01.110: Computational Fabrication

Week 5: Actuators

Hassan Hariri

+65 8401 0454
Hassan_hariri@sutd.edu.sg

SINGAPORE UNIVERSITY OF TECHNOLOGY AND DESIGN

Established in collaboration with MIT

Overview

- What is a classical actuator?
- Soft Actuators for Small-Scale Robotics
- Smart actuators

Overview

- What is a classical actuator?
  - Rotational Actuators
    - AC Motors
    - DC Motors
    - Geared DC Motors
    - R/C Servo Motors
    - Industrial Servo Motors
    - Stepper Motors
  - Linear Actuators
    - DC Linear Actuator
    - Solenoids
    - Muscle wire
    - Pneumatic and Hydraulic
  - Choosing an Actuator
    - Is the actuator being used to move a wheeled robot?
    - Is the motor being used to lift or turn a heavy weight?
    - Is the range of motion limited to 180 degrees?
    - Does the angle need to be very precise?
    - Is the motion in a straight line?
  - Practical Examples
- Soft Actuators for Small-Scale Robotics
  - Examples of small soft robotic systems
  - Important factors to take into consideration when choosing a soft actuator
  - Selection of soft materials and their demonstrated actuation stimuli
- Smart actuators
  - Actuator material classes
  - Why Using Smart Materials in Micro/Nanopositioning

Overview

- What is a classical actuator?
  - Rotational Actuators
    - AC Motors
    - DC Motors
    - Geared DC Motors
    - R/C Servo Motors
    - Industrial Servo Motors
    - Stepper Motors
  - Linear Actuators
    - DC Linear Actuator
    - Solenoids
    - Muscle wire
    - Pneumatic and Hydraulic
  - Choosing an Actuator
    - Is the actuator being used to move a wheeled robot?
    - Is the motor being used to lift or turn a heavy weight?
    - Is the range of motion limited to 180 degrees?
    - Does the angle need to be very precise?
    - Is the motion in a straight line?
  - Practical Examples
- Soft Actuators for Small-Scale Robotics
  - Examples of small soft robotic systems
  - Important factors to take into consideration when choosing a soft actuator
  - Selection of soft materials and their demonstrated actuation stimuli
- Smart actuators
  - Actuator material classes
  - Why Using Smart Materials in Micro/Nanopositioning

What is a classical actuator?

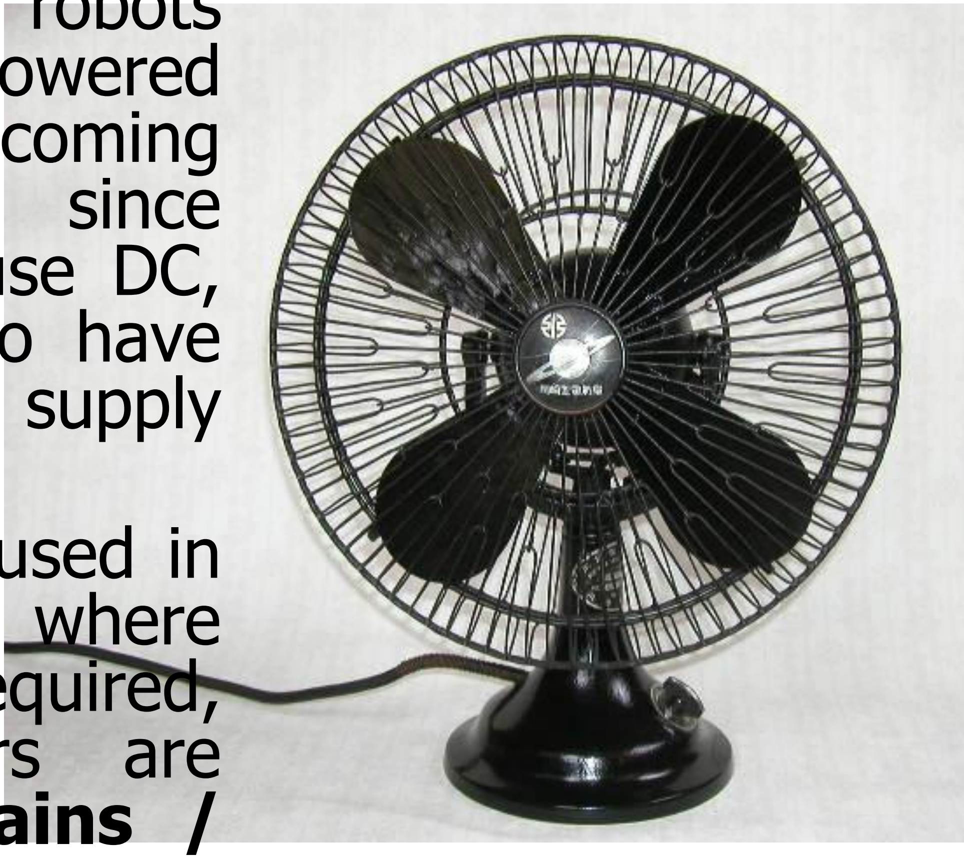
- An "**actuator**" can be defined as a device that converts energy (in robotics, that energy tends to be electrical) into physical motion.
- The vast majority of classical actuators produce either **rotational or linear motion**. For instance, a "DC motor" is therefore a type of actuator.
- **Choosing the right actuators** for your robot requires an understanding of what actuators are available, some imagination, and a bit of math and physics.

Rotational Actuators

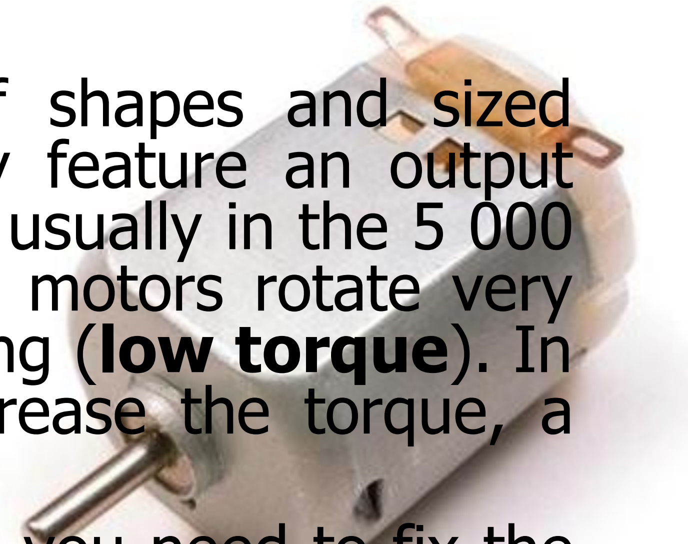
- As the name indicates, this type of actuators transform electrical energy into a **rotating motion**.
- There are two main mechanical parameters distinguishing them from one another:
  - **torque**, the force they can produce at a given distance (usually expressed in N•m or Oz•in),
  - and the **rotational speed** (usually measured in revolutions per minutes, or rpm).

Rotational Actuators-AC Motors

- **AC (alternating current)** is rarely used in mobile robots since most of them are powered with direct current (DC) coming from batteries. Also, since electronic components use DC, it is more convenient to have the same type of power supply for the actuators as well.
- **AC motors** are mainly used in industrial environments where **very high torque** is required, or where the motors are **connected to the mains / wall outlet**.



Rotational Actuators-DC Motors



- **DC motors** come in a variety of shapes and sized although most are cylindrical. They feature an output shaft which rotates at **high speeds** usually in the 5 000 to 10 000 rpm range. Although DC motors rotate very quickly in general, most are not strong (**low torque**). In order to reduce the speed and increase the torque, a **gear can be added**.
- To incorporate a motor into a robot, you need to fix the body of the motor to the frame of the robot. For this reason motors often feature **mounting holes** which are generally located on the face of the motor so they can be mounted perpendicularly to a surface. DC motors can operate in **clockwise** (CW) and **counter clockwise** (CCW) rotation. The **angular motion** of the turning shaft can be measured using **encoders or potentiometers**

Rotational Actuators-Geared DC Motors

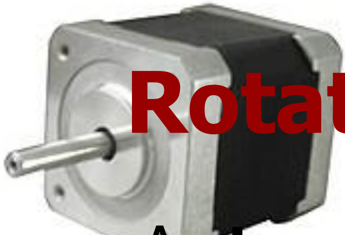
- A **DC gear motor** is a DC motor combined with a **gearbox** that works to decrease the motor's speed and increase the torque. For example, if a DC motor rotates at 10 000 rpm and produces 0.001 N•m of torque, adding a 256:1 ("two hundred and fifty six to one") **gear down** would reduce the speed by a factor of 256 (resulting in 10 000rpm / 256 = 39 rpm), and increase the torque by a factor of 256 (0.001 x 256 = 0.256 N•m).
- The most common types of gearing are "**spur**" (the most common), "**planetary**" (more complex but allows for higher gear-downs in a more confined space, as well as higher efficiency) and "**worm**" (which allows for very high gear ratio with just a single stage, and also prevents the output shaft from moving if the motor is not powered). Just like a DC motor, a DC gear motor can also rotate CW and CCW. If you need to know the number of rotations of the motor, an "encoder" can be added to the shaft.

Rotational Actuators-R/C Servo Motors

- **R/C (or hobby) servo motors** are types of actuators that **rotate to a specific angular position**, and were classically used in more expensive remote controlled vehicles for steering or controlling flight surfaces. Now that they are used in a variety of applications, **the price** of hobby servos **has gone** down significantly, and the variety (different sizes, technologies, and strength) has increased.
- The common factor to most servos is that **the majority only rotate about 180 degrees**. A hobby servo motor actually **includes a DC motor, gearing, electronics and a rotary potentiometer** (which, in essence, measures the angle). The electronics and potentiometer work in unison to **activate the motor and stop the output shaft at a specified angle**. These servos are generally have three wires: **ground, voltage in, and a control pulse**. The control pulse is usually generated with a servo motor controller. A "**robot servo**" is a new type of servo that offers **both continuous rotation and position feedback**. All servos can rotate CW and CCW.

Rotational Actuators-Industrial Servo Motors

- An **industrial servo** motor is controlled differently than a hobby servo motor and is more commonly found on **very large machines**. An industrial servo motor is usually made up of a **large AC** (sometimes three-phase) **motor**, **a gear down** and an **encoder** which provides feedback about angular position and speed. These motors are rarely used in mobile robots because of their weight, size, cost and complexity. You might find an industrial servo in a more powerful industrial robotic arm or **very large robotic vehicles**.



Rotational Actuators-Stepper Motors

- A **stepper motor** does exactly as its name implies; it rotates in specified "**steps**" (actually, specific degrees). The number of degrees the shaft rotates with each step (**step size**) varies based on several factors. Most stepper motors do not include gearing, so just like a DC motor, the **torque is often low**. Configured properly, a stepper can rotate CW and CCW and can be moved to a desired angular position. There are unipolar and bipolar stepper motor types. One notable downside to stepper motors is that if the motor is not powered, **it's difficult to be certain of the motor's starting angle**.
- **Adding gears** to a stepper motor has the same effect as a adding gears to a DC motors: it increases the torque and decreases the output angular speed. Since the speed is reduced by the gear ratio, the step size is also reduced by that same factor. If the non geared down stepper motor had a step size of 1.2 degrees, and you add a gear down of 55:1, the new step size would be 1.2 / 55 = 0.0218 degrees.

Linear Actuators

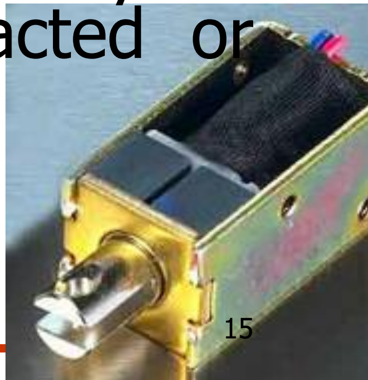
- A **linear actuator** produces linear motion (motion along one straight line) and have three main distinguishing mechanical characteristics: the **stroke** (the minimum and maximum distance the rod can move), in mm or inches), their **force** (in Kg or lbs), and their **speed** (in m/s or inch/s).

Linear Actuators-DC Linear Actuator

- A **DC linear actuator** is often made up of a **DC motor** connected to a **lead screw**. As the motor turns, so does the lead screw. A traveller on the lead screw is forced either towards or away from the motor, essentially **converting the rotating motion to a linear motion**.
- Some DC linear actuators incorporate a **linear potentiometer** which provides linear position feedback. In order to stop the actuator from destroying itself, many manufacturers include **limit switches** at either end which cuts power to the actuator when pressed. DC linear actuators come in a wide variety of sizes, strokes and forces.

Linear Actuators-Solenoids

- **Solenoids** are composed of a **coil wound** around a **mobile core**. When the coil is energized, the core is pushed away from the magnetic field and produces a motion in a single direction. Multiple coils or some mechanical arrangements would be required in order to provide a motion in two directions.
- A **solenoid's stroke** is usually **very small** but their **speed is very fast**. **The strength depends mainly on the coil size and the current going trough it**. This type of actuator is commonly used in valves or latching systems and there is usually **no position feedback** (it's either fully retracted or fully extended).



Linear Actuators-Muscle wire

- **Muscle wire** is a special type of wire that will **contract when an electric current traverses it**. **Once the current is gone** (and the wire cools down) **it returns to its original length**.
- This type of actuator is **not very strong, fast or provides a long stroke**. Nevertheless, it is **very convenient when working with very small parts or in a very confined space**.

Linear Actuators-Pneumatic and Hydraulic

- **Pneumatic and hydraulic actuators** use **air or a liquid** (e.g. water or oil) respectively in order to produce a **linear motion.** These types of actuators can have **very long strokes**, **high force and high speed**.
- In order to be operated they require the use of a **fluid compressor** which makes them more difficult to operate than regular electrical actuators. Because of they high force, speed and generally **large size**, they are mainly **used in industrial environments**.

Choosing a classical actuator

- Is the actuator being used to move a wheeled robot?
  - Drive motors must move the weight of the entire robot and will most likely require a gear down. Most robots use "skid steering" while cars or trucks tend to use rack-and-pinion steering. If you choose skid steering, DC gear motors are the ideal choice for robots with wheels or tracks as they provide continuous rotation, and can have optional position feedback using optical encoders and are very easy to program and use. If you want to use rack-and-pinion, you will need one drive motor (DC gear is also suggested) and one motor to steer the front wheels). For stirring, since the rotation required is restricted to a specific angle, an R/C servo would be the logical choice.

Choosing a classical actuator

- Is the motor being used to lift or turn a heavy weight?
  - Lifting a weight requires significantly more power than moving a weight on a flat surface. Speed must be sacrificed in order to gain torque and it is best to use a gearbox with a high gear ratio and powerful DC motor or a DC linear actuator. Consider using system (either with worm gears, or clamps) that prevents the mass from falling in case of a power loss.

Choosing a classical actuator

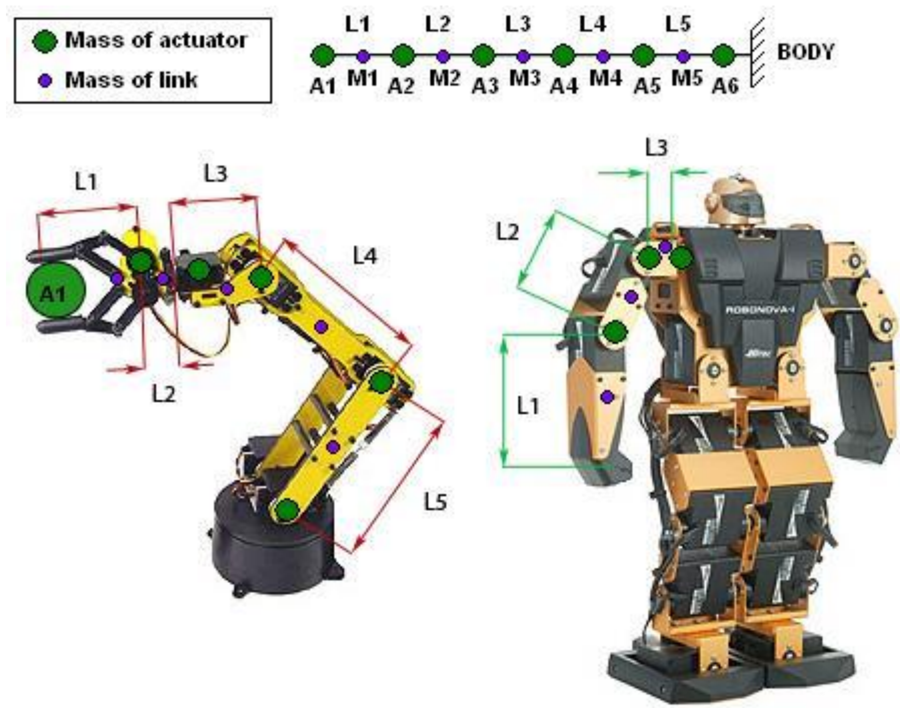
- Is the range of motion limited to 180 degrees?
  - Stepper motors and geared stepper motors (coupled with a stepper motor controller) can offer very precise angular motion. They are sometimes preferred to servo motors because they offer continuous rotation. However, some high-end digital servo motors use optical encoders and can offer very high precision.

Choosing a classical actuator

- Is the motion in a straight line?
  - Linear actuators are best for moving objects and positioning them along a straight line. They come in a variety of sizes and configurations. Muscle wire should be considered only if your motion requires very little force. For very fast motion, consider pneumatics or solenoids, and for very high forces, consider DC linear actuators (up to about 500 pounds) and then hydraulics.

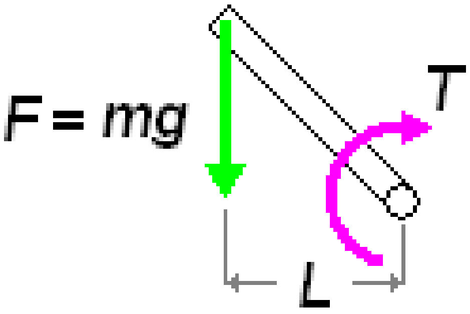
Practical examples-Robot Arm Torque

- To help you choose the right motor for each joint of your robotic arm
  - **L**: length from pivot to pivot.
  - **M**: link mass
  - **A**: Actuator (servo or other) mass. Note: same units as for link masses.
  - **A1**: can represent the load being lifted.



Practical examples-Robot Arm Torque

- The torque required to hold a mass at a given distance from a pivot is



$$\sum T = 0 = F * L - T$$

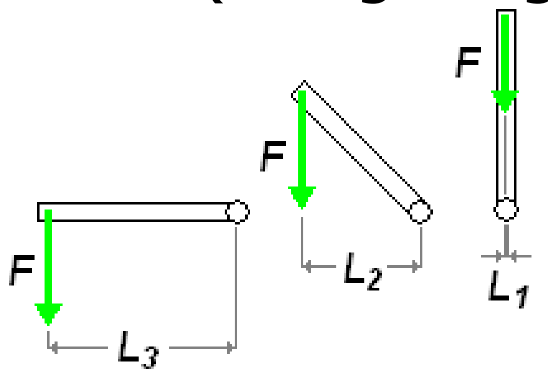
$$T = (m * g) * L$$

- The force above is also considered the object's weight (W):

$$W = m * g$$

Practical examples-Robot Arm Torque

- The torque (T) required at each joint is calculated as a worst case scenario (lifting weight at 90 degrees)

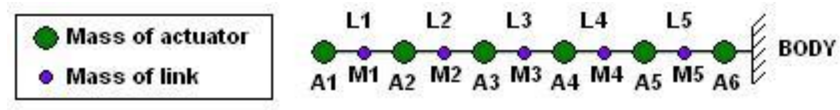


- It can be safe to assume that the actuators in the arm will be subjected to the highest torque when the arm is stretched horizontally. Although your robot may never be designed to encounter this scenario, it should not fail under its own weight if stretched horizontally without a load.

Practical examples-Robot Arm Torque

- The torque required by actuator A2

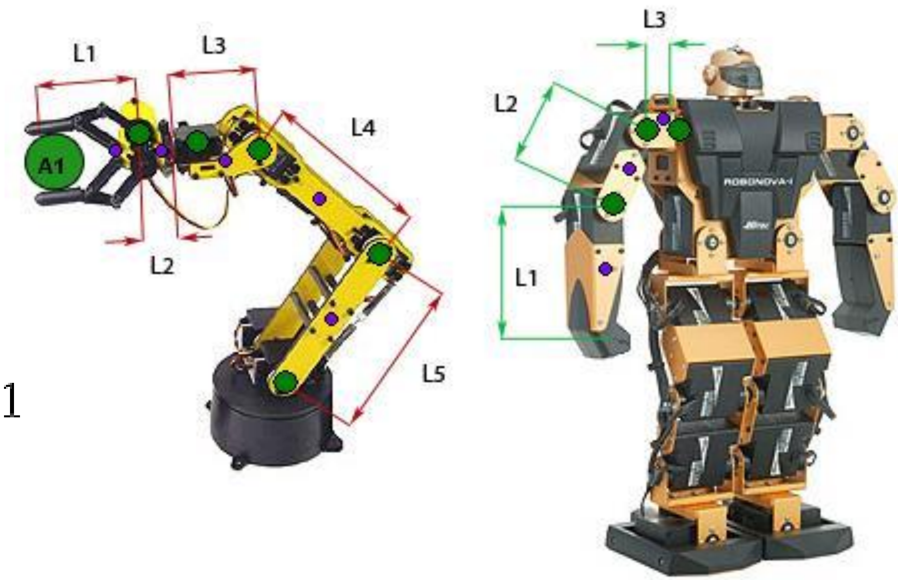
$$T1 = L1 * A1 + \frac{1}{2} L1 * W1$$



- The torque required by actuator A3:

$$T2 = (L1 + L2) * A1 + (\frac{1}{2} L1 + L2) * W1$$

$$+ (L2) * A2 + (\frac{1}{2} L2) * W2$$



- The torques at each subsequent joint can be found similarly, by re-calculating the lengths between each weight and each new pivot point.

Practical examples-Robot Arm Torque

- Note: if any of the joints have two or more motors, they share the torque required evenly. Because the base of the arm is subjected to the highest torque, often two actuators are used instead of one.

Practical examples-Robot Arm Torque

- More advanced: The above equations only deal with the case where the robot arm is being held horizontally (not in motion). This is not necessarily the "worst case" scenario. For the arm to move from a rest position, an acceleration is required. To solve for this added torque, it is known that the sum of torques acting at a pivot point is equal to the moment of inertia (I) multiplied by the angular acceleration (alpha):

$$T = I * \alpha$$

- To calculate the extra torque required to move (i.e. create an angular acceleration) you would calculate the moment of inertia of the part from the end to the pivot using the equation:

$$I = \frac{m * r^2}{2}$$

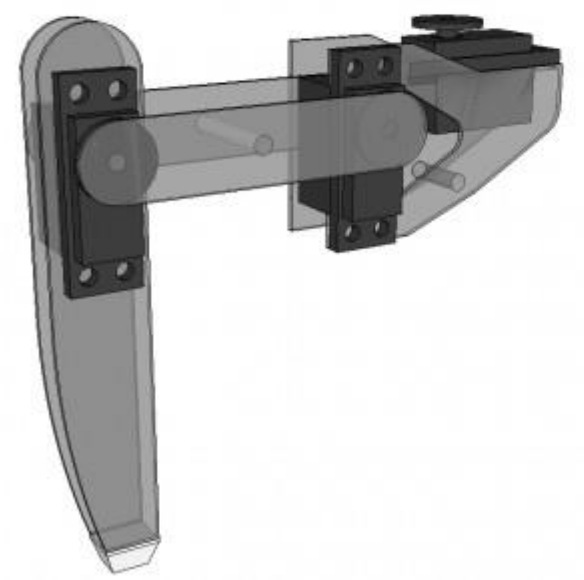
- Note:
  - this equation calculates the moment of inertia about the center of mass (m is the total mass and r is the distance from the center of mass to the pivot).
  - This equation is not universal but rather varies from part to part (hollow vs. solid bar, cylindrical vs. rectangular cross-section etc.). The moment of inertia also differs depending on which axis is considered (Ixx, Iyy, Izz can all be different)

Practical examples-Robot Arm Torque

- Since the moment of inertia varies tremendously from part to part, angular acceleration is not taken into consideration with the Robot Arm Torque. Instead, to correct for possible angular acceleration, a “**safety factor**” is used and set to 2 by default. As with all dynamic tools, inefficiencies in the actuators and joints themselves must also be taken into consideration. This way, the motor at each joint will be able to provide more than the required torque to keep the arm stationary.

Practical examples-Robot Leg Torque

- To find the torques acting at each degree of freedom of a 6-legged (hexapod), 3DOF / leg "insect" robotic leg.



- Home Activity

(optional practice)

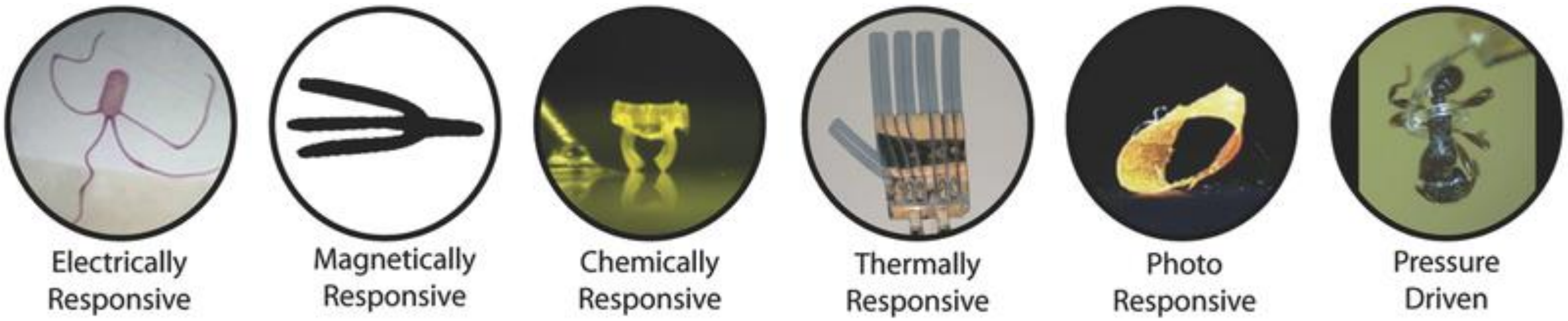
Overview

- What is a classical actuator?
  - Rotational Actuators
    - AC Motors
    - DC Motors
    - Geared DC Motors
    - R/C Servo Motors
    - Industrial Servo Motors
    - Stepper Motors
  - Linear Actuators
    - DC Linear Actuator
    - Solenoids
    - Muscle wire
    - Pneumatic and Hydraulic
  - Choosing an Actuator
    - Is the actuator being used to move a wheeled robot?
    - Is the motor being used to lift or turn a heavy weight?
    - Is the range of motion limited to 180 degrees?
    - Does the angle need to be very precise?
    - Is the motion in a straight line?
  - Practical Examples
- Soft Actuators for Small-Scale Robotics
  - Examples of small soft robotic systems
  - Important factors to take into consideration when choosing a soft actuator
  - Selection of soft materials and their demonstrated actuation stimuli
- Smart actuators
  - Actuator material classes
  - Why Using Smart Materials in Micro/Nanopositioning

Soft Actuators for Small-Scale Robotics

- **Soft robots** present a special design challenge in that their actuation and sensing mechanisms are often highly integrated with the robot body and overall functionality.
- When less than a centimeter, they belong to an even more special subcategory of robots or devices, in that they often lack on-board power, sensing, computation, and control.
- **Soft, active materials** /or so called **soft actuators** are particularly well suited for this task.

Examples of small soft robotic systems



- Actuated with various stimuli. Systems include swimmers, jumpers, rollers, and manipulators.

Important factors to take into consideration when choosing a soft actuator

- Actuation strain and force production
- Operating environment (in solution, air, etc.)
- Size scale
- Remote or tethered power source
- Resistance to other stimuli
- Yield stress
- Power consumption
- Durability and fatigue resistance
- Actuation speed and response time
- Self-healing properties
- Biocompatibility
- Hysteresis (and material viscoelasticity)
- Biodegradability
- Anisotropy

Selection of soft materials and their demonstrated actuation stimuli

	Electric field	Magnetic field	Pressure differential	Heat (electro-, photothermal, etc.)	Light	Chemical (solvent, water, pH, etc.)
Polymers and gels	×	×	×	×	×	×
• Conductive polymers	×					
• Liquid-crystal polymers (LCPs), polymer networks (LCNs), elastomers (LCEs)	×			×	×	×
• Ionic-polymer–metal composites (IPMCs)	×					
• Dielectric elastomer actuators (DEAs)	×					
• Shape-memory polymers				×	×	×
• Hygromorphic polymers				×		×
• Ferrogels and ferroelastomers		×				
• Hydrogels	×	×	×	×	×	×
Fluids	×	×	×	×	×	×
• Electrorheological fluid (ERFs)	×					
• Magnetorhoelogical fluids (MRFs)		×				
• Ferrofluids		×				
• Dielectric fluids (electroconjugate fluids (ECFs))	×					
• Liquid metals	×	×		×	×	×
• Liquid marbles	×	×			×	×
Paper (cellulose)	×	×		×		×
Carbon	×		×	×		
• Carbon nanotube (CNT) sheets, yarn	×		×	×		
• CNT aerogel	×					

Overview

- What is a classical actuator?
  - Rotational Actuators
    - AC Motors
    - DC Motors
    - Geared DC Motors
    - R/C Servo Motors
    - Industrial Servo Motors
    - Stepper Motors
  - Linear Actuators
    - DC Linear Actuator
    - Solenoids
    - Muscle wire
    - Pneumatic and Hydraulic
  - Choosing an Actuator
    - Is the actuator being used to move a wheeled robot?
    - Is the motor being used to lift or turn a heavy weight?
    - Is the range of motion limited to 180 degrees?
    - Does the angle need to be very precise?
    - Is the motion in a straight line?
  - Practical Examples
- Soft Actuators for Small-Scale Robotics
  - Examples of small soft robotic systems
  - Important factors to take into consideration when choosing a soft actuator
  - Selection of soft materials and their demonstrated actuation stimuli
- Smart actuators
  - Actuator material classes
  - Why Using Smart Materials in Micro/Nanopositioning

Smart actuators

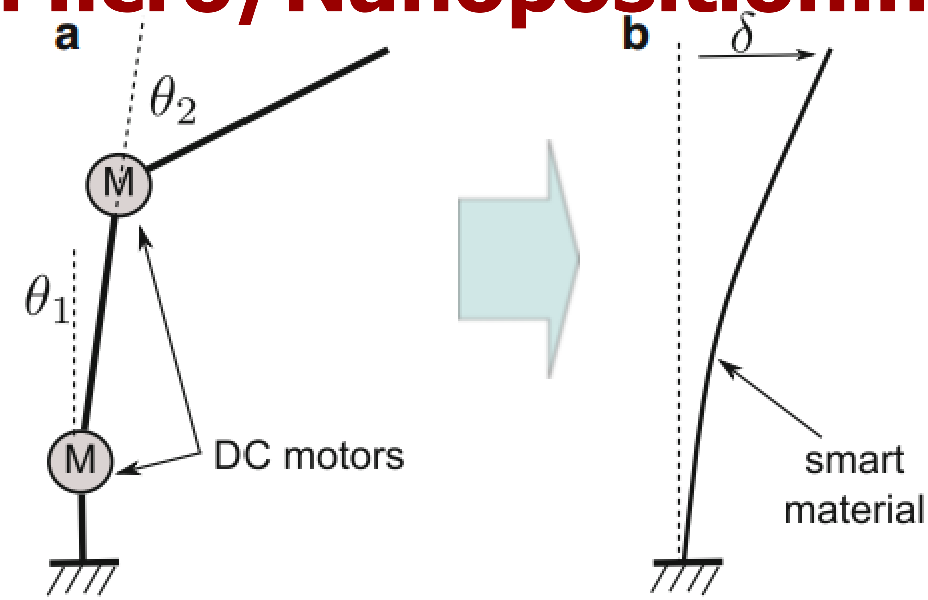
- In 1824, Rochelle salt was discovered to become electrically polarized by the application of heat (sensing capability). That was the first discovery of the effect known as pyroelectricity. Since that time, numerous additional materials have been discovered having the inherent capability to convert one form of energy into another.
- **Smart actuators** are materials that respond to a stimulus in the form of a mechanical property change such as a dimensional or a viscosity change.

Actuator material classes

Actuators

Material Class	Stimulus	Response
Piezoelectrics	Electric Current	Mechanical Strain
Electrostrictors	Electric Current	Mechanical Strain
Magnetostrictors	Magnetic/Electric Field	Mechanical Strain
Shape Memory Alloys	Temperature Change	Mechanical Strain
Electroactive Polymers	Electric Field/pH change	Mechanical Strain
Electrorheological Fluids	Electric Field	Viscosity Change
Magnetorheological Fluids	Magnetic Field	Viscosity Change

Why Using Smart Materials in Micro/Nanopositioning



The main idea is that, instead of using several assembled components (actuators and articulations), one employs smart materials, i.e. materials that react and that can generate motion when excited electrically, magnetically, thermally, etc. Indeed, it is possible to replace an actuator and related articulations by utilizing the same bulk of smart material which consequently **removes many limitations**.

Why Using Smart Materials in Micro/Nanopositioning

- The limitations of using several assembled components (actuators and articulations) at the micro-scale:
  - The available space in an atomic force microscopy (AFM) is very reduced and could not welcome an actuator based on DC motor to position the sample of material to be scanned.
  - Using a “macro” robot to precisely position a biological cell would require many electrical power and it would be more convenient to position the same object with lower power consumption systems such as smaller robot.
  - The mechanical clearances found in the articulations yield a limited resolution of positioning. This limited resolution is not often adapted to the resolution required in nanopositioning.
  - The fact that “macro” systems are based on the assembly of different components, they have minimal sizes that are irreducible to be convenient with the available space in micro.

References

- Materials that sense and respond: an introduction to smart materials, Richard Lane and Benjamin Craig: AMPTIAC Technical Staff, Rome, NY
- Soft Actuators for Small-Scale Robotics, Advanced materials news
- Literature review of Smart Materials /Actuators / Sensors in the Design of Smart flexible life saving Robots
- https://www.robots.com/education/actuators
- http://www.robotshop.com/

QUESTIONS?