# Electric Motors

RSS Technical Lecture 2
Friday, 10 Feb 2012
Prof. Seth Teller

## My Research Focus

- **Perceptive machines alongside people**
  - Integrating experience, models of the environment, and sensor data to plan and carry out useful behaviors
- **Natural interfaces** involving speech, gesture
  - References to shared surroundings
- **Fielded robots** for real-world utility
  - Engagement with user communities


DARPA Urban Challenge:
Self-driving passenger vehicle


Agile Robotics for Logistics:
Gesture-commandable forklift

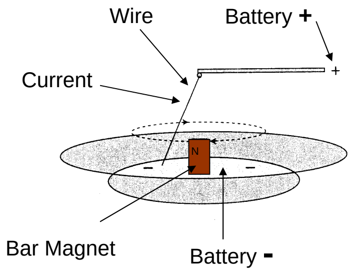

Voice-commandable
autonomous wheelchair

# Today

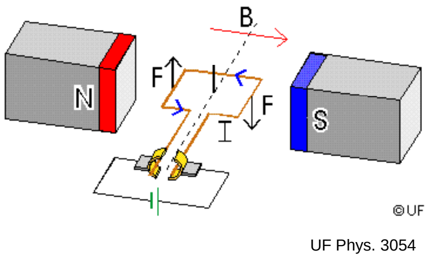
- DC (permanent magnet) motors
  - Basic principles
  - Characterization
  - Sensing rotation with encoders
  - Choosing one that's adequate ("sizing")
  - Gears
  - Electronic support for control
- Servo Motors
- Stepper Motors - time permitting

# Basic Principles

- Orsted : DC current produces a
- Faraday motor ( .)
  - 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



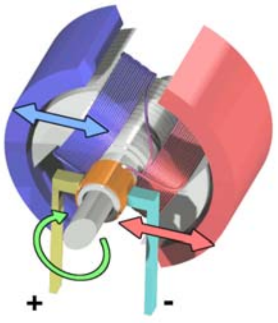
Faraday Motor

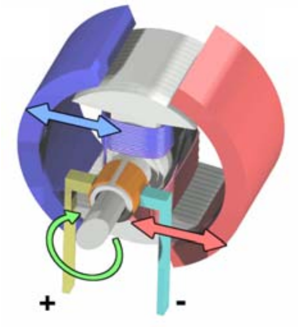


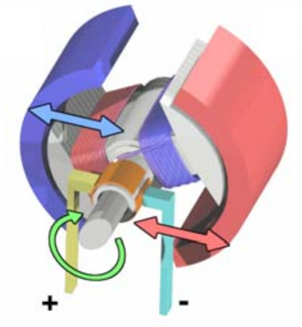
Lorentz Force

## 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



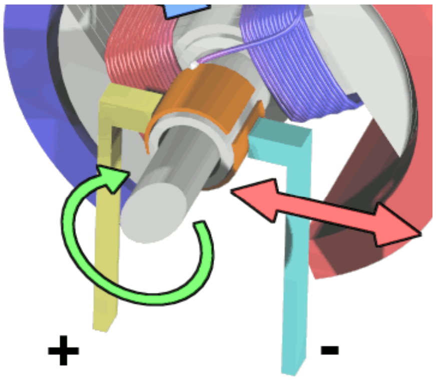


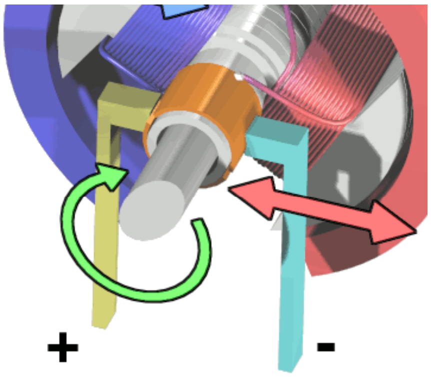


Wikipedia

## 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

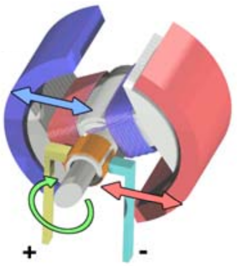
$P_m =$

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

$\omega$ :

Efficiency e = ?

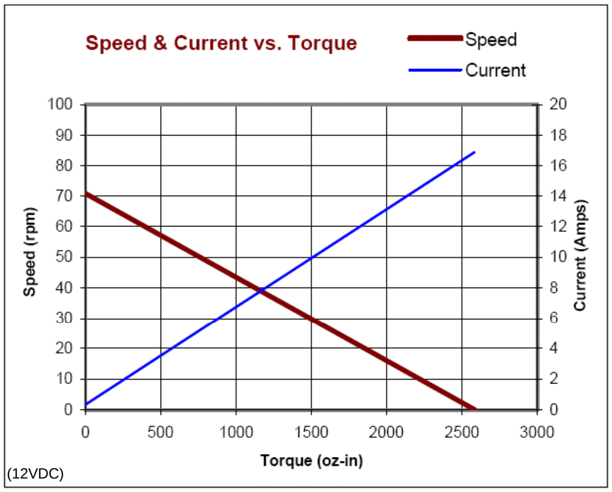
# Back-EMF



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

# Pittman GM9236S025 DC Motor (12VDC)

“Speed-Torque Characteristic at 12VDC”



Pittman

*What does this plot mean?*

*How can we interpret it?*

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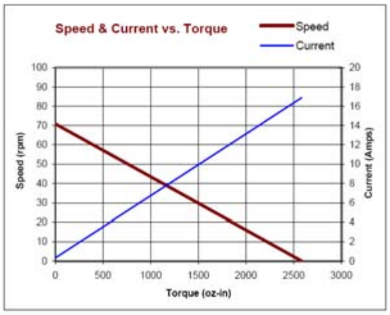
# Load vs. RPM, Power, and Torque

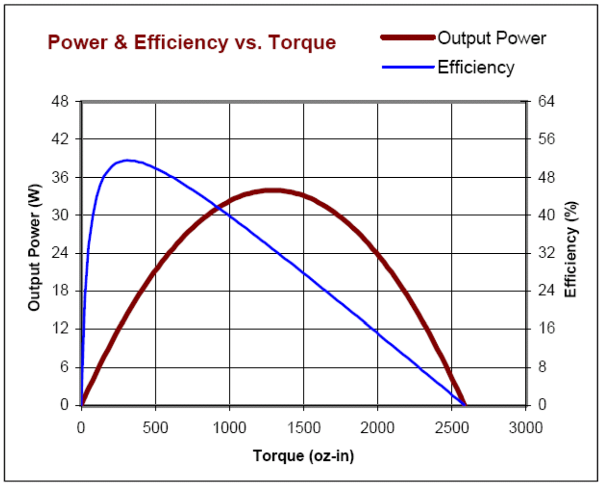
- **Increase load** on the shaft
  - [redacted]
- **Decrease load** on the shaft
  - [redacted]
- What happens under **no load**? [redacted]



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

# Pittman GM9236S025 DC Motor

"Power-Torque Characteristic"

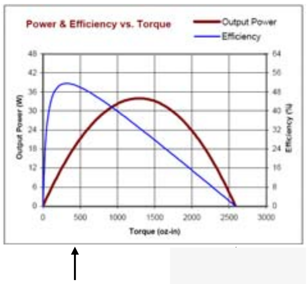


Pittman

*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



Continuous torque

# Example motor datasheet (detail)

**GM9236S025**

Lo-Cog® DC Servo Gearmotor

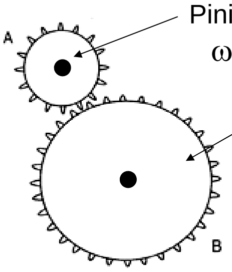
| Assembly Data | Symbol | Units | Value | |
|---|---|---|---|---|
| Reference Voltage | E | V | 12 | |
| No-Load Speed | $S_{NL}$ | rpm (rad/s) | 71 | (7.4) |
| Continuous Torque (Max.)$^1$ | $T_C$ | oz-in (N-m) | 480 | (3.4E+00) |
| Peak Torque (Stall)$^2$ | $T_{PK}$ | oz-in (N-m) | 2585 | (1.8E+01) |
| 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 | $\tau_E$ | ms | 1.06 | |
| Mechanical Time Constant | $\tau_M$ | 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 | $\theta_{MAX}$ | °F (°C) | 311 | (155) |
| Thermal Impedance | $R_{TH}$ | °F/watt (°C/watt) | 56.3 | (13.5) |
| Thermal Time Constant | $\tau_{TH}$ | min | 13.5 | |
| **Gearbox Data** | | | | |
| Reduction Ratio | | | 65.5 | |
| Efficiency$^3$ | | | 0.80 | |
| Maximum Allowable Torque | | oz-in (N-m) | 500 | (3.53) |

Pittman

# 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

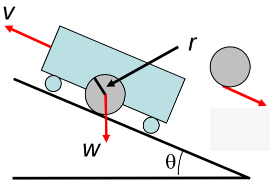


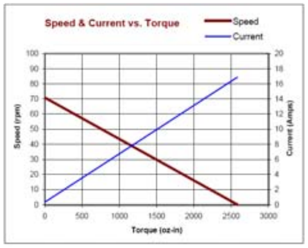
Pinion **A** (driver):
$\omega_{in}$, $T_{in}$

Wheel **B** (follower):
$\omega_{out}$, $T_{out}$

# 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?



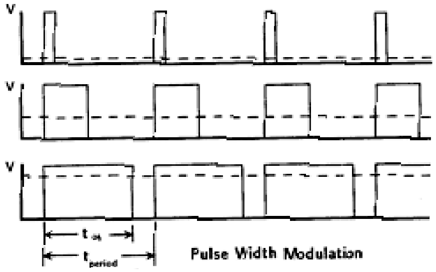


# Interfacing Motor and Microprocessor

- So far, we've looked only at *constant* 12V DC
- In practice, control motor *direction* and *speed*
- Accomplished through electronic support
  - 1. How do we control the motor *speed*?
    - PWM handled by PSOC on μORC
    - Java code provides **percent-on** of duty cycle
  - 2. How do we control motor *direction*?
    - Handled by an H-Bridge

# PWM: Pulse Width Modulation

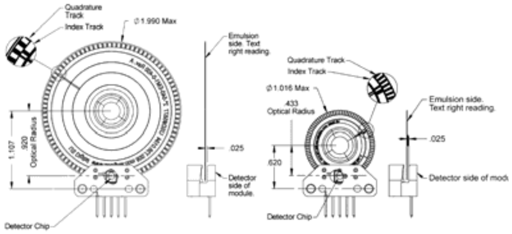
- Apply motor voltage as a *square wave* at *fixed* frequency (from 60Hz to 50KHz; Orc uses ~16KHz)
- Control motor speed/power by changing the *duty cycle* (or *pulse width*) of voltage signal
  - At 0% duty cycle, motor is off
  - At 100%, full power
  - At 50%, half power etc.
- Effectively produces a *time-averaged* voltage signal
- Inductive load of motor smoothes input signal in coils
- Duty cycle: Laptop sends 8-bit value (0..255) to μORC PSOC

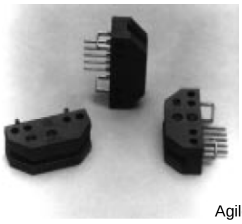


Clark and Owings

# Sensing speed: Motor Shaft Encoders

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

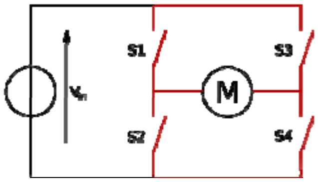




Agilent

- Optical sensor detects 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

# Controlling Motor Direction



- This circuit is called an *H-bridge*.
  - In uORC: L6205 DUAL FULL BRIDGE DRIVER
  - Direction of motor 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”

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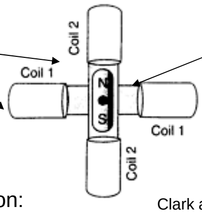
# Stepper Motor (Example: 90-degree bipolar)



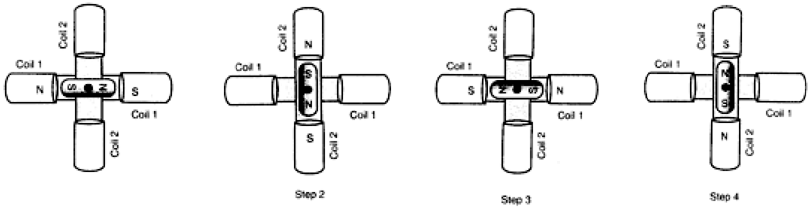
Stator: even N coils arrayed around rotor symmetry axis (out of plane of page)

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<br>Wide variety of sizes<br>Most powerful<br>Easy to interface<br>Must for large robots | Too fast (needs gearbox)<br>High current (usually)<br>Expensive<br>PWM is complex | Large robots |
| Hobby Servo | All in one package<br>Variety; cheap; easy to mount and interface<br>Medium power required | Low weight capability<br>Little speed control | Small, legged robots |
| Stepper Motor | Precise speed control<br>Great variety<br>Good indoor robot speed<br>Cheap, easy to interface | Heavy for output power<br>High current<br>Bulky / harder to mount<br>Low weight capability, low power<br>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