last time

Electrostatics \rightarrow negative spring constant

Tuning: good
Comb drives: can be bad

\[ F = \frac{1}{2} \varepsilon_0 V^2 A \left[ \frac{1}{(x_0 - x)^2} - \frac{1}{(x_0 + x)^2} \right] \]

\[ K_e = \frac{\partial F}{\partial x} \bigg|_{x=0} = 4 \left( \frac{1}{2} \varepsilon_0 V^2 A \right) / x_0^2 \]

Scratch drive
Somewhat run backwards (?)

High force
Compact

Low efficiency
Small step \times high freq = fast

Electrostatic Motors

Comb drive
Gap closers
Wobble motors
Scratch drive

Inchworms

Electrostatic
Inchworm
Inspiration from actin/myosin

\[ \frac{1}{2} \varepsilon_0 V^2 A / g_2 \]

\[ \text{if } V = 150 \text{ V, } g = 1 \text{ mm, } A = 1 \text{ mm}^2 \]

\[ \Rightarrow \left( 100 \text{ nA} \right) \frac{10^6 \varepsilon_0}{10^6 g^2} = 100 \text{ mN} \]

Bob a tiny stroke (1 mm)

Incremental

\[ \text{gear tooth } \rightarrow \text{ shuttle } \rightarrow \text{ tooth } 180^\circ \]

Take many steps
Penskiy

Insulated sidewalls
work out

Efficiency = electrical \rightarrow mechanical

\[ F_e = \frac{1}{2} \varepsilon_0 \frac{V^2}{g^2} \]

\[ W = F_e x \text{ if constant load} \]

Electrical: \[ \frac{1}{2} C(x_0 + x) V^2 - \frac{1}{2} C(x_0) V^2 \]

\[ Q = C V \]

\[ F_0 = \frac{1}{2} \varepsilon_0 \frac{V^2}{g^2} \]

\[ Q_0 = C_0 V_0 \]

\[ \varepsilon = \frac{Q^2}{\varepsilon_0 A} \]

\[ F_s = \frac{1}{2} \varepsilon_0 \frac{V^2}{g^2} \]

\[ Q_{adv} = \frac{1}{2} \left( V_0 \right) (3 C_0) = \frac{3}{2} Q_{adv} \]

\[ F_s = \left( \frac{3}{2} \right) F_0 \]
Charging capacitor

\[ Q = CV \quad U_c = \frac{1}{2} CV^2 \]

\[ U_{bat} = (Q - Q) V = QV - QV \]

\[ U_{sys} = U_{bat} + U_{cap} = QV - \frac{1}{2} CV^2 \]

Half energy goes to cap, half is lost as load

Energy stored in cap at step \( n \): \( \frac{1}{2} C (nV)^2 \)

Energy leaving battery at step \( n \): \( CV_0 (nV) \)

Total energy out of battery at step \( n \): \( \frac{2}{C} CV_0^2 n = \frac{C}{2} CV_0^2 n \)

\[ \text{off} = \frac{\frac{1}{2} CV_0^2 n^2}{CV_0^2 n^2 + n^2} = \frac{n^2}{n^2 (1 + \frac{1}{n})} = 1 - \frac{1}{n} \]

- Can run in reverse. Pull charge off of cap.
  - Put back in battery.
  - Use caps charged in parallel instead of battery.

Micro Scooter energy

Battery = \( \frac{I}{m^3} \) mJ/m^3 \( = \frac{1 mJ}{Kg} \)

Specific altitude = perfect conversion of stored energy to mJ/m^3

\( \frac{I}{m^3} m = m J \)

\( h = \frac{1 mJ/kg}{7.8 \times 10^3} = 10 k = 100 km \)

Say robot is 10% battery.

Meters are 10% efficient battery -> reckoned.

\( 0.3 \text{ m can climb } (10\%) (10\%) (100\%) = 1 \text{ km} \)

Lateral distance = vertical distance \( \frac{i}{1 - \text{off}} \)

E.g. walking distance vs. climbing stairs

\( \text{as be } > 10 \times \)