Actuators in robotics
Overview

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Courtesy to several authors of presentations on the web.
What is an actuator in robotics?

- A mechanical device for actively moving or driving something.

- Source of movement (drive), taxonomy:
  - Electric drive (motor).
  - Hydraulic drive.
  - Pneumatic drive.
  - Internal combustion, hybrids.
  - Miscellaneous: ion thruster, thermal shape memory effect, artificial muscles, etc.
Outline of the lecture

- Servomechanism.
- Electrical motor.
- Hydraulic drive.
- Pneumatic drive.
- Miscellaneous:
  - Artificial muscles.
Servomechanism

- Mechanism exploring feedback to deliver number of revolutions, position, etc.
- The controlled quantity is mechanical.

![Servomechanism Diagram]

- Desired value
  - Signal Processing & Amplification
  - Mechanism
    - Electric
    - Hydraulic Pneumatic
  - Final Actuation Element
    - Actuator
    - Sensor
Properties of a servo

- High maximum torque/force allows high (de)acceleration.
- Can be source of torque.
- High zero speed torque/force.
- High bandwidth provides accurate and fast control.
- Works in all four quadrants
- Robustness.
Rotary shaft encoder
Classification of Electric Motors

- **Electric motors**
  - **Alternating Current (AC) motors**
    - Asynchronous induction
      - Polyphase
      - Single phase
    - Synchronous
  - **Direct Current (DC) motors**
    - Separately excited
    - Self Excited
    - Permanent magnet
      - Series
      - Compound
      - Shunt
  - **Sinusoidal**
  - **Brushless DC**
  - **Stepper**
  - Another

Another...
DC motors

- **Field pole**
  - North pole and south pole
  - Receive electricity to form magnetic field

- **Armature**
  - Cylinder between the poles
  - Electromagnet when current goes through
  - Linked to drive shaft to drive the load

- **Commutator**

- **Overturns current direction in armature**

(Direct Industry, 1995)
How does a DC motor work?
DC motors, cont.

- Speed control without impact power supply quality
  - Changing armature voltage
  - Changing field current

- Restricted use
  - Few low/medium speed applications
  - Clean, non-hazardous areas

- Expensive compared to AC motors
DC motor, a view inside

- Simple, cheap.
- Easy to control.
- 1W - 1kW
- Can be overloaded.
- Brushes wear.
- Limited overloading on high speeds.
DC motor control

- Controller + H-bridge (allows motor to be driven in both directions).
- Pulse Width Modulation (PWM)-control.
- Speed control by controlling motor current=torque.
- Efficient small components.
- PID control.
DC motor modeling

\[ UI = Q + \tau\omega \]

\[ UI \approx I^2 R + \tau\omega \]
DC motor, shunt

- **Separately excited DC motor**: field current supplied from a separate force

- **Self-excited DC motor**: shunt motor

- Field winding parallel with armature winding
- Current = field current + armature current

(Rodwell Int. Corporation, 1999)

Speed constant independent of load up to certain torque

Speed control: insert resistance in armature or field current
DC motor: series motor

Self-excited DC motor: series motor

- Field winding in series with armature winding
- Field current = armature current

Suited for high starting torque: cranes, hoists

- Speed restricted to 5000 RPM
- Avoid running with no load: speed uncontrolled

(Rodwell Int. Corporation, 1999)
DC compound motor

Suites for high starting torque if high % compounding: cranes, hoists

Field winding in series and parallel with armature winding

Good torque and stable speed

Higher % compound in series = high starting torque
Digital control of DC motors

Pulse-Width-Modulated (PWM)

Sample Period

Output is average over sample period

Pulse-Rate-Modulated (PRM)

Constant pulse length

Output is average over all periods
AC motor

- Electrical current reverses direction
- Two parts: stator and rotor
  - Stator: stationary electrical component
  - Rotor: rotates the motor shaft
- Speed difficult to control because it depends on current frequency
- Two types
  - Synchronous motor
  - Induction motor
AC motor inventor

Nikola Tesla
AC synchronous motors

- Constant speed fixed by system frequency
- DC for excitation and low starting torque: suited for low load applications
- Can improve power factor: suited for high electricity use systems

Synchronous speed \((Ns)\):

\[
Ns = \frac{120 f}{P}
\]

\(f\) = supply frequency
\(P\) = number of poles
AC induction motor, components

- **Rotor**
  - Squirrel cage: conducting bars in parallel slots
  - Wound rotor: 3-phase, double-layer, distributed winding

- **Stator**
  - Stampings with slots to carry 3-phase windings
  - Wound for definite number of poles
How induction motors work?

- Electricity supplied to the stator.
- Magnetic field generated that moves around rotor.
- Current induced in rotor.
- Rotor produces second magnetic field that opposes stator magnetic field.
- Rotor begins to rotate.
AC induction motor, a view inside
AC induction motors, properties

Disadvantages:

- About 7x overload current at start.
- Needs a frequency changer for control.

Advantages:

- Simple design, cheap
- Easy to maintain
- Direct connection to AC power source

Advantages (cont):

- Self-starting.
- 0,5kW – 500kW.
- High power to weight ratio
- High efficiency: 50 – 95%
Induction motor, speed and slip

- Motor never runs at synchronous speed but lower “base speed”
- The difference is “slip”
- Install slip ring to avoid this
- Calculate % slip:

\[
\text{% Slip} = \frac{N_s - N_b}{N_s} \times 100
\]

Ns = synchronous speed in RPM
Nb = base speed in RPM
AC Induction motor load, speed, torque relationship

At start: high current and low “pull-up” torque

At 80% of full speed: highest “pull-out” torque and current drops

At full speed: torque and stator current are zero
Delta $\Delta$ – star $Y$

- Inter-phase (L-L) voltage 400 V.
- The inrush current can be too large (~7 times the nominal current).
- Phase-ground (L-N) voltage 230 V.
- $Y\Delta$ starting reduces the inrush current.

Courtesy: Ivo Novák, images
Single phase induction motor

- One stator winding.
- Single-phase power supply.
- Squirrel cage rotor.
- Use several tricks to start, then transition to an induction motor behavior.
- Up to 3 kW applications.
- Household appliances: fans, washing machines, dryers, airconditioners.
- Lower efficiency: 25 – 60 %
- Often low starting torque.
Single-phase induction motor

- Three-phase motors produce a rotating magnetic field.
- When only single-phase power is available, the rotating magnetic field must be produced using other means.
- Two methods to create the rotating magnetic field are usually used:
  1. Shaded-pole motor.
  2. Split-phase motor.
Ad 1. Shaded-pole motor

- A small squirrel-cage motor with an auxiliary winding composed of a copper ring or bar.
- Current induced in this coil induce a 2\textsuperscript{nd} phase of magnetic flux.
- Phase angle is small $\Rightarrow$ only a small starting torque compared to torque at full speed.

- Used in small appliances as electric fans, drain pumps of a washing machine, dishwashers.
Ad 2. Split-phase motor (1)

- Has a startup winding separate from the main winding. Fewer turns of smaller wire than the main winding, so it has a lower inductance (L) and higher resistance (R).
- The lower L/R ratio creates a small phase shift, not more than about 30 degrees.
- At start, the startup winding is connected to the power source via a centrifugal switch, which is closed at low speed.
- The starting direction of rotation is given by the order of the connections of the startup winding relative to the running winding.
Once the motor reaches near operating speed, the centrifugal switch opens, disconnecting the startup winding from the power source.

The motor then operates solely on the main winding.

The purpose of disconnecting the startup winding is to eliminate the energy loss due to its high resistance.

Commonly used in major appliances such as air conditioners and clothes dryers.
A capacitor start motor is a split-phase induction motor with a starting capacitor inserted in series with the startup winding.

An LC circuit produces a greater phase shift (and so, a much greater starting torque) than a split-phase motor.
Voice coil motor

- The name comes from the original use in loudspeakers.
- Either moving coil or moving magnet.
- Used for proportional or tight servomechanisms, where the speed is of importance.
- E.g. in a computer disc drive, gimbal or other oscillatory applications.
Linear electric motors

- There are some true linear magnetic drives.
  - BEI-Kimco voice coils:
    - Up to 30 cm travel
    - 100 lbf
    - > 10 g acceleration
    - 2.5 kg weight
    - 500 Hz corner frequency.

- Used for precision vibration control.
Tubular linear motor
Force

- Peak: 744 - 1860 N
- Continuous: 137 - 276N

Maximum Velocity

- Up to 9.4 m/s

Feedback

- Built-in position sensor
- 1V pk-pk sin/cos
- 25 micron repeatability

Range of motion

- Travel lengths up tp 1362 mm

Dimensions

- W x H: 70 x 122mm
- Rod diameter: 38mm

ServoTube delivers the speed of a belt-drive system with the clean reliability of a linear forcer at a price unprecedented in the industry. Familiar form factor, integral position feedback and large air gap make installation simple.

The ServoTube forcer components consist of an IP67 rated forcer and a sealed stainless steel thrust rod enclosing rare-earth magnets. Four models deliver a continuous force range of 137–276 N (31–62 lb) with peak forces up to 1860 N (418 lb). A ServoTube is an ideal OEM solution for easy integration into pick-and-place gantries and general purpose handling machines. The load is mounted directly to the forcer typically supported by a single bearing rail. The Thrust Rod is mounted at both ends, similar to a ballscrew. A large air gap reduces alignment constraints.

The tubular forcer has superior thermal efficiency, radiating heat uniformly. High duty cycles are possible without the need for forced-air or water cooling.
Stepper Motors

- A sequence of (3 or more) poles is activated in turn, moving the stator in small “steps”.
- Very low speed / high angular precision is possible without reduction gearing by using many rotor teeth.
- Can also perform a “microstep” by activating both coils at once.
Driving stepper motors

- Signals to the stepper motor are binary, on-off values (not PWM).
- In principle easy: activate poles as A B C D A ... or A D C B A ... Steps are fixed size, so no need to sense the angle! (open loop control).
- In practice, acceleration and possibly jerk must be bounded, otherwise motor will not keep up and will start missing steps (causing position errors).
- Driver electronics must simulate inertia of the motor.
Stepper Motor Selection

- Permanent Magnet / Variable Reluctance
- Unipolar vs. Bipolar
- Number of Stacks
- Number of Phases
- Degrees Per Step
- Microstepping
- Pull-In/Pull-Out Torque
- Detent Torque
Brushless DC electric motor

- A brushless DC motor (BLDC) is a permanent magnet synchronous electric motor.
- Position and speed sensor, usually Hall-effect sensor, needed for electronic control.
- Video explaining the principle.
Hydraulic actuators

- Linear movement.
- Big forces without gears.
- Actuators are simple.
- Used often in mobile machines.
- Bad efficiency.
- Motor, pump, actuator combination is lighter than motor, generator, battery, motor & gear combination.
Hydraulic actuators, examples
Hydraulic pump (1)

- **Gear pump**
  - Lowest efficiency ~ 90%

- **Rotary vane pump**
  - Mid-pressure ~ 180 bars
Hydraulic pump (2)

- Archimedes screw pump
- Bent axis pump
Hydraulic pump (3)

- Axial piston pumps, swashplate principle
- Radial piston pump
  High pressure (~ 650 bar)
  Small flows.
Hydraulic cylinder
Vane motor
Gear motor
Semi-rotary piston motor

300 degrees
Large torque at low speed.

180 degrees
Doubles the torque.
Radial piston motor

High starting torque
Real hydraulic motor
Pneumatic actuators

- Like hydraulic except power from compressed air.

- Advantages:
  - Fast on/off type tasks.
  - Big forces with elasticity.
  - No hydraulic oil leak problems.

- Disadvantage:
  - Speed control is not possible because the air pressure depends on many variables that are out of control.
Other Actuators

- Piezoelectric.
- Magnetic.
- Ultrasound.
- Shape Memory Alloys (SMA).
- Inertial.
Examples
Muscles

- Muscles contract when activated.
- Muscles are also attached to bones on two sides of a joint. The longitudinal shortening produces joint rotation.
- Bilateral motion requires pairs of muscles attached on opposite sides of a joint are required.
Muscles inside

- Muscles consist of long slender cells (fibres), each of which is a bundle of finer fibrils.
- Within each fibril are relatively thick filaments of the protein myosin and thin ones of actin and other proteins.
- Tension in active muscles is produced by cross bridges.
Artificial muscles, properties

- **Mechanical properties**: elastic modulus, tensile strength, stress-strain, fatigue life, thermal and electrical conductivity.
- **Thermodynamic issues**: efficiency, power and force density, power limits.
- **Packaging**: power supply/delivery, device construction, manufacturing, control, integration.
Artificial muscles, technology 1

1. Traditional mechatronic muscles, e.g. pneumatic.
2. Shape memory alloys, e.g. NiTi.
3. Chemical polymers - gels (Jello, vitreous humor)
   - 1000-fold volume change ~ temp, pH, electric fields. Force up to 100 N/cm².
   - 25 μm fiber → 1 Hz, 1 cm fiber → 1 cycle/2.5 days.
4. Electro active polymers
   - Store electrons in large molecules. Deformation ~ (voltage)².
   - Change length of chemical bonds.
5. **Biological Muscle Proteins**
   - Actin and myosin.
   - 0.001 mm/sec in a petri dish.

6. **Fullerenes and Nanotubes**
   - Graphitic carbon.
   - High elastic modulus $\rightarrow$ large displacements, large forces.
   - Macro-, micro-, and nano-scale
   - Potentially superior to biological muscle.
Pneumatic artificial muscle

- Called also McKibben muscle.
- In development since 1950s.
- Contractile or extensional devices operated by pressurized air filling a pneumatic bladder.
- Very lightweight, based on a thin membrane.
- Current top implementation: Shadow hand.
Artificial Muscles: McKibben Type

- (Brooks, 1977) developed an artificial muscle for control of the arms of the humanoid torso Cog.
- (Pratt and Williamson 1995) developed artificial muscles for control of leg movements in a biped walking robot.
Shape memory alloys 1

- Nickel Titanium – *Nitinol*.
- Crystallographic phase transformation from Martesite to Austenite.
- Contract 5-7% of length when heated - 100 times greater effect than thermal expansion.
- Relatively high forces.
- About 1 Hz.
- Structural fatigue – a failure mode caused by which cyclic loading which results in catastrophic fraction.
Robot Lobster, an example

- A robot lobster developed at Northeastern University used SMAs very cleverly
- The force levels required for the lobster’s legs are not excessive for SMAs
- Because the robot is used underwater cooling is supplied naturally by seawater

More on the robot lobster is available at: http://www.neurotechnology.neu.edu
Artificial Muscles: Electroactive Polymers

- Like SMAs, Electroactive Polymers (EAPs) also change their shape when electrically stimulated.
- The advantages of EAPs for robotics are that they are able to emulate biological muscles with a high degree of toughness, large actuation strain, and inherent vibration damping.
- Unfortunately, the force actuation and mechanical energy density of EAPs are relatively low.
Electroactive Polymer Example

Robotic face developed by a group led by David Hanson. More information is available at: www.hansonrobotics.com