Announcements

- Lab hours:
  - 2-6 on Saturday and Sunday
  - 11-1 on Monday
- Check off 2-3 on Monday
- 2001 A Space Odyssey and pizza:
  - In STAR room @ 6 pm on Saturday

Practical Aspects of Motors for Mobile Robots

RSS Technical Lecture 2

Friday, Feb 4 2011

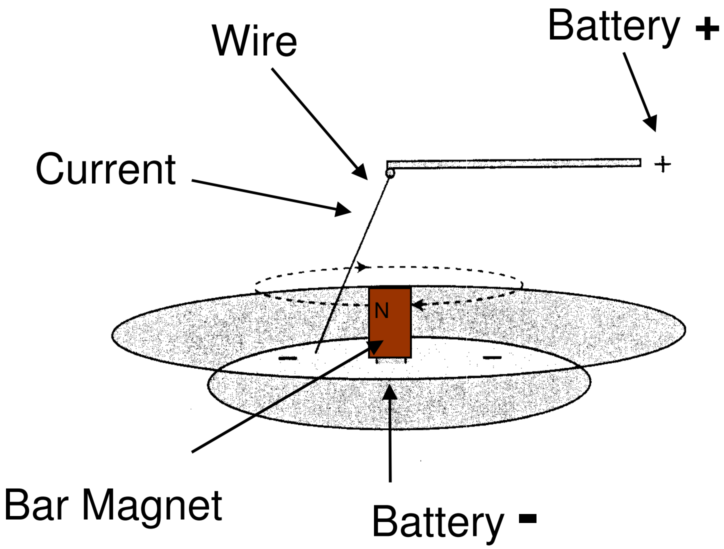
Cagdas Onal

Today

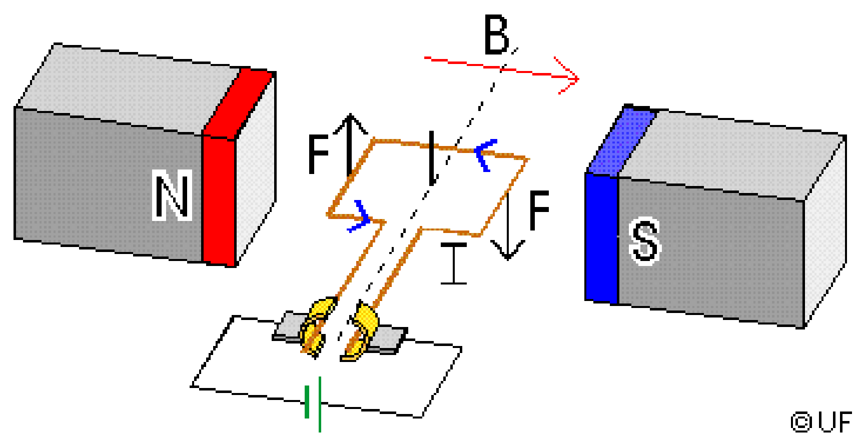
- DC (permanent magnet) motors
  - Basic principles
  - Characterization
  - Sensing rotation with encoders
  - Choosing one that’s adequate (“sizing”)
  - Gears
  - Electronic support for control
- Servo Motors
- Stepper Motors - time permitting

Basic Principles

- Orsted (1819): DC current produces a
- Faraday motor (1821)
  – Magnet; bowl of mercury; stiff wire attached at top
  – Run DC current through wire; it rotates about magnet
- Effect came to be known as "Lorentz force"
  – Induced force perpendicular to



Faraday Motor

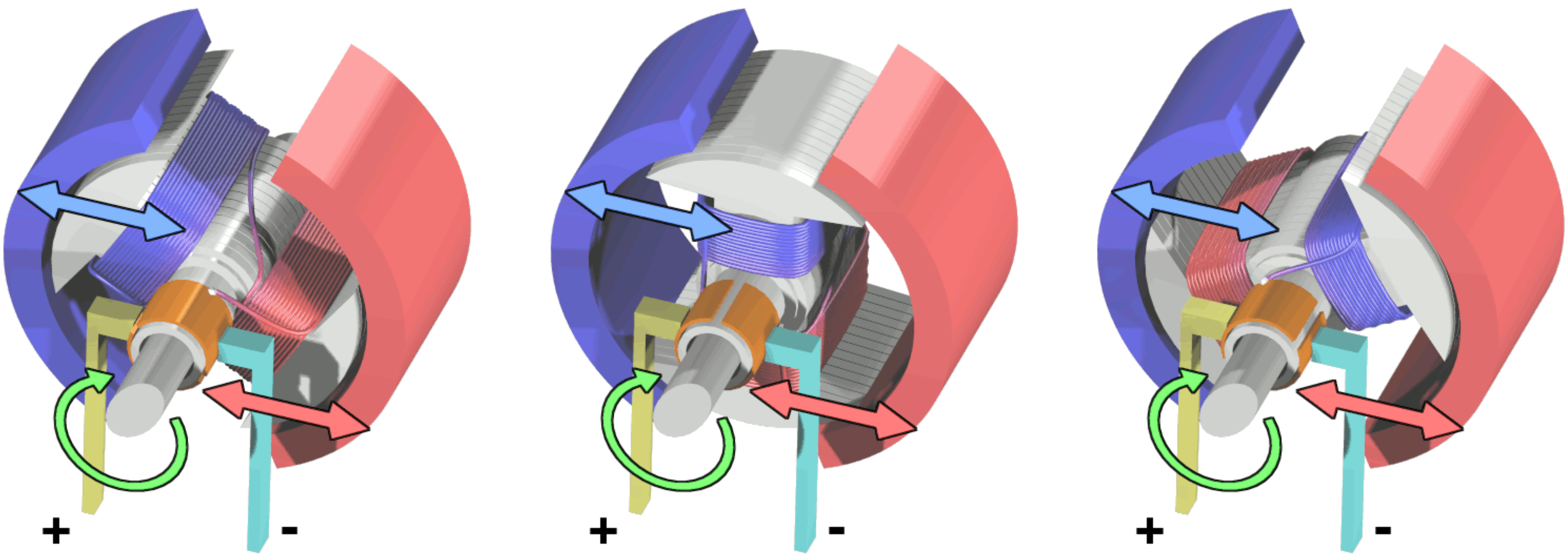


UF Phys. 3054

Lorentz Force

DC motor (based upon Lorentz force)

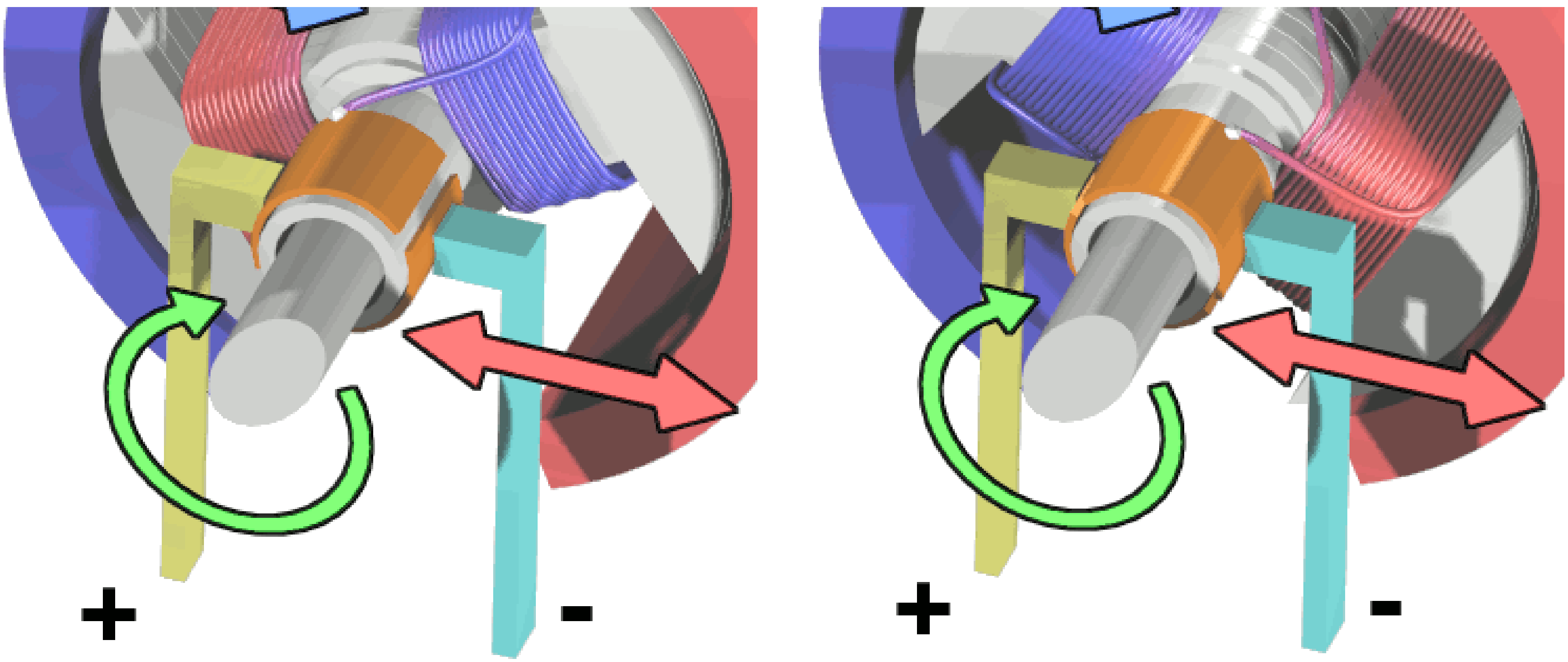
- Wind wire *coil* around *armature* to strengthen B field
- Mount armature on *rotor;* attach rotor to *drive shaft*
- Enclose rotor and drive shaft within *stator*
  - Permanent magnet or electromagnet
- Supply DC *voltage* and *current* as shown below



Wikipedia

Completing a rotation

- Reverse current direction
- Commutator (copper) and brushes (not shown)
- Blue coil is the one in contact with **+** terminal

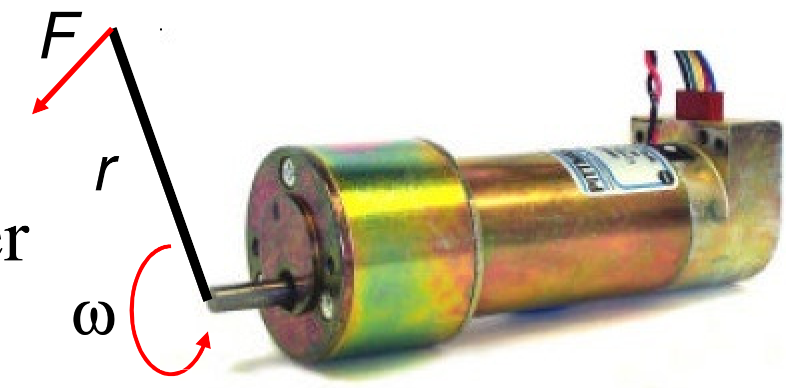


Wikipedia

Motor Power, Torque, and Efficiency

P_e : Supplied Electrical Power, in watts [J / s]

$P_e =$



P_m : Output Mechanical Power

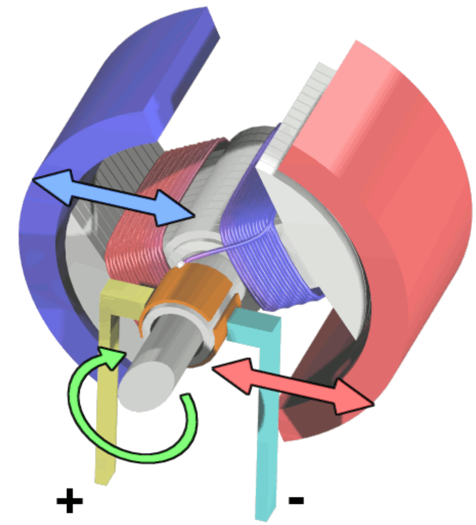
$P_m =$

$T =$ is the *torque*; it is the tangential force F delivered at a distance r from shaft center [N m]

ω :

Efficiency e = ? P_m / P_e

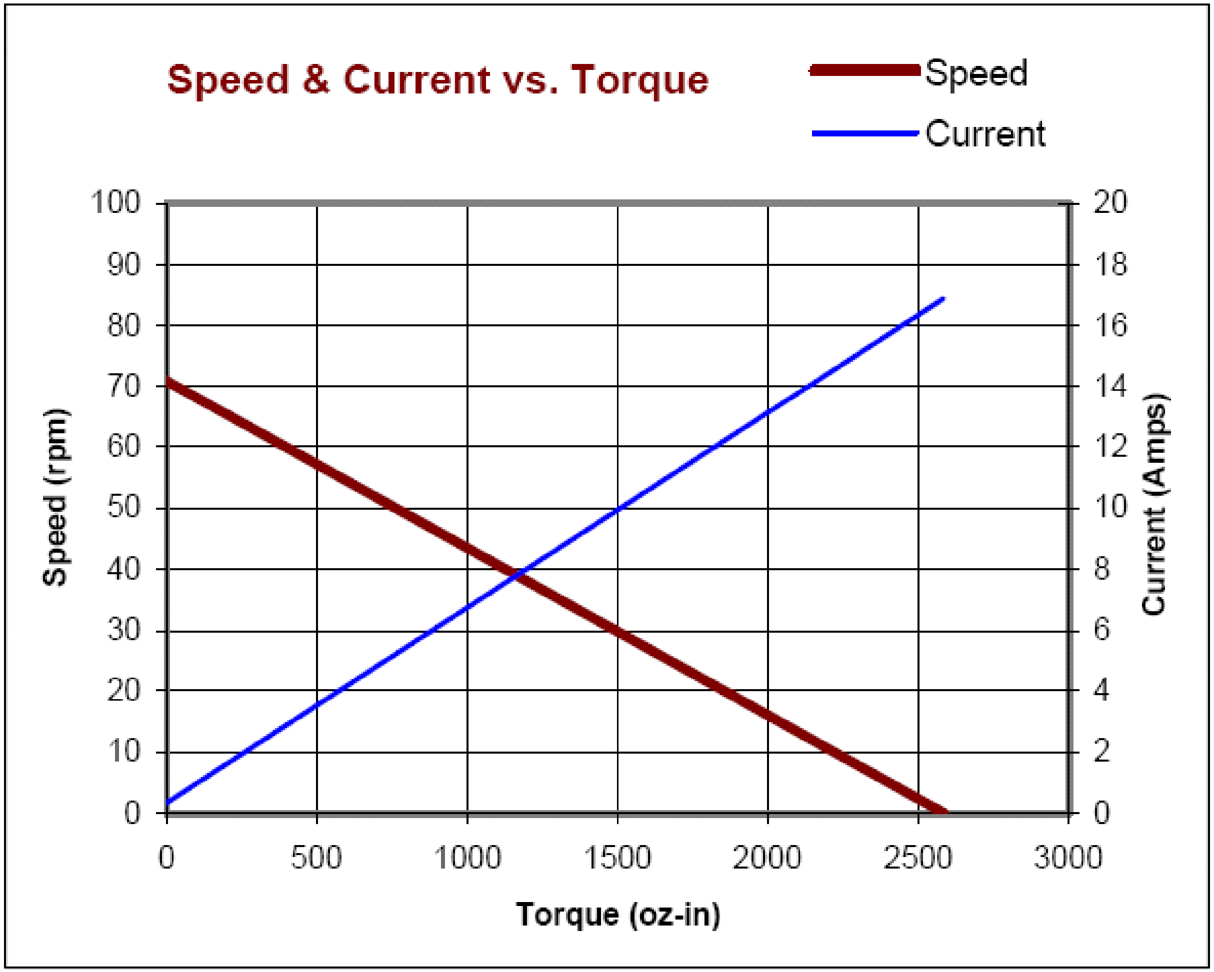
Back-EMF



- When a conductor moves within a static magnetic field:
  - Current is produced in conductor
  - Current is called "back-EMF"
  - Back-EMF is *proportional* to shaft angular velocity, and *opposes* current supplied by PS
  - Thus as shaft (armature) angular velocity increases, rotation-induced current **increases**
  - Thus supplied current from PS **decreases**
  - Thus as ω increases, torque **decreases** !

Pittman GM9236S025 DC Motor (12VDC)

"Speed-Torque Characteristic"



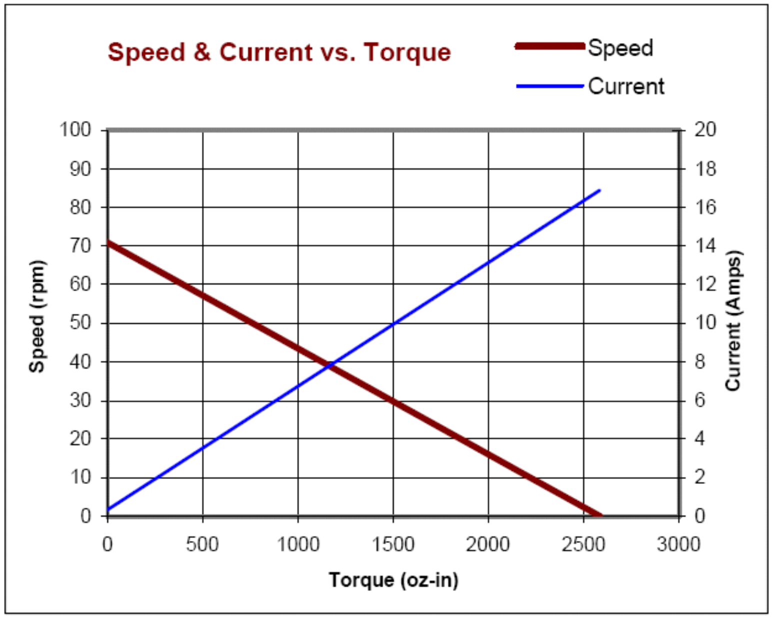
Pittman

What does this plot mean?

How can we interpret it?

Load vs. RPM, Power, and Torque

- **Increase load** on the shaft
  - RPM drops (direction on plot?)
  - Rotation-induced voltage across armature (opposing PS) decreases
  - Thus (since V=IR) **more** current will flow from the power supply
  - Thus **more torque** will be produced



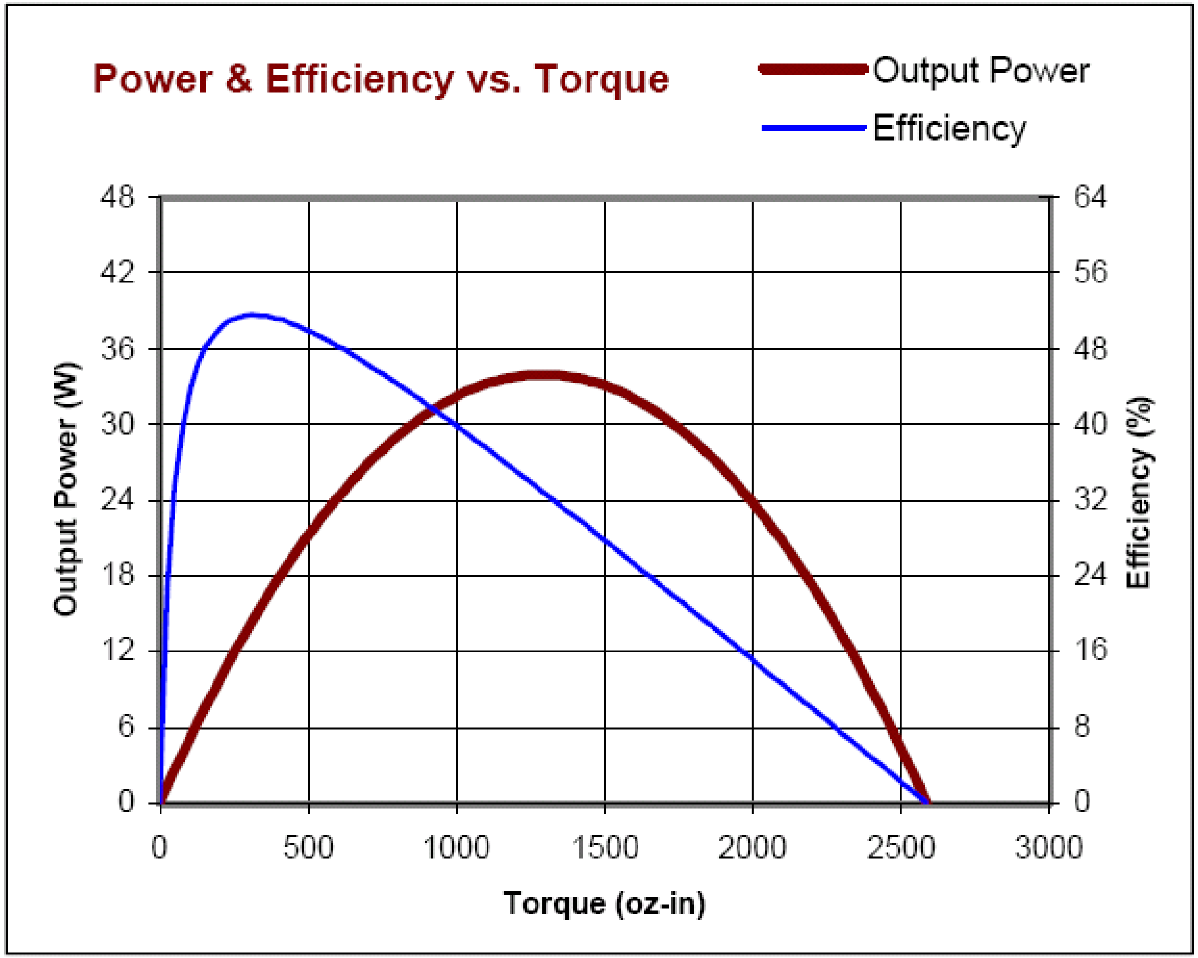
(Details depend on the motor geometry, materials, # of windings, supply voltage)

- **Decrease load** on the shaft
  - RPM goes up (direction on plot?)
  - Rotation-induced voltage across armature (opposing PS) increases
  - Thus (since V=IR) **less** current will flow from the power supply
  - Thus **less torque** will be produced

- **What if** you apply 12 voltage V at no load?

Pittman GM9236S025 DC Motor

"Power-Torque Characteristic"

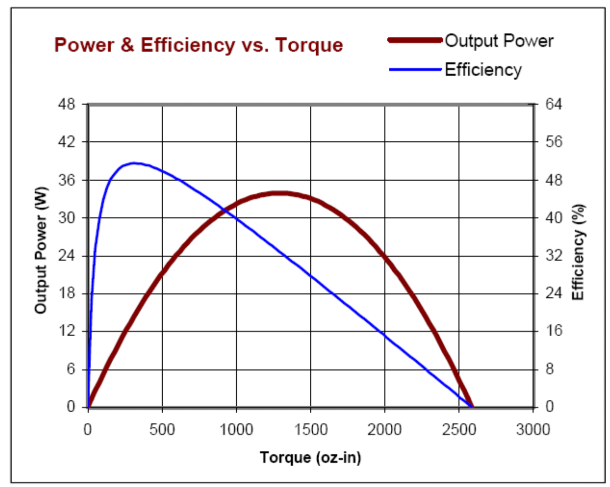


Pittman

What info is in this plot?

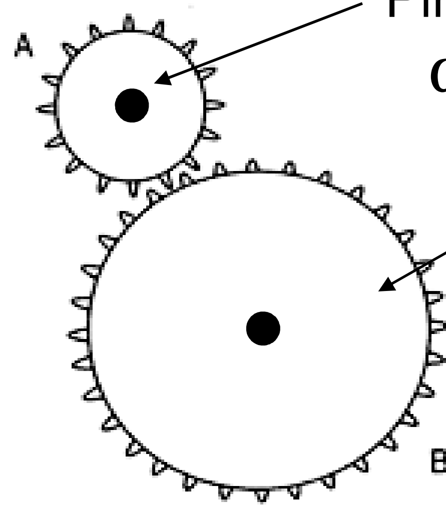
Motor operating regimes

- *Continuous torque (480 oz. in. for Pittman motor)*
  –
- *Peak torque (oz. in. for Pittman motor)*
  – Momentary, intermittent or acceleration torque
  – Torque maximized at
- *Peak output power (T · ω)*
  – Calls for much more than continuous torque level
- *Peak efficiency*
  – Maximum battery duration
  – But only ~10% of peak torque!



Gearing Down

- Gearbox:
  - Transmits power mechanically
  - Transforms shaft angular velocity ω and torque T (how?)



- Gear ratio

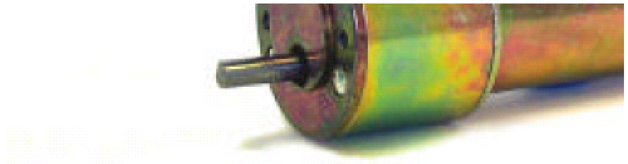
  $R = \#\ teeth_{out} / \#\ teeth_{in}$

- So $\omega_{out} = \omega_{in} / R$
- $T_{out} = e\,(T_{in} \cdot R)$
- What is e ?
  - Gearbox efficiency, $0 < e < 1$
- Where does (1-e) part go?
  - Heat (friction, deformation), sound

Example motor datasheet (detail)

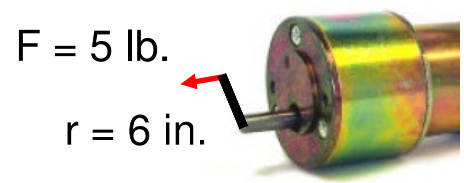
GM9236S025

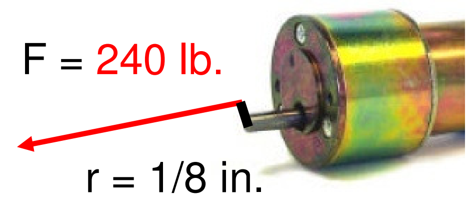
Lo-Cog® DC Servo Gearmotor

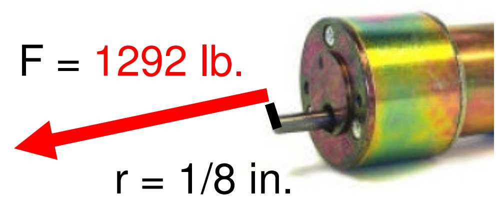


Assembly Data	Symbol	Units	Value	
Reference Voltage	E	V	12	
No-Load Speed	S_{NL}	rpm (rad/s)	71	(7.4)
Continuous Torque (Max.)[1]	T_C	oz-in (N-m)	480	(3.4E+00)
Peak Torque (Stall)[2]	T_{PK}	oz-in (N-m)	2585	(1.8E+01)
Weight	W_M	oz (g)	23.7	(671)
Motor Data				
Torque Constant	K_T	oz-in/A (N-m/A)	3.25	(2.29E-02)
Back-EMF Constant	K_E	V/krpm (V/rad/s)	2.40	(2.29E-02)
Resistance	R_T	Ω	0.71	
Inductance	L	mH	0.66	
No-Load Current	I_{NL}	A	0.33	
Peak Current (Stall)[2]	I_P	A	16.9	
Motor Constant	K_M	oz-in/√W (N-m/√W)	4.11	(2.90E-02)
Friction Torque	T_F	oz-in (N-m)	0.80	(5.6E-03)
Rotor Inertia	J_M	oz-in-s^2 (kg-m^2)	1.0E-03	(7.1E-06)
Electrical Time Constant	τ_E	ms	1.06	
Mechanical Time Constant	τ_M	ms	8.5	
Viscous Damping	D	oz-in/krpm (N-m-s)	0.053	(3.5E-06)
Damping Constant	K_D	oz-in/krpm (N-m-s)	12.5	(8.5E-04)
Maximum Winding Temperature	θ_{MAX}	ºF (ºC)	311	(155)
Thermal Impedance	R_{TH}	ºF/watt (ºC/watt)	56.3	(13.5)
Thermal Time Constant	τ_{TH}	min	13.5	
Gearbox Data				
Reduction Ratio			65.5	
Efficiency[3]			0.80	
Maximum Allowable Torque		oz-in (N-m)	500	(3.53)

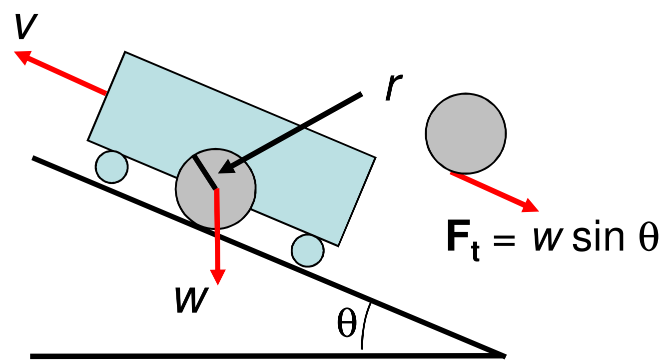
Pittman







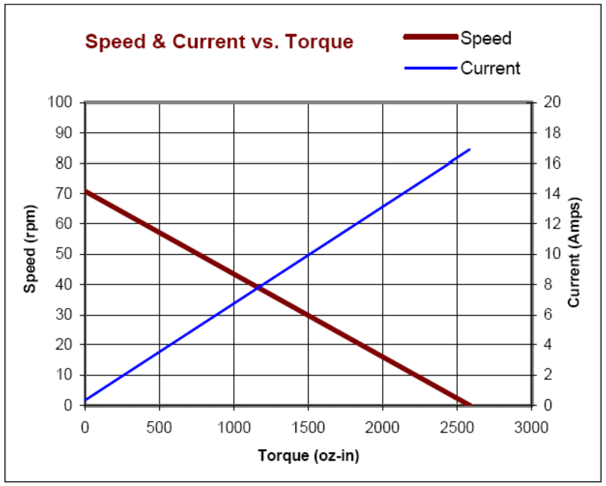
Motor Sizing Example



- Robot's task: climb ramp of inclination $\theta = \pi/6$ at constant velocity $v = 1$ in/sec
- How much *torque* must each wheel motor deliver? (*Current, power needed?)*
- What else do you need to know?
  - Weight w = *~25 lbs;*
  - Wheel radius r = ~2.5 in.
- $\mathbf{F_t} = w \sin\theta$ (tangential component)
- Equate power terms: $\mathbf{F_t}\, v = 2\, T\, \omega$
- Since $v = \omega\, r$
- Then $\mathbf{F_t}\, \omega\, r = 2\, T\, \omega$
- So that $T = \mathbf{F_t}\, r / 2$

  $= w \sin\theta\, r / 2$

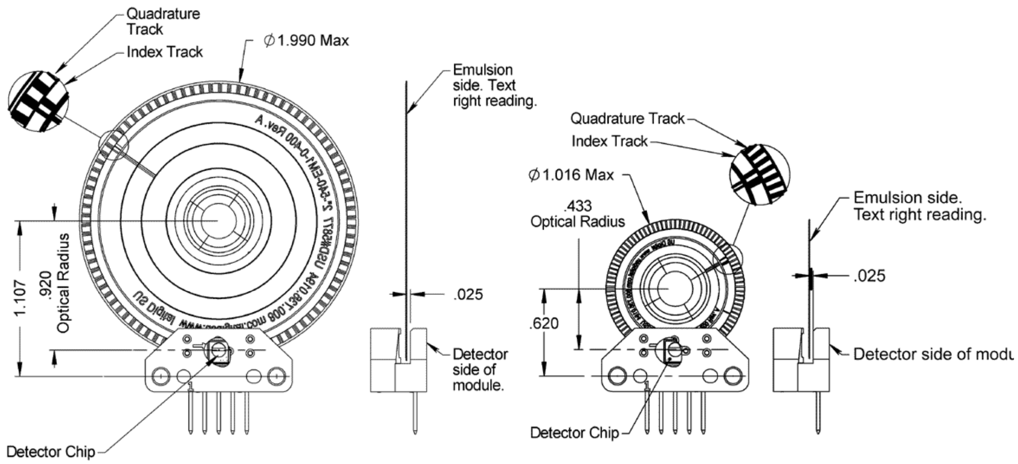
  $= (25 \text{ lb.})(0.5)(2.5 \text{ in}) / 2$

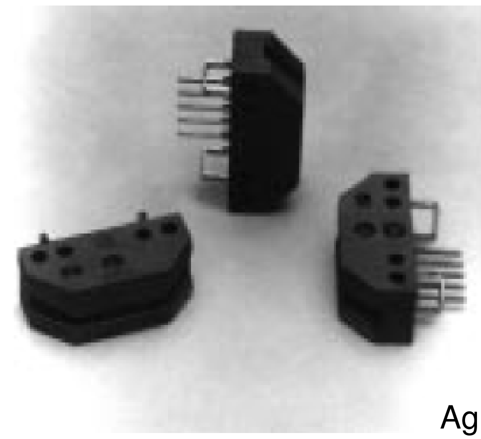


- Convert units: = 15.625 lb.-in. = **250 oz.-in. required torque**
- Current (from datasheet) = ~**2 A**; Power = I V = 2A * 12V = ~**25 W**

Shaft Encoders

- Report motor shaft speed (easy) or position (harder)
- Codewheel: Circular disk mounted on motor shaft with many alternating black and white regions





Agilent

- Optical sensor reads / emits codewheel region transitions
- Counting the pulses produced in any time interval yields *change* in shaft angle (how to compute distance traveled?)
- This is basic *odometry* used for control & “dead reckoning,” or estimation of position relative to some starting point

Interfacing Motor and Microprocessor

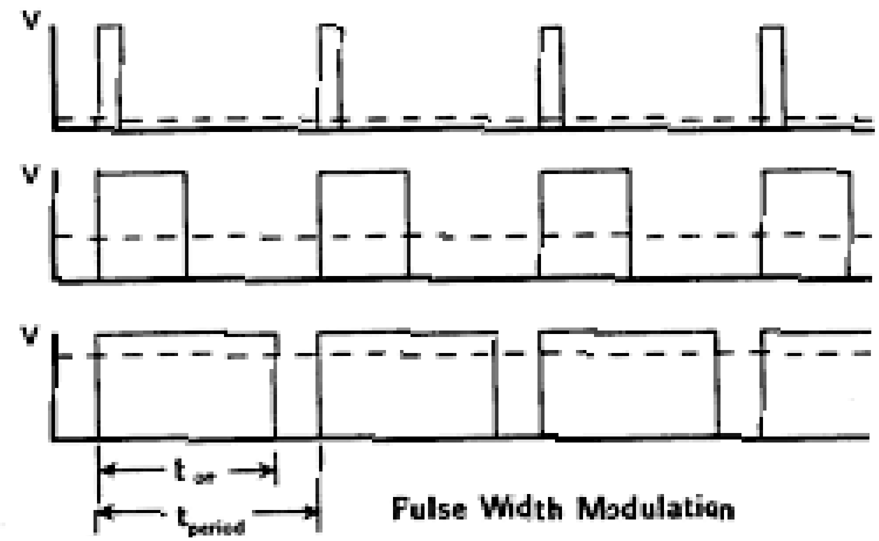
- So far, we've looked only at constant 12V DC
- In reality, must *control* motor *direction* and *speed*
- Accomplished through electronic support

  – 1. How do we control the motor speed?
    - PWM handled by PSOC on μ-orc
    - Java code provides %-on of duty cycle

  – 2. How do we control motor direction?
    - Handled by an H-Bridge

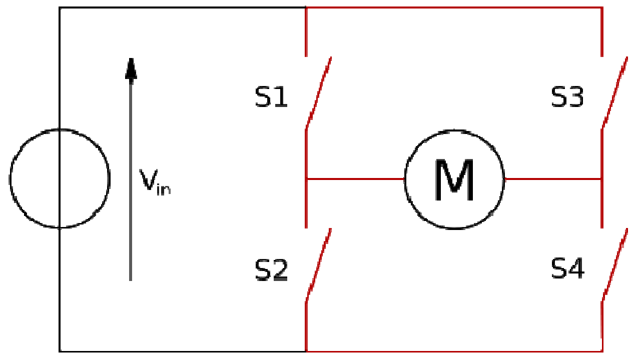
PWM: Pulse Width Modulation

- Apply motor voltage as *square wave* at *fixed* frequency (from 60Hz to 50KHz; Orc uses ~16KHz)
- Control motor speed/power by changing the *duty cycle* (or *pulse width*) of voltage signal
  - At 0% duty cycle, motor is off
  - At 100%, full power
  - At 50%, half power etc.
- Effectively produces a *time-averaged* voltage signal
- Inductive load of motor smoothes input signal in coils



Clark and Owings

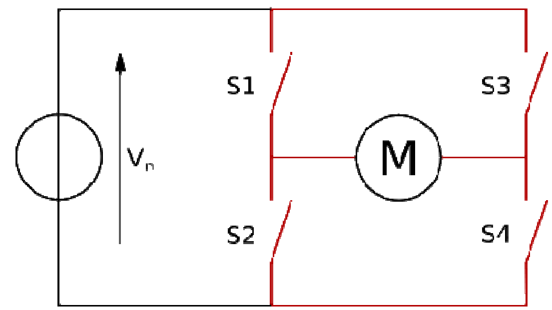
Motor Direction Control



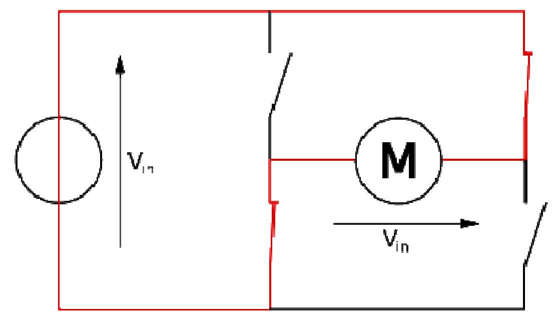
- This circuit is called an *H-bridge*.
  - In ORCboard, it's in an L6205 DUAL FULL BRIDGE DRIVER
  - Direction of motor is determined by corner-paired switch that determines direction of potential and thus current flow

H-Bridge Circuit States

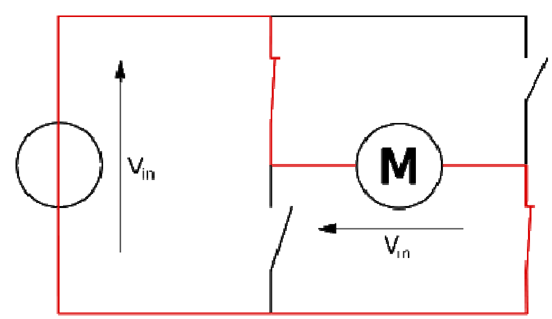
- Open
  - No voltage applied across motor M



- Forward
  - V_{in} applied



- Reverse
  - V_{in} applied



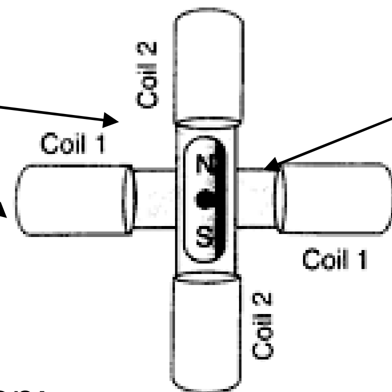
Wikipedia

Servomechanisms (servo motors, servos)

- DC motor in an integrated package with 3 extra elements:
  - Gearbox between motor shaft and output shaft
    - Provides low-speed, high-torque output
  - Feedback-based *position control* circuit (pulse-width control)
    - Drives servo to commanded "position" (shaft angle)
    - Shaft angle sensing (potentiometer)
    - Current sense for torque sensing
  - Limit stops on output shaft
    - These mechanically delimit servo's minimum & maximum "position"

Stepper Motor (Example: 90-degree bipolar)

Stator: even N coils arrayed around rotor symmetry axis (out of plane of page)

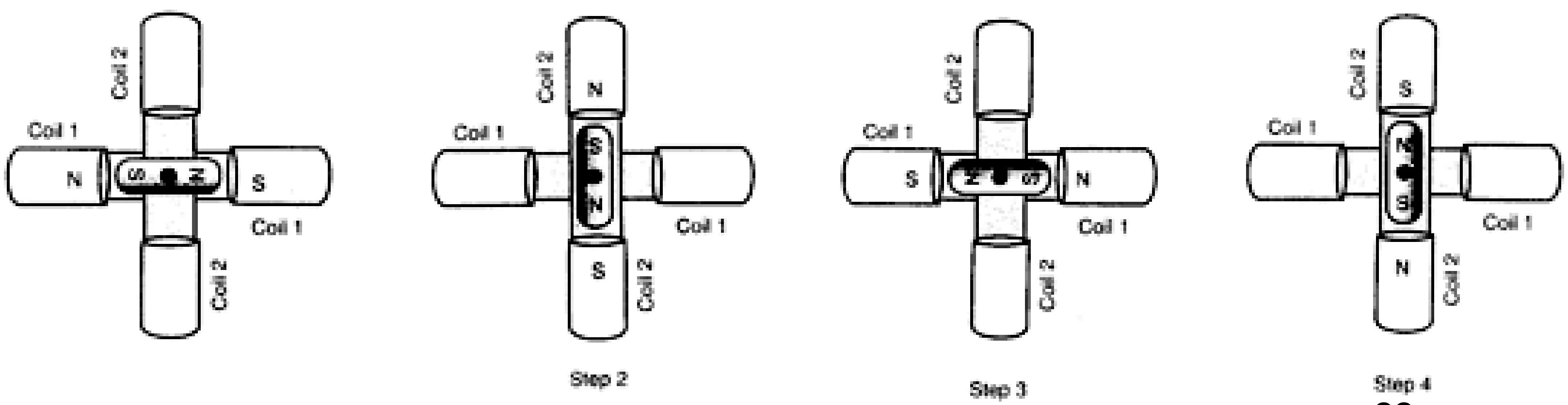


Rotor: permanent magnet(s) mounted on output drive shaft

Clark and Owings

- Controller does commutation: Energizes coils in rotational sequence; rotor swings into alignment to successive states
- When the coil is kept energized, motor produces "holding torque"

- Adv: holding torque, speed and position control without using encoders or feedback
- Angular resolutions of < 1deg are available!
- Brushless!



Comparison of Motor Types

Type:	Pluses:	Minuses:	Best For:
DC Motor	Common Wide variety of sizes Most powerful Easy to interface Must for large robots	Too fast (needs gearbox) High current (usually) Expensive PWM is complex	Large robots
Hobby Servo	All in one package Variety; cheap; easy to mount and interface Medium power required	Low weight capability Little speed control	Small, legged robots
Stepper Motor	Precise speed control Great variety Good indoor robot speed Cheap, easy to interface	Heavy for output power High current Bulky / harder to mount Low weight capability, low power Complex to control	Line followers, maze solvers

Clark and Owings, p. 29

Supplementary Reading

- Theoretical
  - Foundations of Electric Power, J.R. Cogdell
  - Electric Motors and their Controls: An Introduction, Tak Kenjo
- Practical
  - Building Robot Drive Trains, D. Clark and M. Owings
  - Mobile Robots: Inspiration to Implementation, J.L. Jones, B. Seiger, A.M. Flynn

Lecture Wrap Up

REVIEW

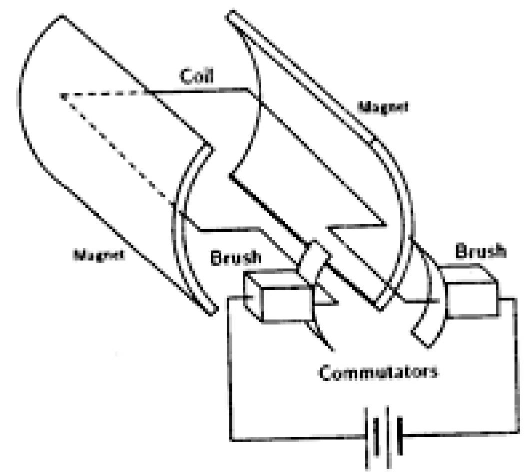
- Covered practical aspects of DC motors
  - To help characterize your motor for velocity controller design

Next Lecture (Monday 1pm)

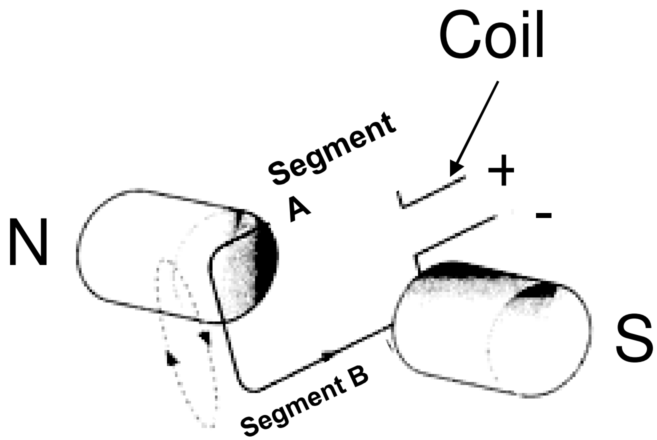
- Motor controllers
  - Ramping to desired speed and error correction

Motor Nomenclature

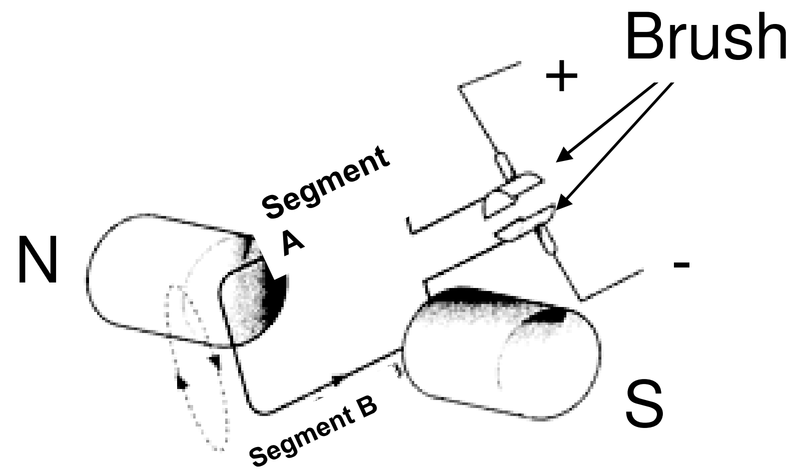
- Armature: 1 or more coils mounted on a central shaft which transmits torque
  - Loading with iron will increase magnetic flux
- Commutator: split plates that touch the half-cylinder brushes, providing power to coils
- Stator: the permanent magnet surrounding the shaft/armature
- Motors have multiple (odd nmr'd quantity) of coils with each coil of multiple turns (aka windings) for more torque



Coil in Flux and Commutation



Coil in Flux



Commutation;
Alternation of current through the coil

Quadrature Encoder

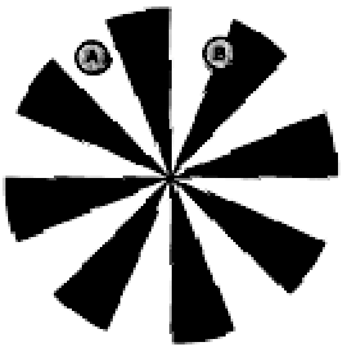


Figure 8-27 Sensor placement for quadrature encoding

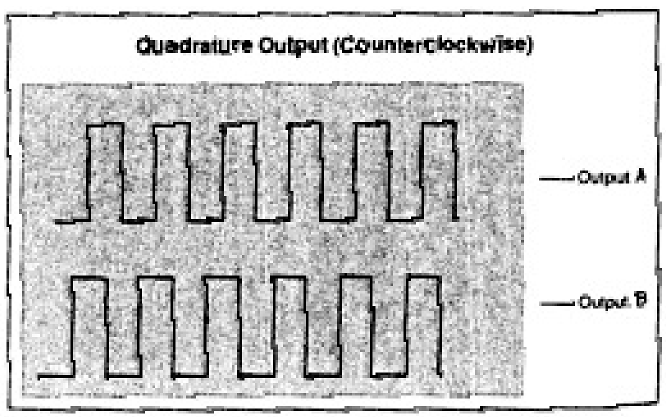


Figure 8-28 Quadrature encoder output

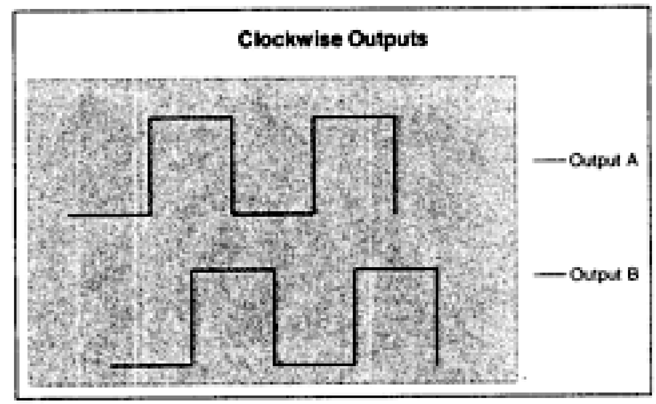


Figure 8-29 Quadrature output as the encoder disk turns clockwise

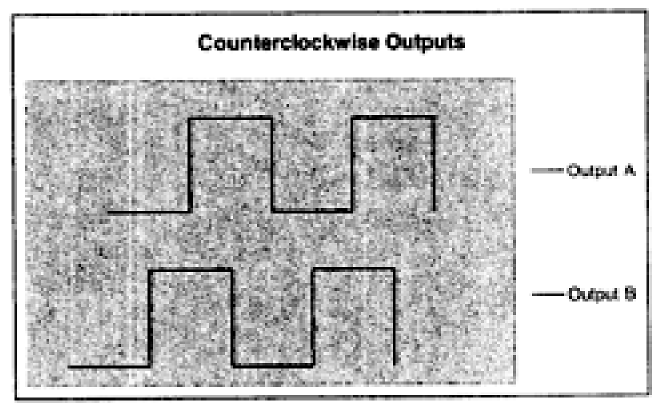
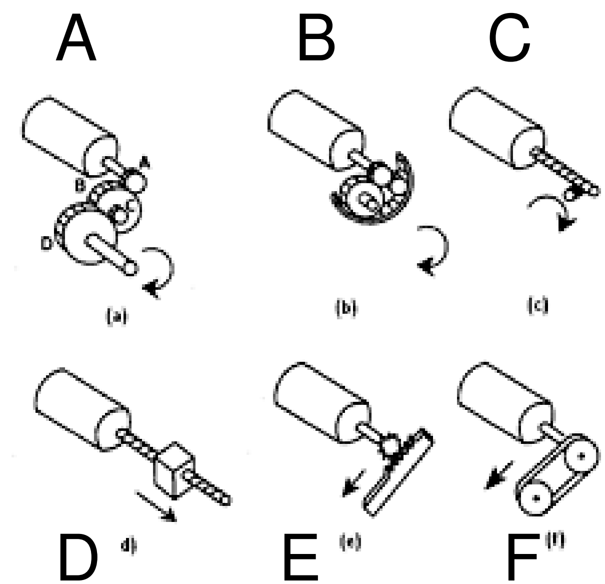


Figure 8-30 Quadrature output as the encoder disk turns counter-clockwise

Clark and Owings

Gears for other purposes

- Can change angle of rotation or direction of rotation: e.g. c
- Can convert rotational motion to linear motion (eg E)
- Can change location of rotational motion (eg a)



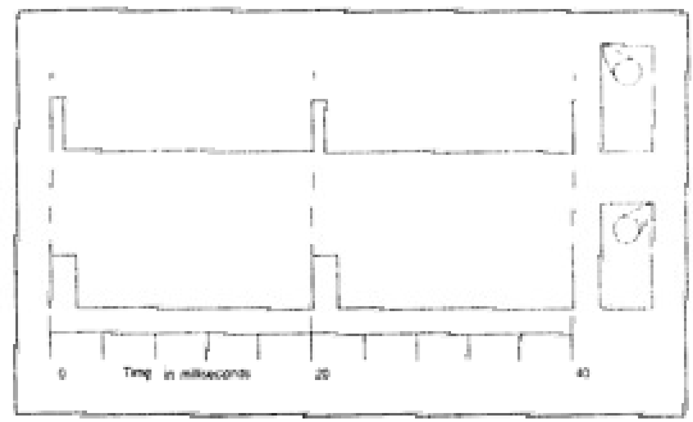
A: spur gear
B: Planetary gears
C: Worm gear
D: Ball screw
E: rack and pinion
F: belt and pulley

Gear Knowledge

- Backlash: the amount of space between an engaging tooth and the tooth space of the mating gear
  – built-in to most gear systems for lubricant to flow
  – When objectionable, it's "slop": noise and low durability
- Efficiency of gear: decreases with gear ratio
  – Loss due to mechanical friction

PPM for Servo Motors

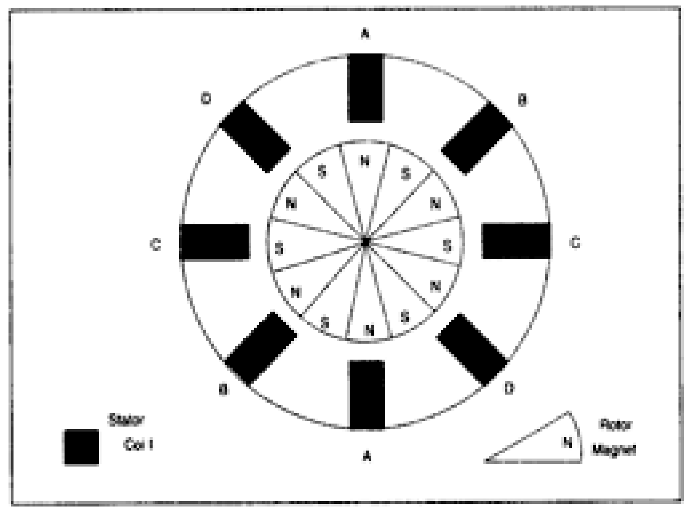
- **Position** control, not speed control -- closed loop
- Pulse proportional modulation: width of pulse is the encoded information needed by controller (I.e. the position to which the shaft should turn)
- Use 1-2ms out of a possible 20 ms time period to encode the position info
- Typical:
  - Center: 1.3 ms pulse,
  - range: 0.7ms - 1.7 ms



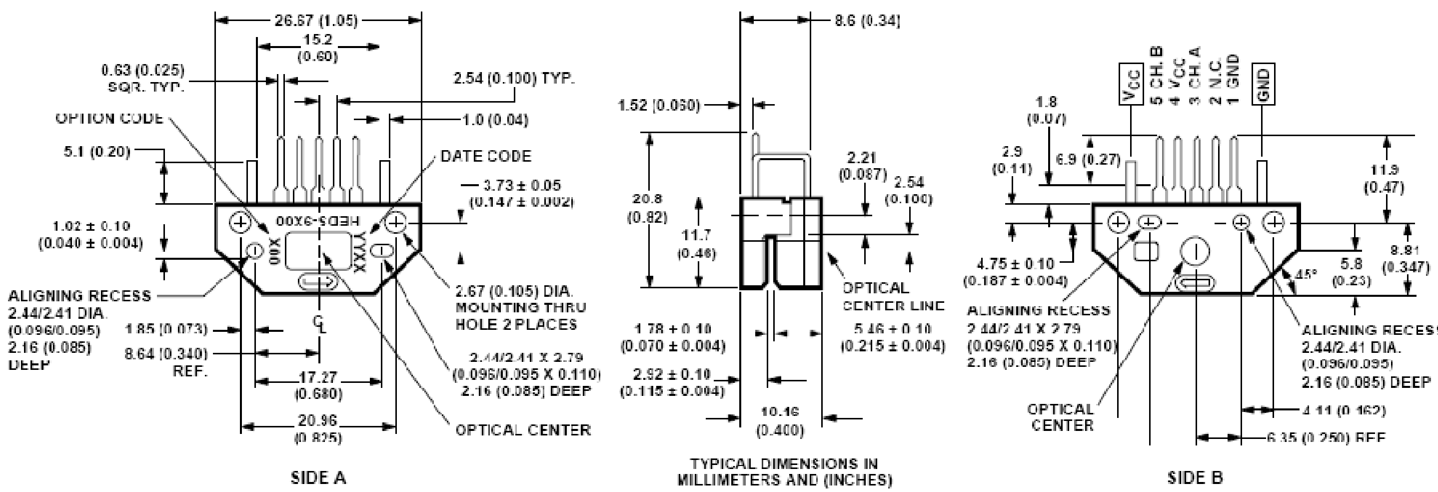
Servo Motors

- Hobby, 5V supply,
- Complete package of
  - DC motor and geartrain
  - Limit stops (minimum, maximum shaft angle)
  - Shaft angle sensing with a potentiometer
  - Integrated circuit for shaft angle control
  - 3 wires:
    - power, ground, pulse-width control input
- Servos to a position: ie. Electric circuit directs motor to rotate to commanded position, and keeps it there. If you interfere, circuit reads pot and makes correction with increased current, which increases torque

More Realistic Diagram of Stepper



RSS Encoders

- HEDS-9000
- 2 channel quadrature
- Optical encoders and codewheel for rotary position (angle) sensing
- 

Electronic current switching

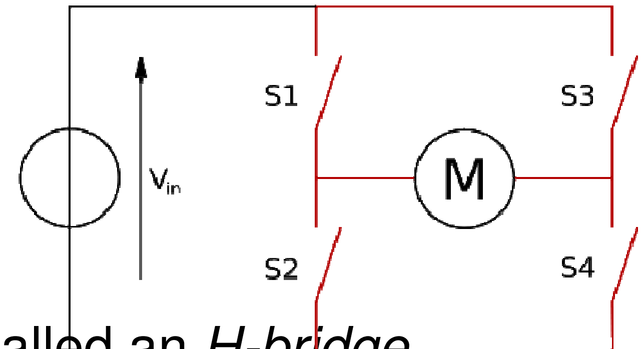
- Brushless motors sense the armature position and use logic to alternate the current direction
- Brushless motors are quieter, and last longer

Interfacing Motor and Microprocessor

- So far, we’ve looked only at constant 12VDC
- In reality, must *control* motor *direction* and *speed*
- Two issues:
  - 1. PSOC alone can’t provide sufficient current
  - 2. How do we control the motor speed?

Interfacing Motor and Microprocessor

- Combine **separate power source** with control signals from microprocessor using some interface circuitry:



- This circuit is called an *H-bridge*.
  - In ORCboard, it's in an L6205 DUAL FULL BRIDGE DRIVER
  - Direction of motor is determined by corner-paired switch that determines direction of potential and thus current flow

QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

H-Bridge Circuit States

- Open
  - No voltage applied across motor M
- Forward
  - V_{in} applied
- Reverse
  - V_{in} applied

Wikipedia