

Energy Efficient Variable Stiffness Actuators

Conceptual Design and Implementation

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Motivation

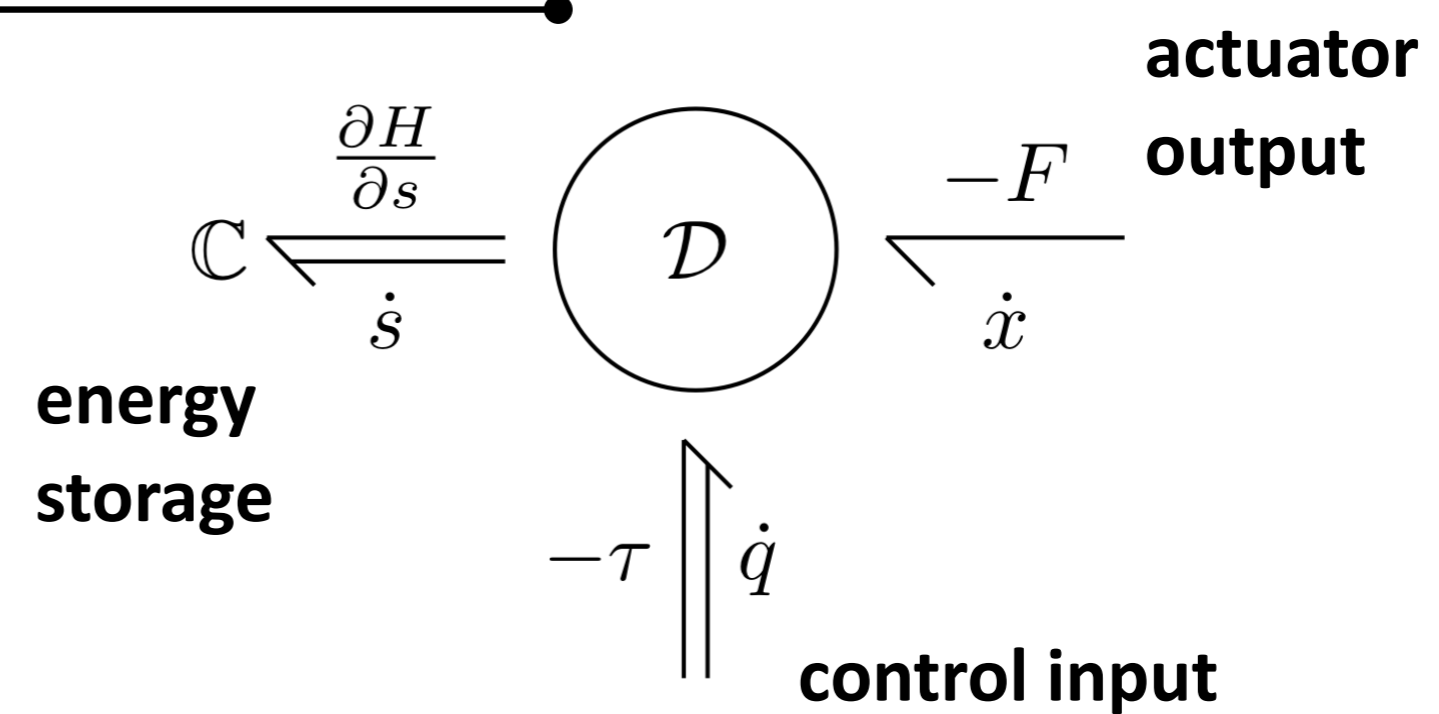
Variable stiffness actuators have internal degrees of freedom and internal springs:

- + the degrees of freedom are used to change the **apparent output stiffness**;
- + the apparent output stiffness can be changed independently of the output position;
- + the springs can be used to store **energy**;
- + the **configuration** of the degrees of freedom determines **power flow** between the **springs** and the **output**.

Goal:

Change the output stiffness without changing the energy stored in the springs.

Port-based Modeling



The **Dirac structure** \mathcal{D} defines the power flows among the bonds:

$$\begin{bmatrix} \dot{s} \\ \tau \\ F \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & A(q, x) & B(q, x) \\ -A^T(q, x) & 0 & 0 \\ -B^T(q, x) & 0 & 0 \end{bmatrix}}_{\mathcal{D}} \begin{bmatrix} \frac{\partial H}{\partial s} \\ \dot{q} \\ \dot{x} \end{bmatrix}$$

Variation of the **energy** in the spring:

$$\frac{dH}{dt} = \frac{\partial H}{\partial s} (A(q, x)\dot{q} + B(q, x)\dot{x})$$

Conceptual Design

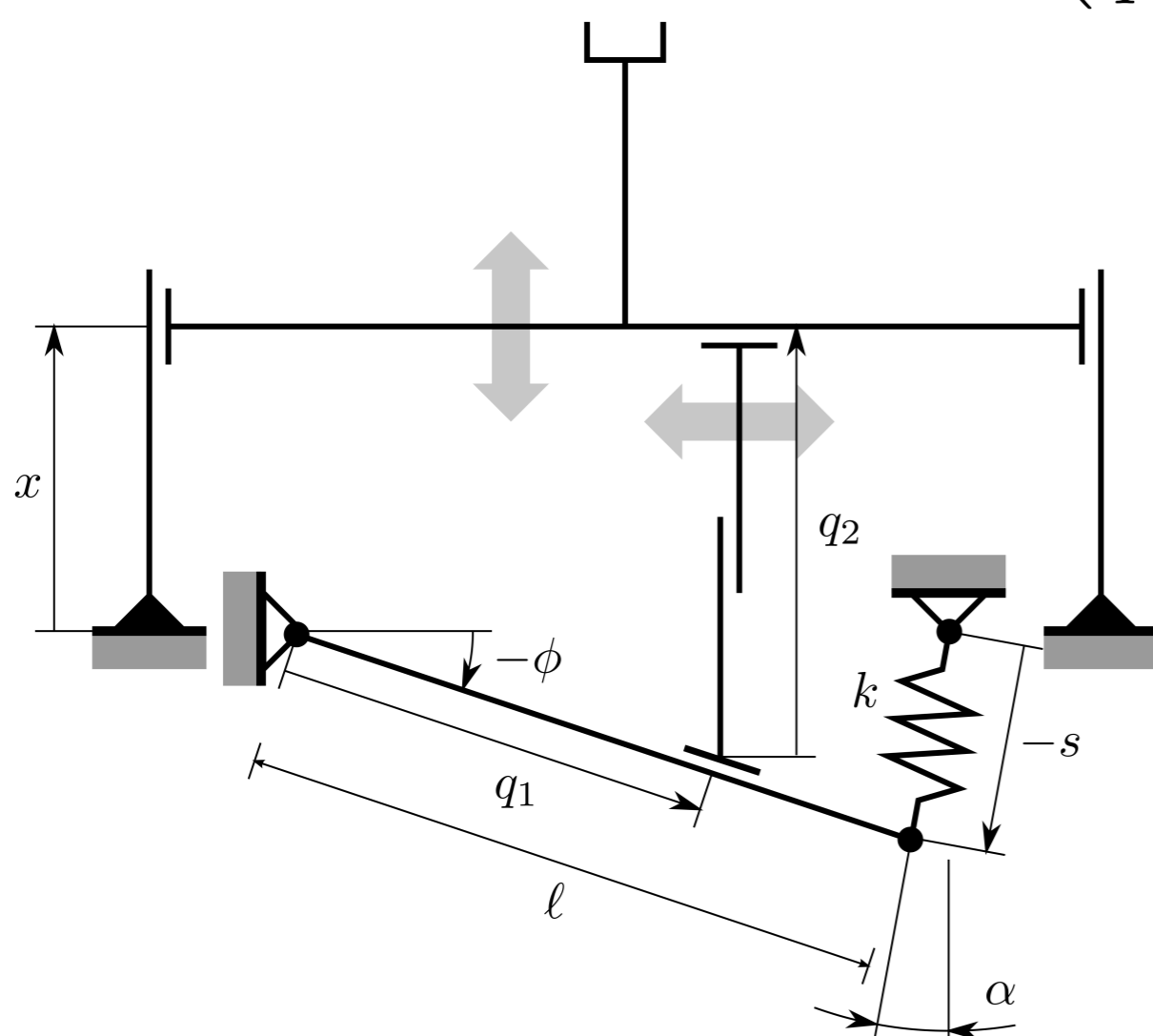
The energy in the spring changes with **no power flow via the control port** if:

$$\dot{q} \in \ker A(q, x), \quad \forall q, x$$

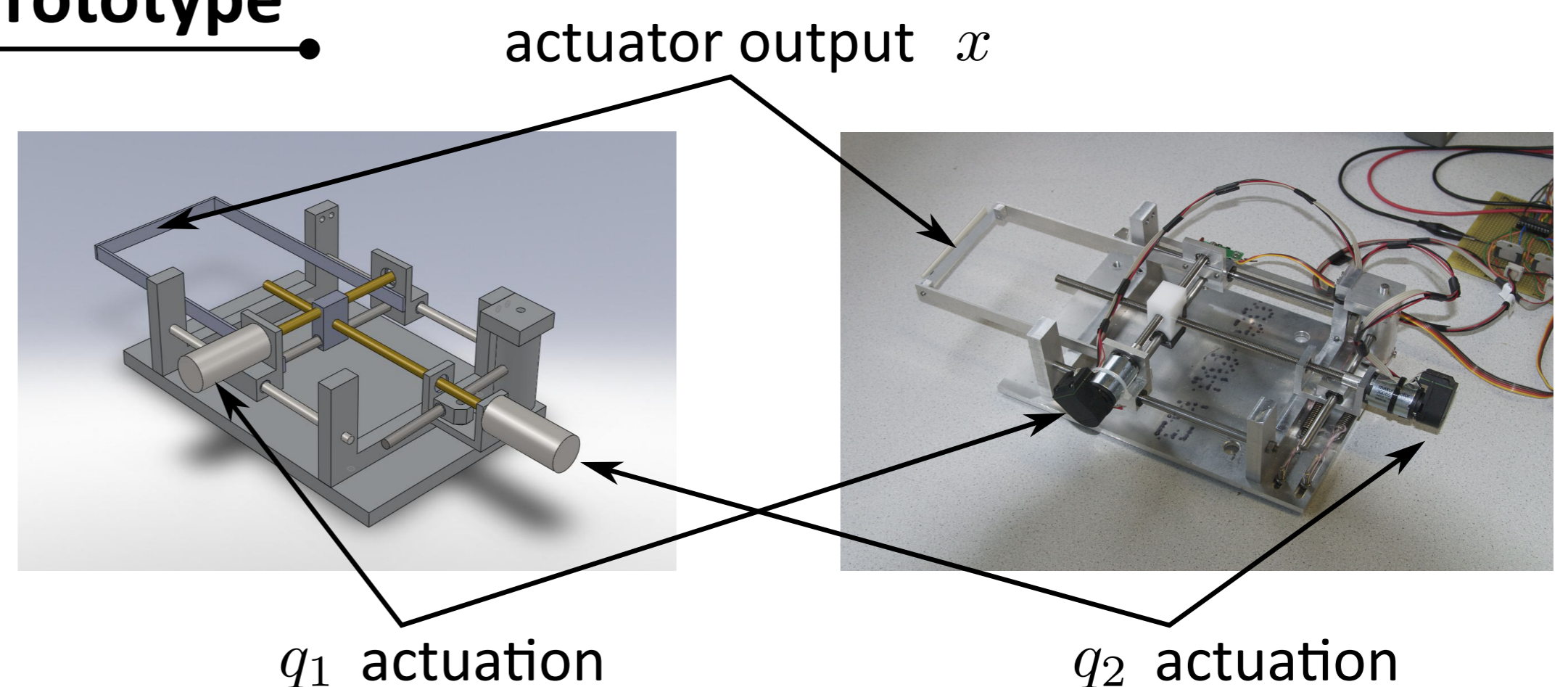
The conceptual design has:

$$A(q, x) = \frac{\ell}{q_1} \begin{bmatrix} \sin \phi & 1 \end{bmatrix}$$

The output stiffness is: $K := \frac{\partial F}{\partial x} = \left(\frac{\ell}{q_1}\right)^2 k$



Prototype



- + Output **position** and **stiffness** are mechanically **decoupled**.
- + The **output stiffness** can be changed **without changing the energy stored** in the springs.

