Robotic Vehicle Design

Actuators, control and interfacing

Jim Keller

July 2008
What are actuators and Why are they needed?

• Computers/microprocessors are good at calculating **what** should be done to control a robot or machine but… in almost all cases they lack the power to move **anything**
  – Failure to include a properly sized actuator will lead to:
    • Burn out of electrical components
    • Failure to cause desired movement
      – Speed/travel shortfall
    • Poor hold position performance
    • Poor capture of commanded position (overshoot/undershoot)
Types

• Power Source:
  – Electrical
  – Mechanical
  – Pneumatic/Hydraulic

• Type of Motion:
  – Linear
  – Rotary

• Control
  – On/off
  – Proportional
DC Motor Background from Physics

- Principal Technology: Direct current flowing through a magnetic field induces a force on the conductor carrying the current:
  \[ F = I \times B \]
  \[ I = \frac{V}{R} \]

- Motion of a conductor through a magnetic field induces a Voltage (commonly referred to as the electromotive force (emf))
  \[ V_{emf} = - \text{change in magnetic flux with respect to time} \]
  \[ V = IR \]
DC Motor Design Background

- Principal Technology: if current is directed through a coil within a magnetic field by connecting coil to a voltage source: \( I = \frac{V}{R} \)

\[
\text{Torque} = r \times F
\]

- What happens when the configuration looks like this:

What is the torque on the coil?
The commutator solves the problem of sustaining motion...

http://student.britannica.com/comptons/art-53254/In-a-DC-motor-electrons-from-the-DC-power-supply
What Happens When the Motor Starts to Spin?

• Motion of a conductor through a magnetic field induces a Voltage…
  – This voltage is proportional to the motor speed

• What happens when the motor is connected to a load?
  – The rotation speed increases until the torque supplied (by the motor) equals the load torque
    • Speed then stays fixed at equilibrium

• What happens when the motor has no load?
More Detail on DC Motors

Back EMF evidences itself on this chart in a few ways:

- most importantly, the motor reaches a steady speed in the absence of an external load because the back EMF cancels the applied (i.e. battery) voltage so that there is no torque
  - Notice at the highest speed, there is no torque output, but there must still be current flowing through the motor
- The slope of the speed vs. torque curve is set by the back EMF:
  \[ \text{Slope of Speed-Torque Curve} = \frac{R}{K_E K_T} \text{ (krpm/oz. in.)} \]

How To Draw Speed Torque Curve

Parameters:
- \( K_T \) torque constant, units are torque/Amp of current
- \( K_E \) voltage constant (back EMF), units are volts/speed
- \( R \) is the motor armature resistance, units are Ohms
Efficiency… why is it important?

- **Power Supplied = Power Consumed**
  - Electrical Power supplied to the motor:
    - $V \times I$ (Watts)
  - Power Consumed by the motor:
    - Electrical = $I^2R$ (Watts)
      - The motor heats up! We didn’t count on that but we have to live with it…
    - Mechanical = Torque * angular rate = $Q \times \omega$ (Nm/s = Watts)
      - The motor does useful work!
      - Angular rate must be measured in radians/sec to get the units to match

  $$VI = I^2R + Q\omega$$

- **Efficiency = Mechanical Power Out/Electrical Power In**
  - As efficiency is reduced, motor heats up more and more, which leads to failure
Other Types of Electric Motors

Stepper Motor:
- Use permanent magnet rotor with electromagnets in the stator
- Use circuitry to control excitation of stators
- Design stator geometry to set step size
- *User selects step size and hold torque*

Motors can be configured for linear motion
Pulse Width Modulation for Proportional Control

- **Why use PWM?**

  **Light dimmer circuit example**
  1. Variable resistor in series
     - Power wasted through resistor
     - Resistor generates heat
  2. PWM controlled switch
     - Circuitry needs to be considered
     - Frequency of pulsing may create RF noise

---

PWM is an easy and effective way to proportionally control electrical actuators without loss of power to the load being driven.
**Hobby Servo-actuators**

- Available in many sizes/magnitudes of output
  - Typically rotary; use push rods to effect linear motion

<table>
<thead>
<tr>
<th>Item: Hitec HS-311 Standard Hobby Servo Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part Number: <strong>SVOS</strong></td>
</tr>
<tr>
<td>Price: <strong>$12.00</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Size (L x W x H):</strong></th>
<th>1.6 x 0.8 x 1.4 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40 x 20 x 37mm</td>
</tr>
<tr>
<td><strong>Weight:</strong></td>
<td>1.7 oz. / 48.5 grams</td>
</tr>
<tr>
<td><strong>Ball Bearings:</strong></td>
<td>No</td>
</tr>
<tr>
<td><strong>Metal Gears:</strong></td>
<td>No</td>
</tr>
<tr>
<td><strong>Torque (4.8V):</strong></td>
<td>42 oz.in / 3.3 kg.cm.</td>
</tr>
<tr>
<td><strong>Transit Time (4.8V):</strong></td>
<td>0.19 sec./60°</td>
</tr>
<tr>
<td><strong>Torque (6.0V):</strong></td>
<td>51 oz.in / 3.7 kg.cm.</td>
</tr>
<tr>
<td><strong>Transit Time (6.0V):</strong></td>
<td>0.15 sec./60°</td>
</tr>
</tbody>
</table>
SAAST 2008 Servo-actuators

• Futaba S3305 High Torque Analog Servo

Manufacturer’s note: This is the Futaba S3305 High Torque, Metal Gear Servo. per Futaba this servo is approved for use with NiCd batteries ONLY!

This servo can produce high-current draw from your batteries. If using NiMH or LiPo batteries, make sure they are capable of delivering sufficient amps.
PWM provides the Command *NOT* the Muscle

- PWM generators are typically based on timing IC chips (555) or microprocessors (Basic Stamp)
  - These devices cannot provide much current
    - Voltage\(*\)current = power = force\(*\)distance\(/\)time
- PWM controllers for motors also include an amplifier stage to source as much current as specified.
  - *Failure to adhere to maximum current ratings = burned out processors… it only takes a fraction of a second.*
Mechanical Actuators

• Bimetallic springs
  – Thermostats (combined sensor/actuator)

• Shaped memory alloys
  – Temperature triggered bi-stable mechanical configuration
  • Temperatures above threshold cause mechanism to jump to a new shape
    – Repeatable switch over many cycles
Hydraulic vs. Pneumatic Actuators

• Hydraulic systems use fluid (typically a specially developed oil)
  – Incompressible
    • Excessive pressures can rupture components!
• Pneumatic systems use gas (typically air)
  – Compressible
    • Actuator is “stiff” to a certain force level and then it has a compliance as the load is too heavy to move
      – Can be used to design advantage
        » Pneumatic muscles behave like real ones…
Why Hydraulics Are Important

Part 1: equal area pistons

\[ F_i = \text{force input}, \quad D_i = \text{Input Motion} \]

\[ F_o = \text{force output}, \quad D_o = \text{Output Motion} \]

\[ \text{Piston: Area} = \pi r^2 \]

\[ P = \text{Pressure in Fluid} \]

\[ F_i = F_o \quad \text{when piston areas are equal} \]

\[ D_i = D_o \quad \text{when piston areas are equal} \]
Why Hydraulics Are Important

Part 2: *unequal* area pistons

\[ F_i = \text{force input}, \quad D_i = \text{input motion} \quad \text{and} \quad F_o = \text{force output}, \quad D_o = \text{output motion} \]

\[
P = \frac{F_i}{A_i} \quad \text{Piston:} \quad \text{Area} = \pi r^2
\]

\[
P = \text{Pressure in Fluid}
\]

\[
F_o = F_i \frac{A_o}{A_i} \quad \text{Significant amplification possible}
\]

\[
F_o \cdot D_o = F_i \cdot D_i \quad \text{Work equivalent}
\]
Why is this particular actuator called an unbalanced system?
Hydraulic and Pneumatic Actuators
Include a Servo-valve

• Servo-valve is interface between computer/controller and actuator
  – A smaller version of the large piston with electrical or mechanical command interface
    • Example
      Mechanical - power brakes in a car
      Electrical – aircraft control surface actuator
    • Sometimes done in stages to build amplification level
      – Electrical – mini hydraulic – large scale hydraulic
Digital Control Processing
(delay or latency is most overlooked issue)
Digital Control Processing
(delay or latency is *THE* most overlooked issue)

- Sampling introduces delay of $T/2$
- Finite computation time increases delay
References/Sources

• Servos:

• Stepper Motors:
  http://www.interq.or.jp/japan/se-inoue/e_step1.htm

• Electric Motors: