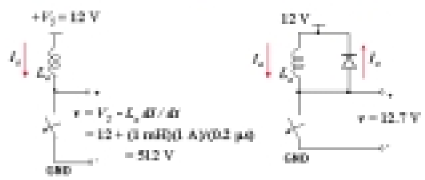
- Ground of bridge can be connected through sense resistor
- R_S = 0.1 Ω for minimal voltage disturbance
- v_{sense} is proportional to torque
- Small sense signal; may need to filter out noise



http://www.ece.cmu.edu/~ece778/lecture-notes/Motor-drive-lecture/index.htm

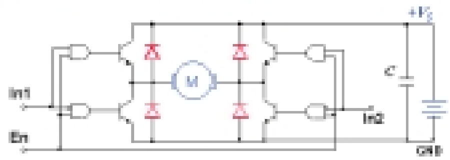
Flyback (Freewheel) Diodes

- Voltage spikes are generated by switching motor inductance off
- Diodes must be placed across motor to limit voltage excursions to (V_S + 0.7) V
- High-current, fast-recovery diodes required (0.2 μs)



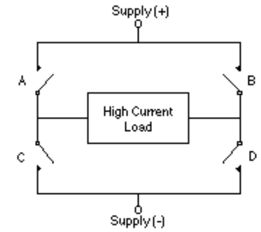
H-Bridge Flyback Diodes

- Four flyback diodes placed from motor to power and ground
- Clamp motor voltage when switches open
- No braking torque associated with diodes
- Current decays in ~1 ms ($\tau = L_a/R_a$)



Summary: H-Bridges

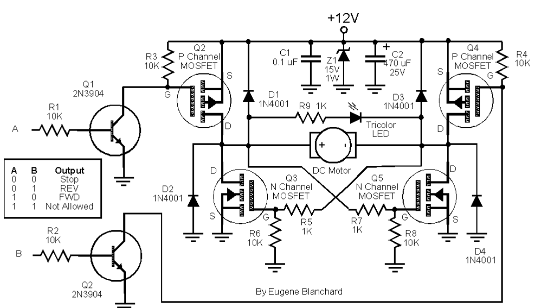
- Issues we looked at:
  - Flyback diodes
  - Voltage spiking
  - Heat Sinks
  - Multiple transistors
  - Permit fast switching PWM

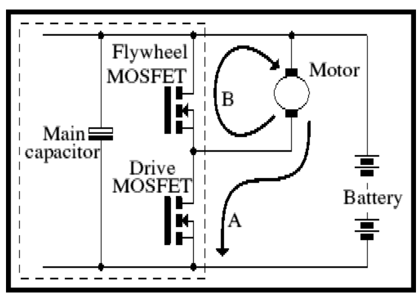


combination	Polarity	Effect
A & D	Forward	Motor spins forward
B & C	Reverse	Motor spins backward
A & B	Fixed	Motor acts as a brake
None	Free	Motor floats freely

- The L298 Kit that is provided along with the lab experiment actually

MOSFET H Bridge Circuit



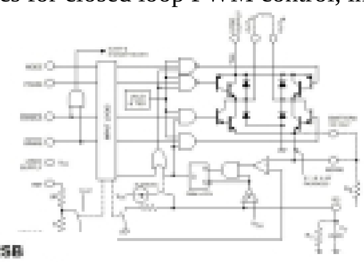


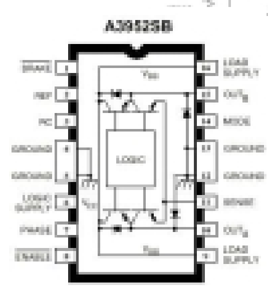
Full Bridge

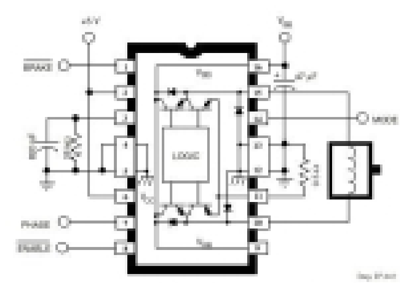
Half Bridge

MOSFET H-Bridge Integrated Chips

- Allegro Micro Systems
  - For motor currents below 2A integrated circuits are available with all the electronics for closed loop PWM control, including the H bridge.

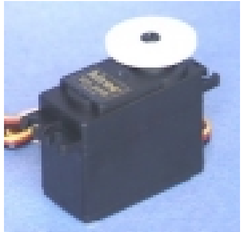


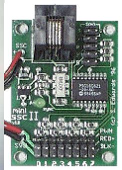




Typical DC Servo Motor Application

RC Servos





- **SVMT-42:** Power supply voltage: 4.8-6 volts Torque: 49oz/in Speed: 0.16sec/60º Weight: 1.56oz $16.75
- A servo consists of a small motor, a gearset, a feedback potentiometer (variable resistor), and some control electronics.
- Closed-loop feedback system.
- Power, Ground and Control.
- Servos are controlled using a system called Pulse Code Modulation (PCM).
- Futaba servo 90 position (middle) pulse-width of about 1.5 ms (at least once every 20 ms)
- No pulses for about 50 ms or so "sleep mode" (require processor resources)
- Serial Servo controllers
-

RC Servos

http://www.hvwtech.com/about_servos.htm
http://www.repairfaq.org/filipg/RC/F_Servos.html
Host of other info on Web

Stepper Motors

http://www.ericsson.se/microe/pdf/Industri/app/motorbas.pdf

Industrial Circuits Application

Stepper Motor

A stepper motor is an electromechanical device which converts electrical pulses into discrete mechanical movements. The shaft or spindle of a stepper motor rotates in discrete step increments when electrical command pulses are applied to it in the proper sequence. The motors rotation has several direct relationships to these applied input pulses. The sequence of the applied pulses is directly related to the direction of motor shafts rotation. The speed of the motor shafts rotation is directly related to the frequency of the input pulses and the length of rotation is directly related to the number of input pulses applied.

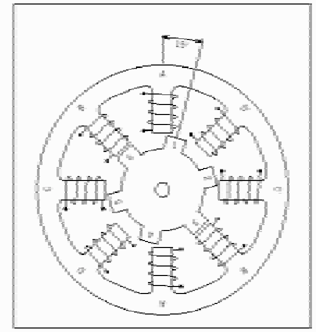


Figure 1. Cross-section of a variable-reluctance (VR) motor.

Stepper Motor Advantages and Disadvantages

Advantages

1. The rotation angle of the motor is proportional to the input pulse.
2. The motor has full torque at standstill (if the windings are energized)
3. Precise positioning and repeatability of movement since good stepper motors have an accuracy of 3 – 5% of a step and this error is non cumulative from one step to the next.
4. Excellent response to starting/stopping/reversing.
5. Very reliable since there are no contact brushes in the motor. Therefore the life of the motor is simply dependant on the life of the bearing.
6. The motors response to digital input pulses provides open-loop control, making the motor simpler and less costly to control.
7. It is possible to achieve very low speed synchronous rotation with a load that is directly coupled to the shaft.
8. A wide range of rotational speeds can be realized as the speed is proportional to the frequency of the input pulses.

Disadvantages

1. Resonances can occur if not properly controlled.
2. Not easy to operate at extremely high speeds.

References

- **Stepper Motors**
  - Ultimate Reference on Stepper Motors you will need

Control of Stepping Motors, a tutorial

http://www.cs.uiowa.edu/~jones/step/index.html

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Other Motor Control Web Pages

- Ericcson's Stepper Motor Application Notes
  an excellent tutorial from a major manufacturer of stepping motor control ICs.
- Tom Porter's Motor Control Web Page
- Ian Harries on Stepping Motors
  with a nice set of information on reverse engineering salvaged motors and a number of example applications.
- Tony Mercer's web pages
  with an introductory stepper tutorial.
- Euclid Research MotionScope™ demo
  excellent illustrations of physical behavior of some real motors.