2.12 INTRODUCTION TO ROBOTICS
LECTURE I - ACTUATORS AND DRIVES
(by Alberto Rodriguez)

→ Actuators and drives are one of the fundamental building blocks of robotic systems.

→ Today we will talk about the most basic type of robot, the SINGLE AXIS DRIVE SYSTEM.

→ We can abstract the basic question of robotics as:

"How do we transform power into controlled behavior of a load?"

In practice:

PC -> MICROCONTROLLER (Arduino) -> DC Motor + Encoder -> LOAD

This is what you will do in lab 4 this week.
ACTUATOR

- They come in many, many types, and design for different sources of power (pneumatic, hydraulic, electric, piezoelectric, ...)

- The most common in robotics is the electric motor, and among these, the DC MOTOR is the King.

- The DC MOTOR converts: direct current → mechanical rotation.

**Basic Principle:**

\[ \mathbf{F} = q \mathbf{E} + q \mathbf{v} \times \mathbf{B} \]

- The loop wants to rotate when there is a current passing through. (at least for 180°)

- Motors use curved magnets for more effective magnetic field
- More winding → more torque
- Commutation: to get a full rotation it is necessary to switch the direction of the current.

  → Mechanically with brushes → BRUSHED DC MOTOR.
  → Electronically → BRUSHLESS " ".

**Basic components:**

- **STATOR** (Magnet + Armor)
- **ROTOR** (Cables)
- **COMMUTATOR**
- **BRUSHES**
- **SHAFT**
Model:

- The first characteristic relationship: $\tau_m = K_t \cdot i$ (from Lorentz law)

  $K_t$ is TORQUE CONSTANT, depends on:
  - strength of magnetic field.
  - number of windings.
  - radius of motor.
  - material properties.

- We are also interested in the output motor velocity $(w_m)$.

  Output power $P_{out} = \tau_m \cdot w_m$ (mechanical)

  Input power $P_{in} = E \cdot i$ (electrical)

  Voltage drop $\Delta V$

  For a LOSSLESS TRANSUDER: $P_{in} = P_{out}$

  $\tau_m \cdot w_m = E \cdot i \rightarrow E = K_t \cdot w_m$

  $P_{in} = P_{out}$

  Ideal Transducer

  Electrical Power

  Torque, $\tau_m$

  Angular, $w_m$

  Velocity

  NOTE: Power is the rate at which a system produces work

  $P = \frac{dW}{dt} = \frac{d}{dt} \int_{C} F \cdot dr = \frac{d}{dt} \int_{C} F \cdot v \, dt = F \cdot v$ (or $\tau \cdot \omega$ in the case of rotational motion)

  $P = \frac{dW}{dt} = v \cdot \Delta \text{charge} = v \cdot \Delta i$
For a transducer with LOSSES:

There is resistance (energy loss) and inductance (energy storage) in the rotor windings and commutation mechanism.

\[ M = Ri + L \frac{di}{dt} + E \]
\[ \frac{dM}{dt} = R \frac{d}{dt} \left( \frac{2m}{k_t} \right) + K_e \omega_m \]
\[ 2m = \frac{K_e M - K_e^2 \omega_m}{R} + L \frac{d}{dt} \left( \frac{2m}{R} \right) \]

- Characteristic time called MOTOR REACTANCE
- Slows down transitions
- Often negligible for practical purposes

\[ T_e = \frac{L}{k_t} \]

Damping term:
- Same as before \[ \omega_m \]
- But now with a term that increases with speed: \[ \frac{d}{dt} \omega_m \]

The curve moves up with applied voltage.
- Tradeoff between speed and torque.
Motor efficiency:

\[ P_{\text{dissipated}} = R_i^2 = R \frac{z_m^2}{k_s^2} \rightarrow \sqrt{P_d} = \frac{\sqrt{R}}{k_s} \frac{z_m}{z_s} = z_m \cdot \frac{1}{K_m} \]

where \( K_m = \frac{k_s}{\sqrt{R}} \) we call MOTOR CONSTANT

→ and reflects how efficient is the motor at converting electric power into mechanical power.

→ We get larger \( K_m \) by:
  - using larger magnets, thicker windings
  - larger motor diameter

→ But damping becomes more significant

\[ P_{\text{out}} = z_m \cdot w_m = (\frac{k_s \cdot u - k_s^2 \cdot w_m}{R}) w_m \text{ which looks like:} \]

\[ P_{\text{max}} \]

\[ w_{\text{max}} = \frac{u}{k_s} \]

↑ most effective point of operation. ≈ 50% \( w_{\text{max}} \)

DYNAMICS AND CONTROL

→ So how do we effectively change the output velocity and torque?

GEARS for impedance matching. Electric motor: \( w_m \uparrow \rightarrow z_m \downarrow \)

Robotics worst: \( w_m \downarrow \rightarrow z_m \uparrow \uparrow \)

→ IMPEDANCE MOTOR

\[ z_m = \frac{z_m}{w_m} \]

\[ \text{Motor} \rightarrow \text{Load} \]

\[ z_m, w_m \]

\[ d_1, d_2 \]
GEAR REDUCTION \[ r = \frac{d2}{dn} \rightarrow \omega_e = \frac{1}{r} \omega_m, \quad z_e = r \cdot z_m \]

**Dynamics:**

Motor: \[ I_m \dot{\theta}_m = z_m - \frac{1}{r} z_{\text{load}} \]

Load: \[ I_e \dot{\theta}_e = z_{\text{load}} - b \omega_{\text{load}} \]

\[ I_m \ddot{\theta}_m = z_m - \frac{1}{r} (I_e \dot{\theta}_e + b \omega_{\text{load}}) \]

\[ r^2 I_m \ddot{\theta}_e + I_e \ddot{\theta}_e + b \dot{\theta}_e = z_m \cdot r = r \left( \frac{K_b m}{A} - \frac{K_e^2 \omega_m}{R} \right) \]

\[ (I_e + r^2 I_m) \ddot{\theta}_e + (b + r^2 K_e^2) \dot{\theta}_e = \frac{r K_b m}{R} \]

\[ I \dot{\theta}_{\text{load}} + B \dot{\theta}_{\text{load}} = K m \]

**NOTE:**

1) \( m \) is the control input
2) It is a dynamic system \( \rightarrow \) will need some level of control.
3) Equation is independent of \( \dot{\theta}_e \)
   \( \rightarrow \) But this is because we have not considered external forces (e.g., gravity, contact) which are essential to robotics.
4) The effective inertia of the motor is \( r^2 \) times larger on the load side
   \( r = 100 \rightarrow 10,000 \) larger effect
   \( \rightarrow \) We want motors with very small inertia.
POWER ELECTRONICS

→ How do we provide the desired control voltage?

1) Naive solution: Linear Amplifier

→ By controlling $V_{ce}$, we can control $u$, and isolate control from power

→ Problem: Very inefficient because of power dissipated at the transistor:

$$P_{loss} = (V - u) i = \frac{1}{R} (V - u) u$$

worst case, we lose $\frac{1}{2}$ power

• inefficient and damages the transistor.

• only used for very small motors.

2) PWM: The transistor is very efficient when operating at OV or $V$.

• Set it only to ON-OFF and provide the desired voltage in average.

Duty Cycle: $\frac{\text{ON} \cdot 100\%}{T}$

In this case 50%

NOTES: The bandwidth of a robot motion system is usually below 100Hz

→ We set $f_{pwm} \sim 2-20\, \text{kHz}$ so that it is not affected.
The residual inductance of the motor acts as a charge "BUFFER", or low-pass filter and smooth the PWM signal.

Fast PWM is:
- GOOD: Smooth motor behavior.
- BAD: Heat loss. In the transitions, the voltage still has to go from 0 → V → 0 → V ...

We use MOSFET Transistors
(fast switching 15-100KHz)
- Current spikes: \[ I = R \cdot I + L \frac{dI}{dt} + E \] at OFF
  Not negligible any more
- Use diodes for current protection.
- Electromagnetic interference specially with long wires.
- Integrate PWM generator in motor body.

H-BRIDGE (+ PWM)

Solution for bi-directional rotation

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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| ON  | OFF | OFF | ON  | FORWARD
| OFF | ON  | ON  | OFF | REVERSE
| OFF | ON  | OFF | OFF | FREE SPINNING
| OFF | OFF | OFF | ON  | BRAKING
|     |     |     | OFF | wear-free resistance |

V

A

B

C

D

E
SENSORS

→ We want to measure the position of the output shaft to close the loop in the controller.

1) POTENTIOMETERS (very rarely used)

→ Resistor that changes resistance with the angular position of the shaft.
→ Wear and noise due to mechanical contact.

2) MAGNETIC ENCODERS

→ Based on distance measurements with sensors that measure the intensity of the magnetic field. (HALL effect)
→ Absolute sensors.

3) OPTICAL ENCODERS (most common)

→ Digital signal → high SNR.
→ No mechanical contact → no wear or noise.

LED → Translucent disk.
(Light Emitting Diode)
PHOTO DETECTOR

→ When the pattern rotates it generates pulses.

→ How do we detect the direction of rotation?

Use two shifted tracks and two photo detectors

A: \[\text{Direction} \rightarrow \frac{1}{2}11111111 A \rightarrow \text{LEADS}\]
B: \[\text{Direction} \rightarrow \frac{1}{2}11111111 B \rightarrow \text{LEADS}\]
How do we recover absolute position?

A) Homing the sensor (RESET) + counting "ticks"

CALIBRATION

CHIP COUNTER

\[ \begin{array}{c}
A \\
B \\
\end{array} \rightarrow \text{n-bit count.} \\
\text{RESET}
\]

B) With more complicated patterns and more photo detectors.

E.g.