ME 327: Design and Control of Haptic Systems
Spring 2020

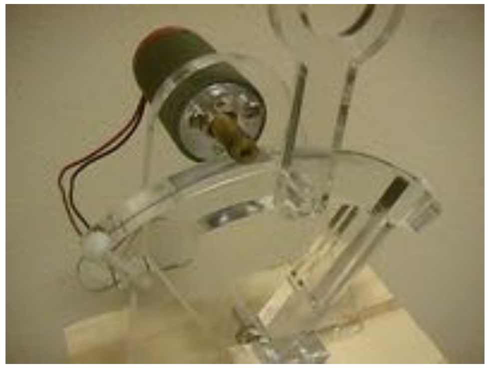
Lecture 11:
Kinesthetic haptic devices: multi-DOF design

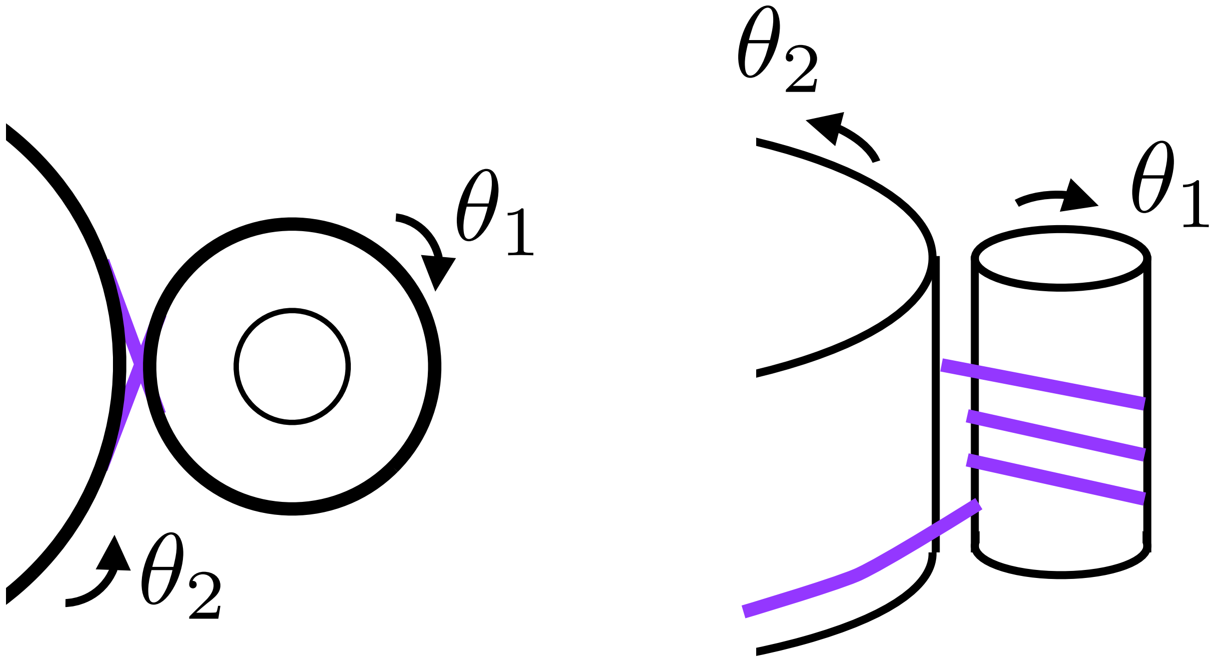
Allison M. Okamura
Stanford University

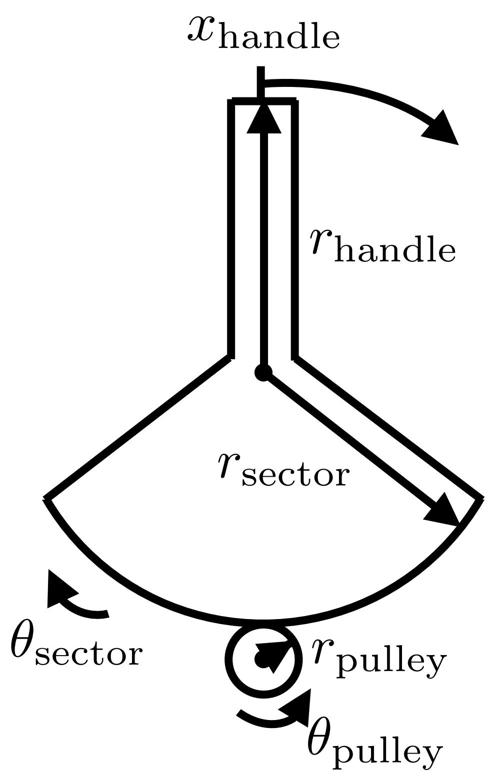
Kinesthetic device kinematics

Hapkit kinematics reminder

Capstan drive

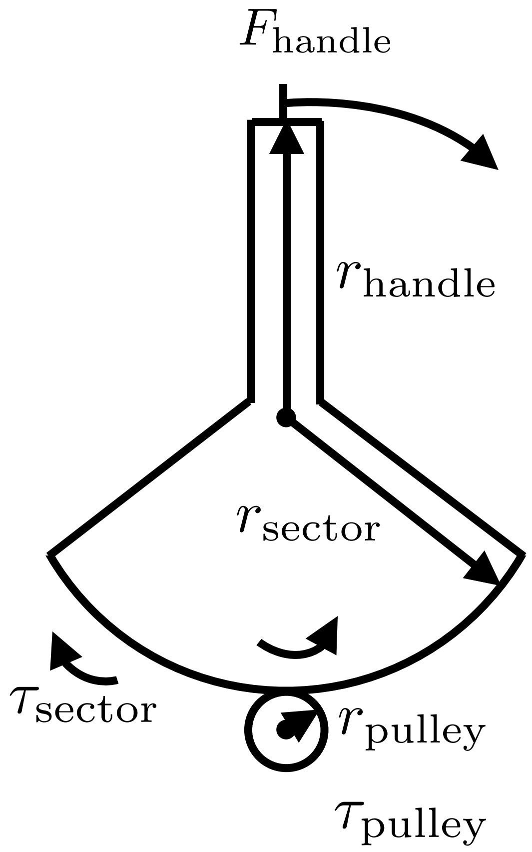






$$x_{\text{handle}} = \frac{r_{\text{handle}} r_{\text{pulley}}}{r_{\text{sector}}} \theta_{\text{pulley}}$$

$$F_{\text{handle}} = \frac{r_{\text{sector}}}{r_{\text{handle}} r_{\text{pulley}}} \tau_{\text{pulley}}$$



suggested references

- Introduction to robotics : mechanics and control
  John J. Craig
- Robot modeling and control
  Mark W. Spong, Seth Hutchinson, M. Vidyasagar
- A mathematical introduction to robotic manipulation
  Richard M. Murray, Zexiang Li, S. Shankar Sastry
- Springer handbook of robotics
  B. Siciliano, Oussama Khatib (eds.)
  https://link-springer-com.stanford.idm.oclc.org/book/10.1007%2F978-3-319-32552-1

kinematics

- The study of movement
- The branch of classical mechanics that describes the motion of objects without consideration of the forces that cause it
- Why do you need it?
  - Determine endpoint position and/or joint positions
  - Calculate mechanism velocities, accelerations, etc.
  - Calculate force-torque relationships

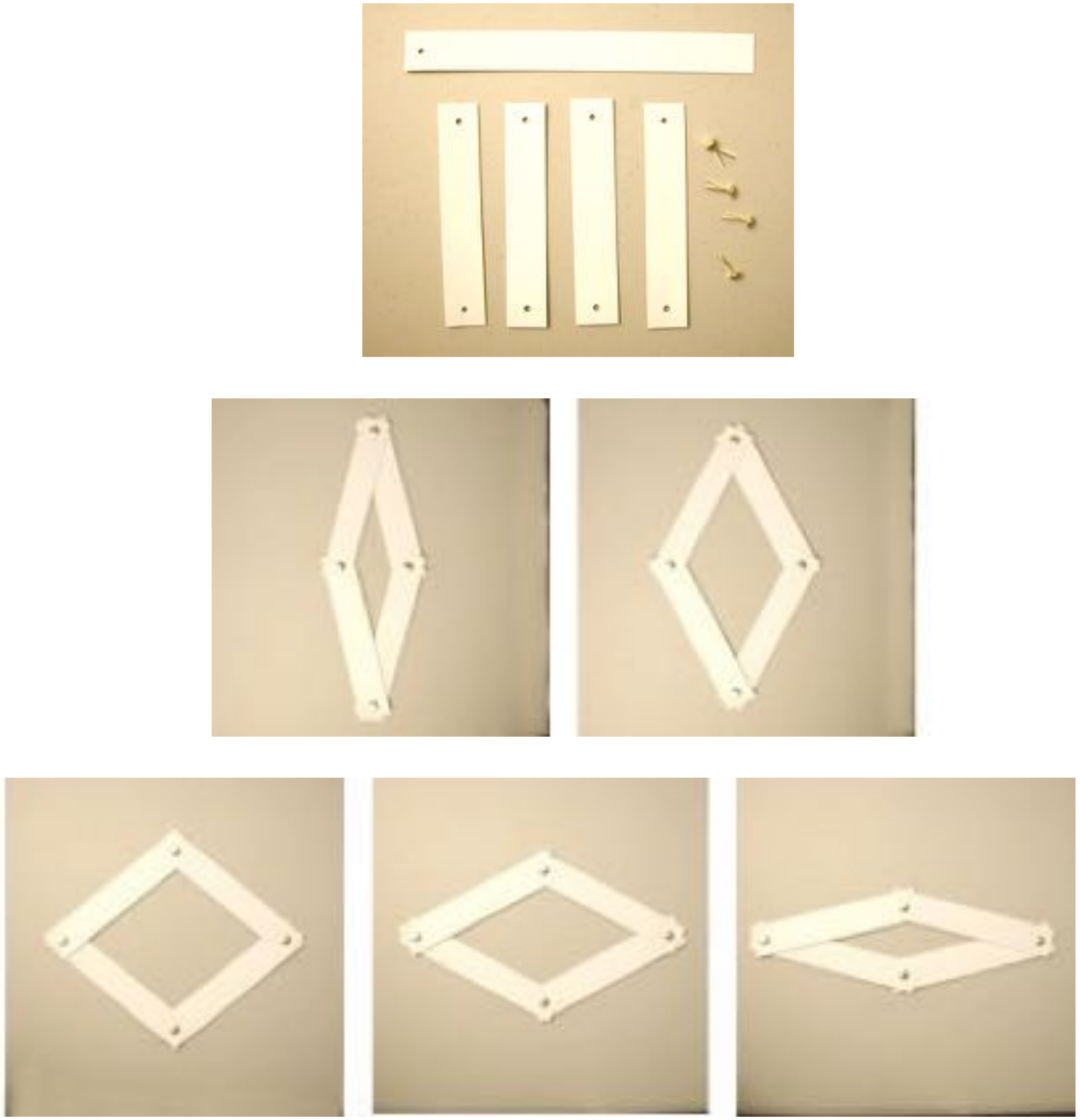
degrees of freedom

- Number of independent position variables needed to in order to locate all parts of a mechanism
- DOF of motion
- DOF of sensing
- DOF of actuation
- The DOF of a mechanism does not always correspond to number of joints

it will help to prototype!

round head
paper fasteners

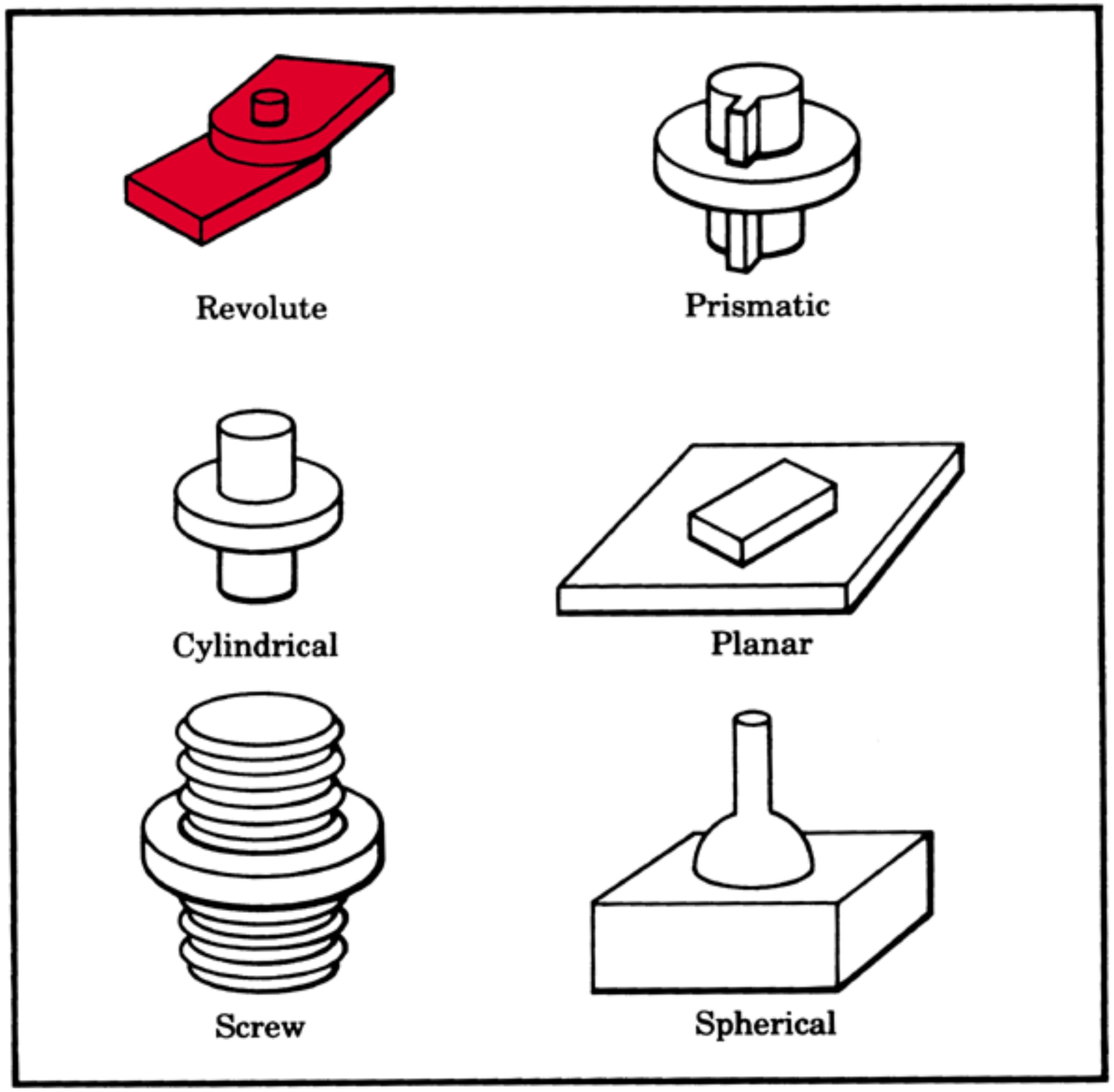
officedepot.com



www.rogersconnection.com/triangles

joints

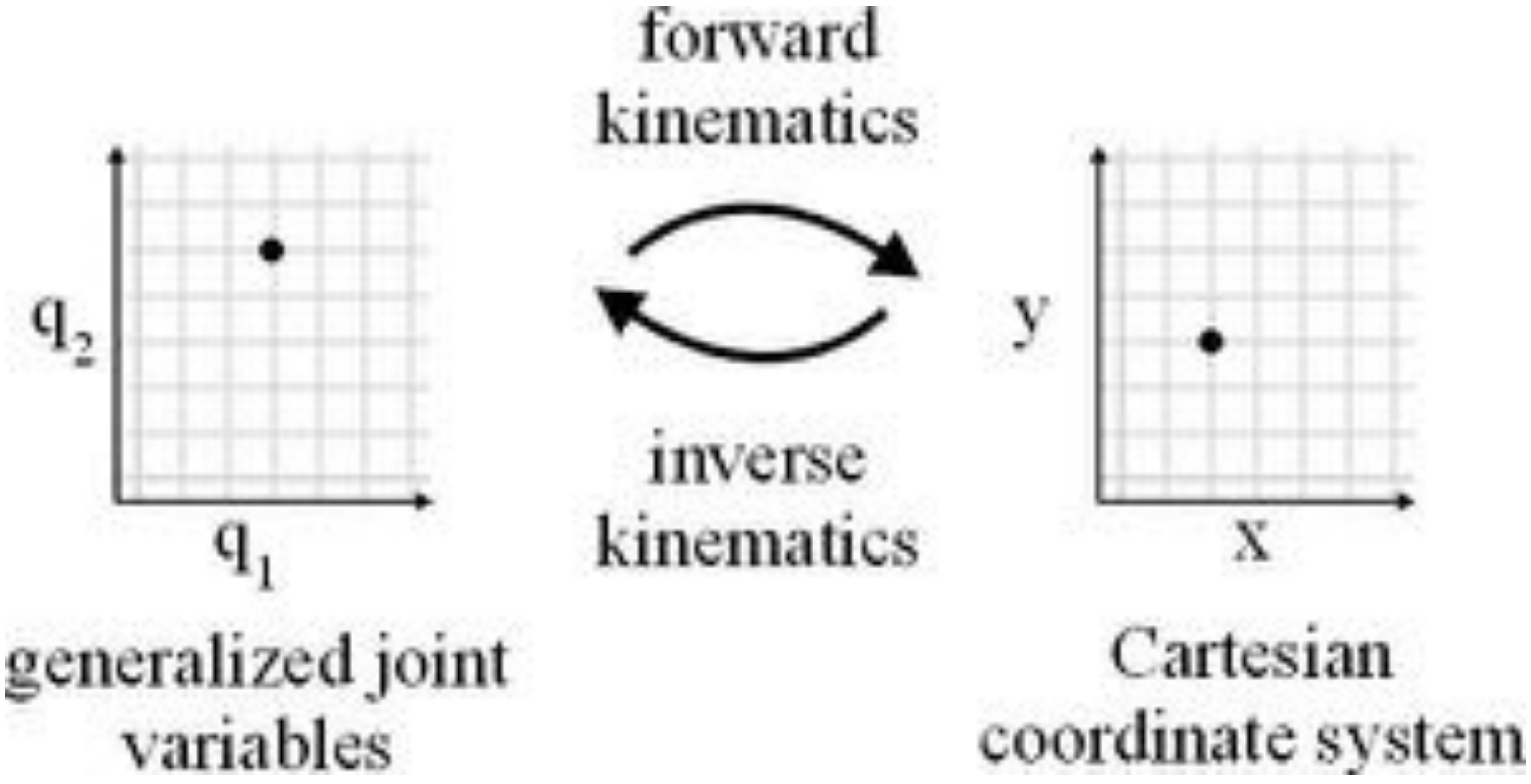
- Think of a manipulator/ interface as a set of bodies connected by a chain of joints
- **Revolute** is the most common joint for robots



From Craig, p. 69

forward kinematics for higher degrees of freedom

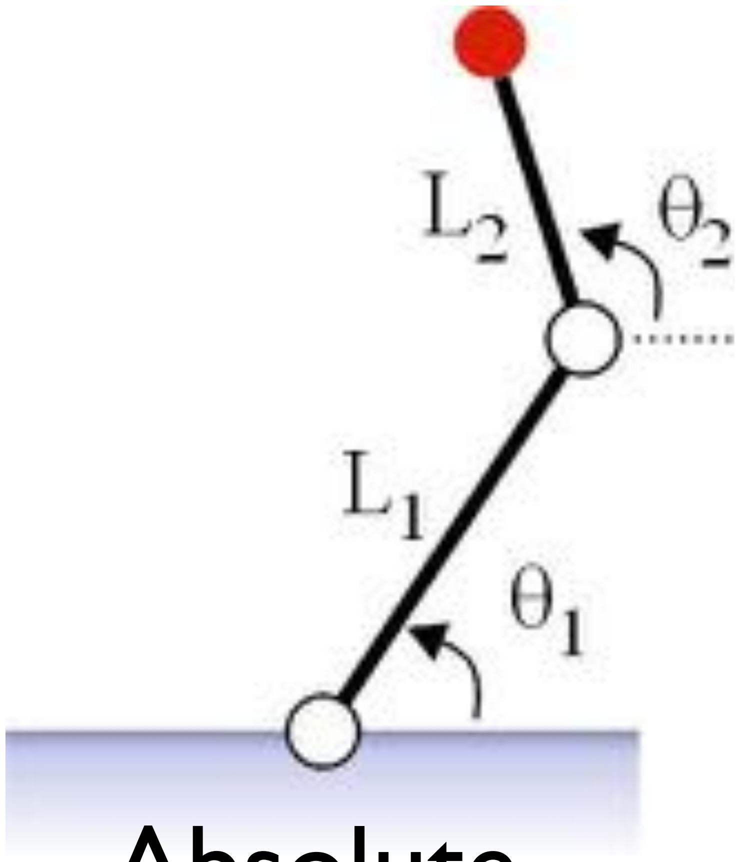
for mechanical trackers that use joint angle sensors, you need a map between ***joint space*** and ***Cartesian space***



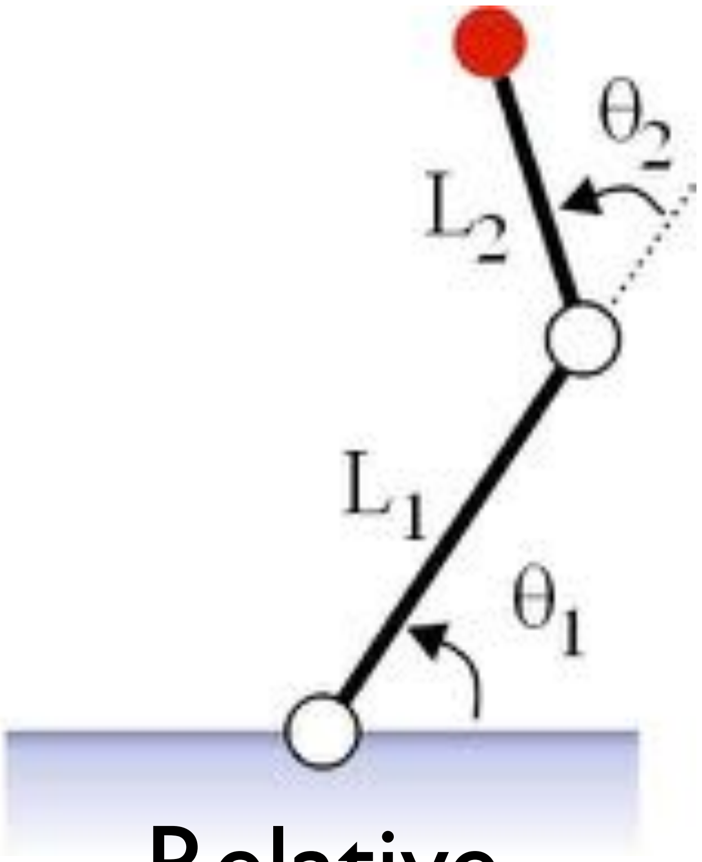
fwd kinematics: from joint angles, calculate endpoint position

joint variables

Be careful how you define joint positions



Absolute



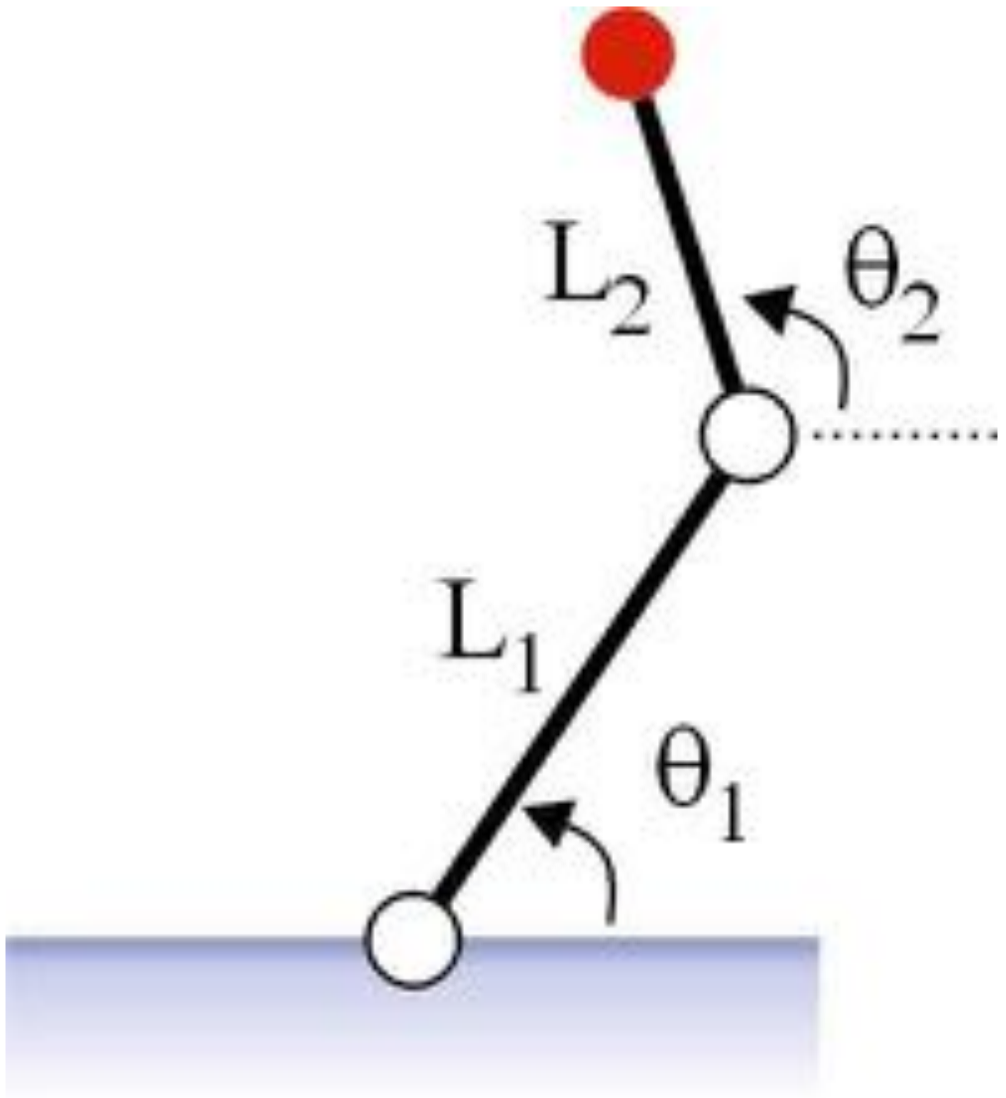
Relative

absolute forward kinematics

$$x = L_1\cos(\theta_1) + L_2\cos(\theta_2)$$

$$y = L_1\sin(\theta_1) + L_2\sin(\theta_2)$$

(Often done this
way for haptic devices)

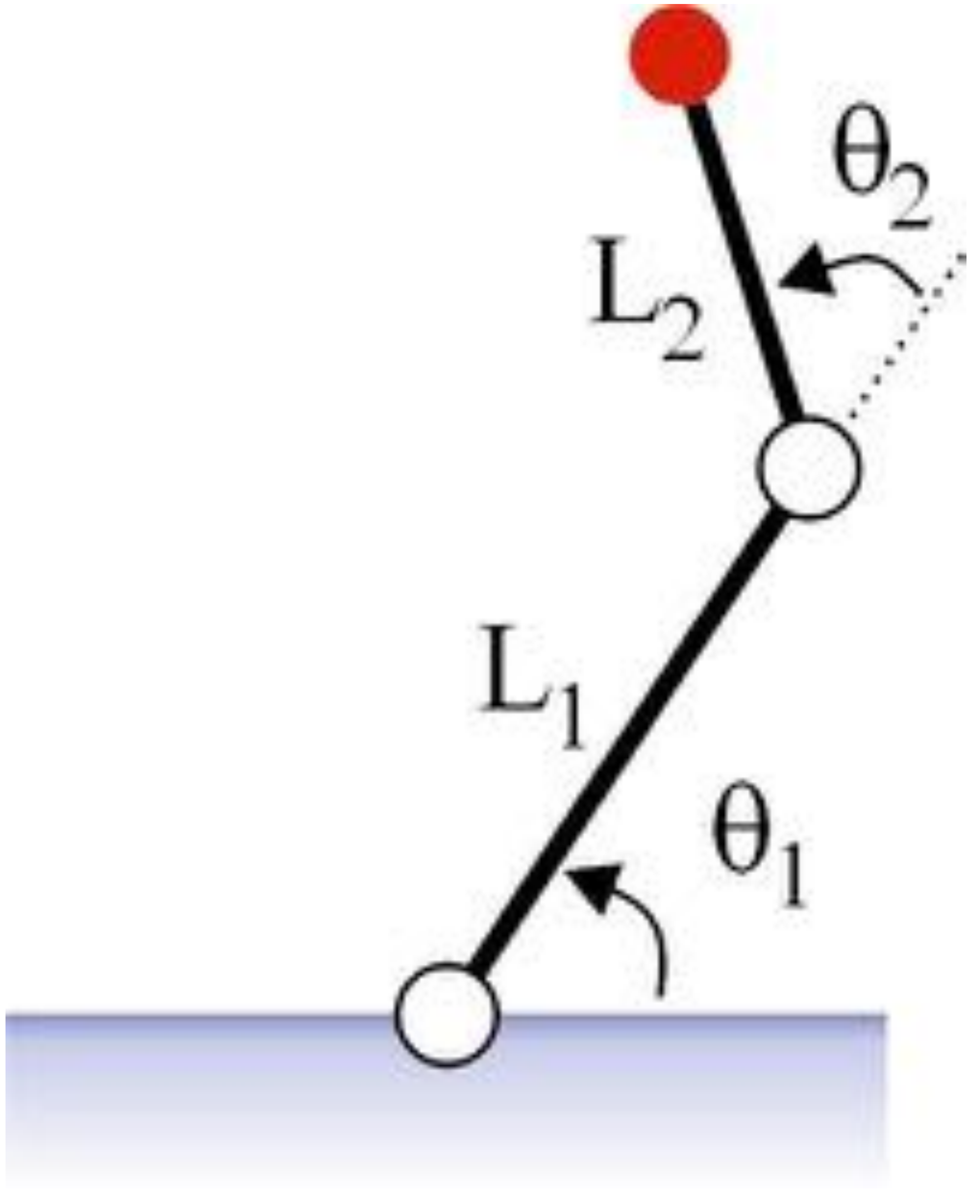


relative forward kinematics

$$x = L_1\cos(\theta_1) + L_2\cos(\theta_1+\theta_2)$$

$$y = L_1\sin(\theta_1) + L_2\sin(\theta_1+\theta_2)$$

(Often done this way for robots)

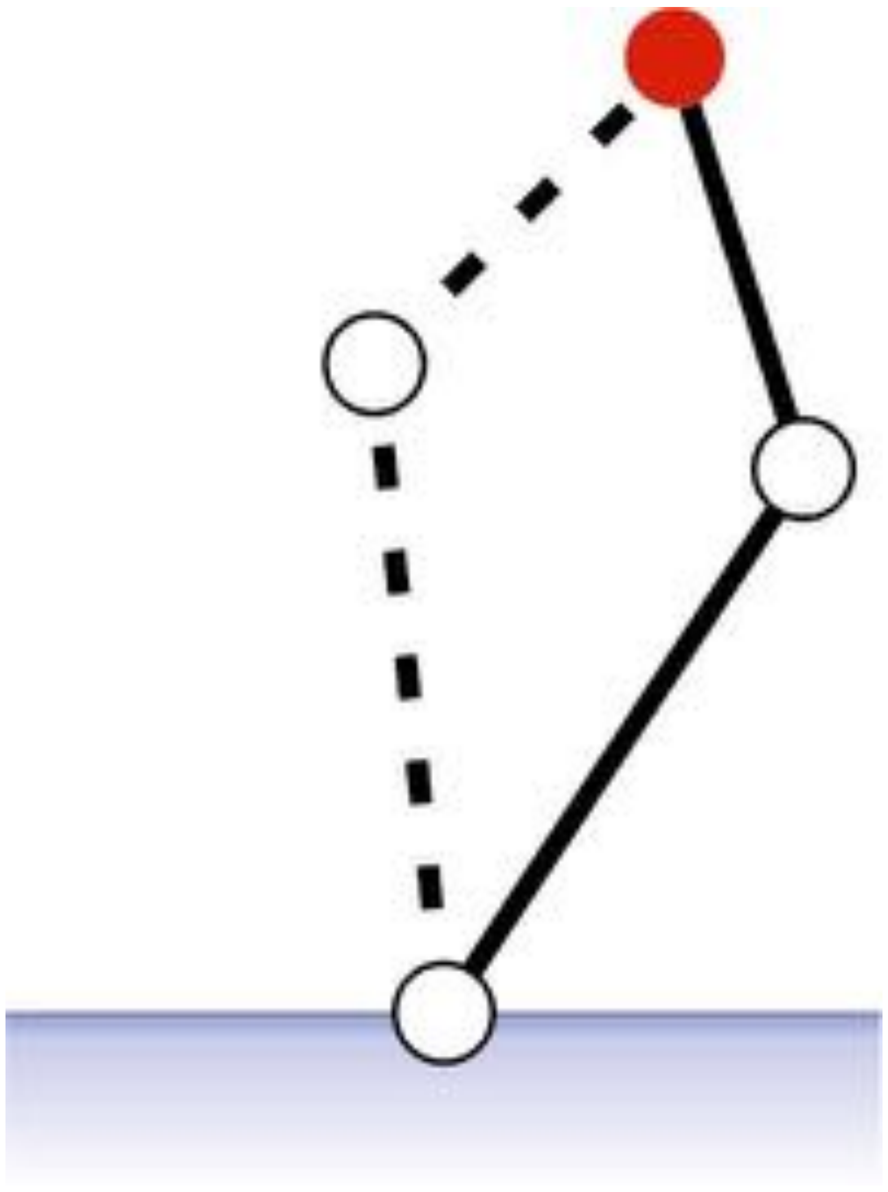


Inverse Kinematics

- Using the end-effector position, calculate the joint angles necessary to achieve that position
- Not used often for haptics
  - But could be useful for planning/design
- There can be:
  - No solution (workspace issue)
  - One solution
  - More than one solution

example

- Two possible solutions
- Two approaches:
  - algebraic method (using transformation matrices)
  - geometric method
- Your devices should be simple enough that you can just use geometry



computing end-effector velocity

- forward kinematics tells us the endpoint *position* based on joint positions
- how do we calculate endpoint velocity from joint velocities?
- use a matrix called the ***Jacobian***

$$\dot{\mathbf{x}} = J\dot{\mathbf{q}}$$

formulating the Jacobian

multidimensional form of the chain rule:

$$\dot{x} = \frac{\partial x}{\partial q_1}\dot{q}_1 + \frac{\partial x}{\partial q_2}\dot{q}_2 + \cdots$$
$$\dot{y} = \frac{\partial y}{\partial q_1}\dot{q}_1 + \frac{\partial y}{\partial q_2}\dot{q}_2 + \cdots$$
$$\vdots$$

assemble in matrix form:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial q_1} & \frac{\partial x}{\partial q_2} \\ \frac{\partial y}{\partial q_1} & \frac{\partial y}{\partial q_2} \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix}$$

$$\dot{\mathbf{x}} = J\dot{\mathbf{q}}$$

Singularities

- Many devices will have configurations at which the Jacobian is singular
- This means that the device has lost one or more degrees of freedom in Cartesian Space
- Two kinds:
  - Workspace boundary
  - Workspace interior

Singularity Math

- If the matrix is invertible, then it is non-singular.

$$\dot{\theta} = J^{-1}\dot{\mathbf{x}}$$

- Can check invertibility of J by taking the determinant of J. If the determinant is equal to 0, then J is singular.
- Can use this method to check which values of θ will cause singularities.

Calculating Singularities

Simplify text: $\sin(\theta_1+\theta_2)=s_{12}$

$$\det\big(J(\theta)\big)=\begin{vmatrix}-L_1s_1-L_2s_{12} & -L_2s_{12}\\ L_1c_1+L_2c_{12} & L_2c_{12}\end{vmatrix}$$

$$=(-L_1s_1-L_2s_{12})L_2c_{12}+(L_1c_1+L_2c_{12})L_2s_{12}$$

For what values of θ_1 and θ_2 does this equal zero?

compute the necessary joint torques

the Jacobian can also be used to relate ***joint torques*** to ***end-effector forces***:

$$\boldsymbol{\tau} = J^T \mathbf{f}$$

this is a key equation for multi-degree-of-freedom haptic devices

how do you get this equation?

the **Principle of virtual work**

states that changing the coordinate frame does not change the total work of a system

$$\mathbf{f} \cdot \delta \mathbf{x} = \boldsymbol{\tau} \cdot \delta \mathbf{q}$$

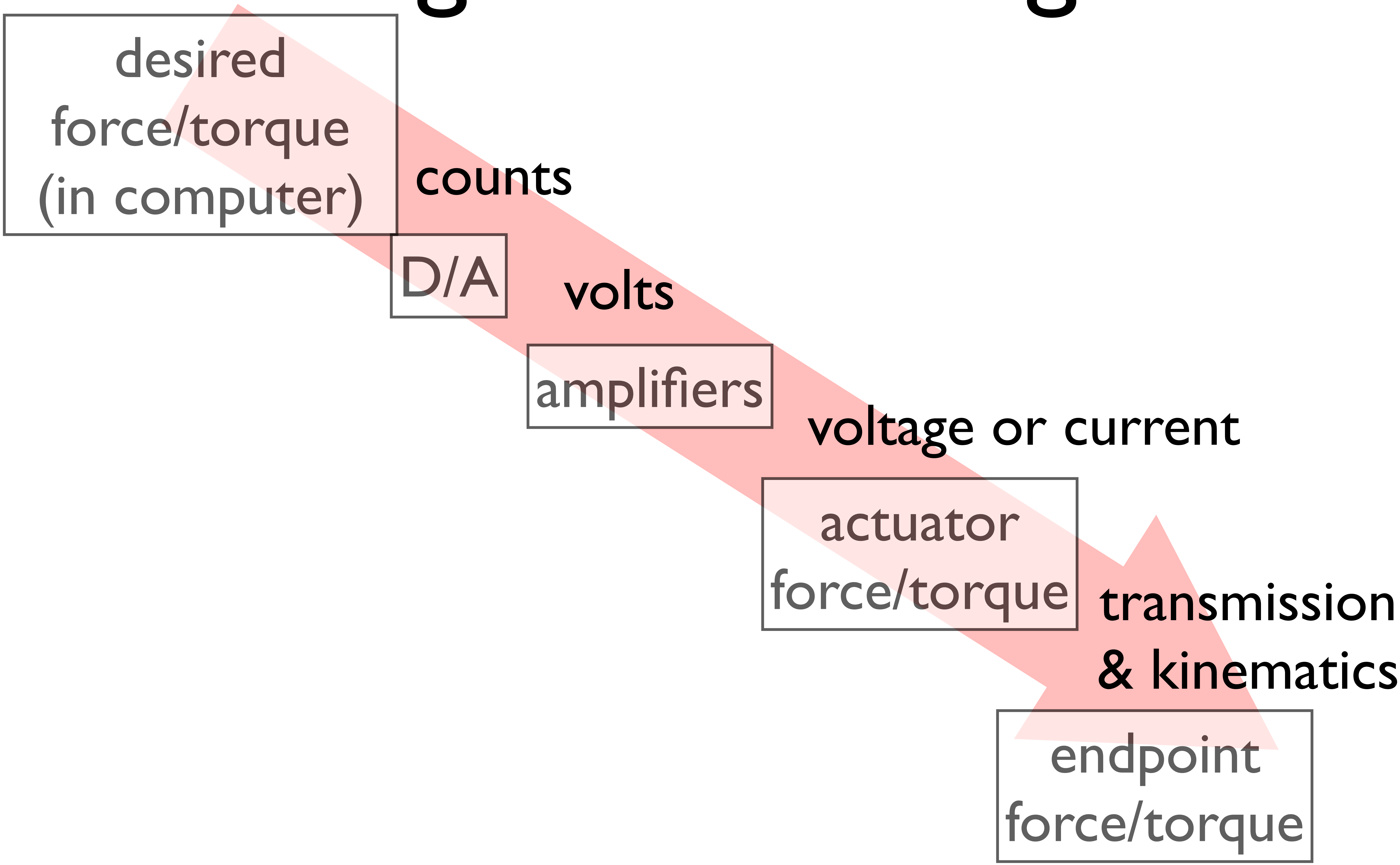
$$\mathbf{f}^T \delta \mathbf{x} = \boldsymbol{\tau}^T \delta \mathbf{q}$$

$$\mathbf{f}^T J \delta \mathbf{q} = \boldsymbol{\tau}^T \delta \mathbf{q}$$

$$\mathbf{f}^T J = \boldsymbol{\tau}^T$$

$$J^T \mathbf{f} = \boldsymbol{\tau}$$

force generation signals



desired force/torque (in computer)

counts

D/A

volts

amplifiers

voltage or current

actuator force/torque

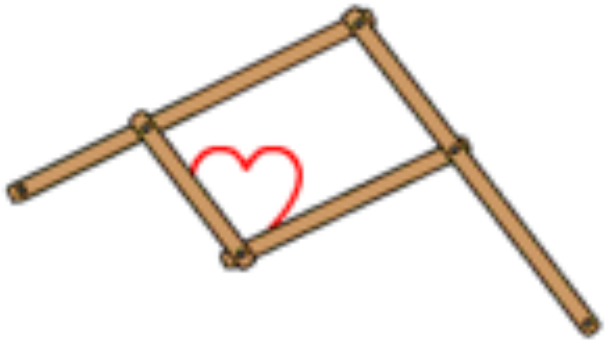
transmission & kinematics

endpoint force/torque

pantograph mechanism

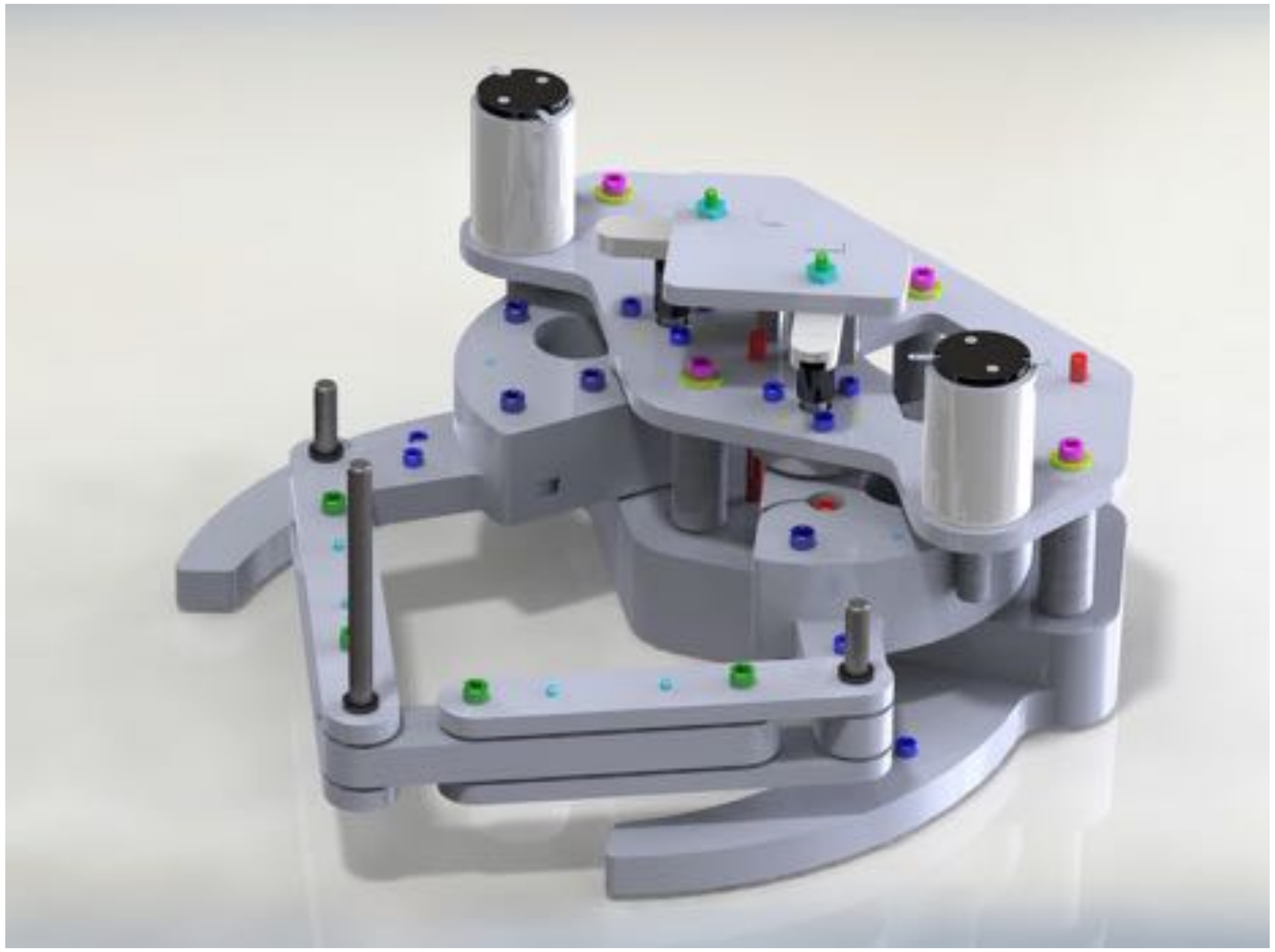
pantograph

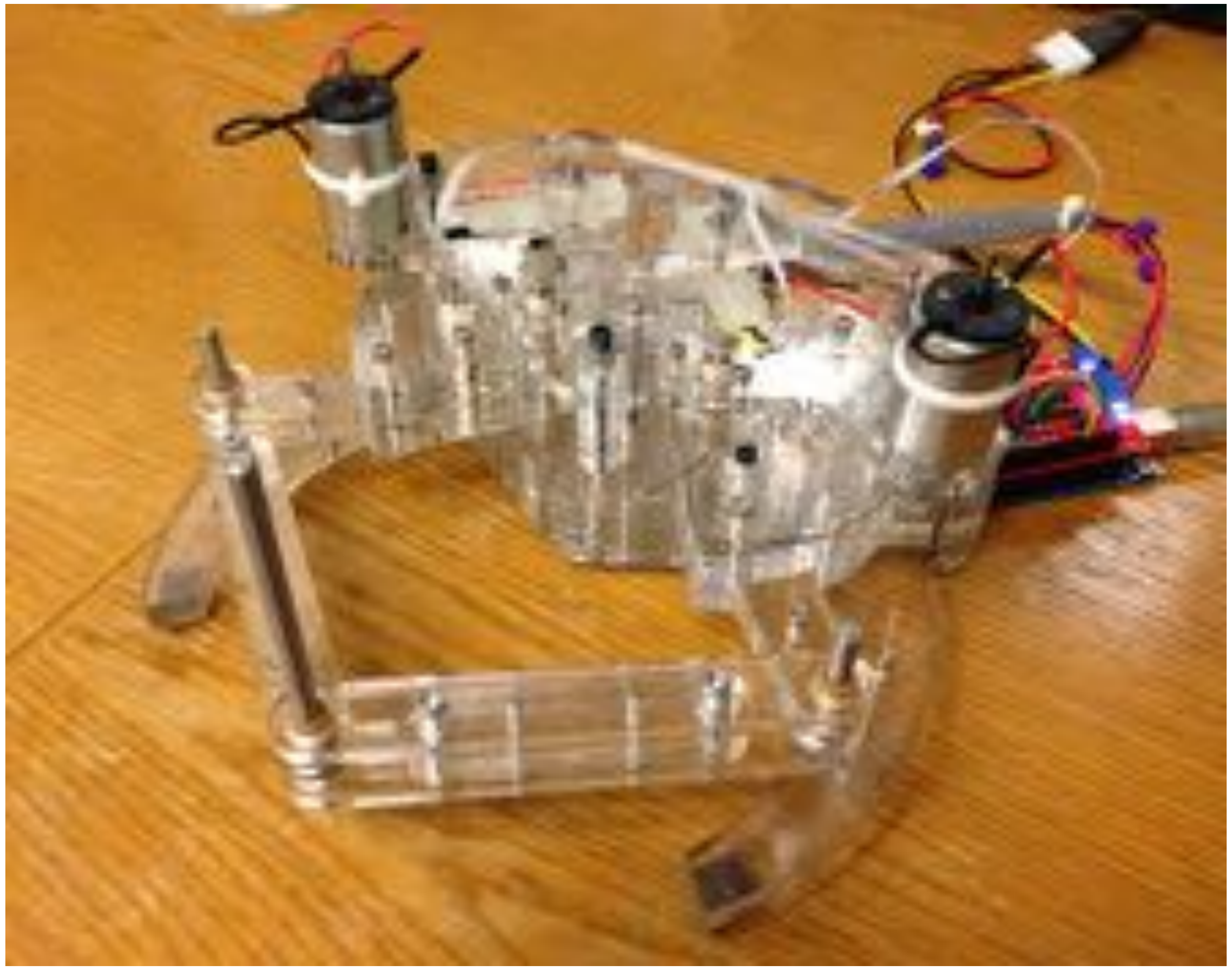
Definition 1: a mechanical linkage connected in a manner based on parallelograms so that the movement of one pen, in tracing an image, produces identical movements in a second pen.



Definition 2: a kind of structure that can compress or extend like an accordion

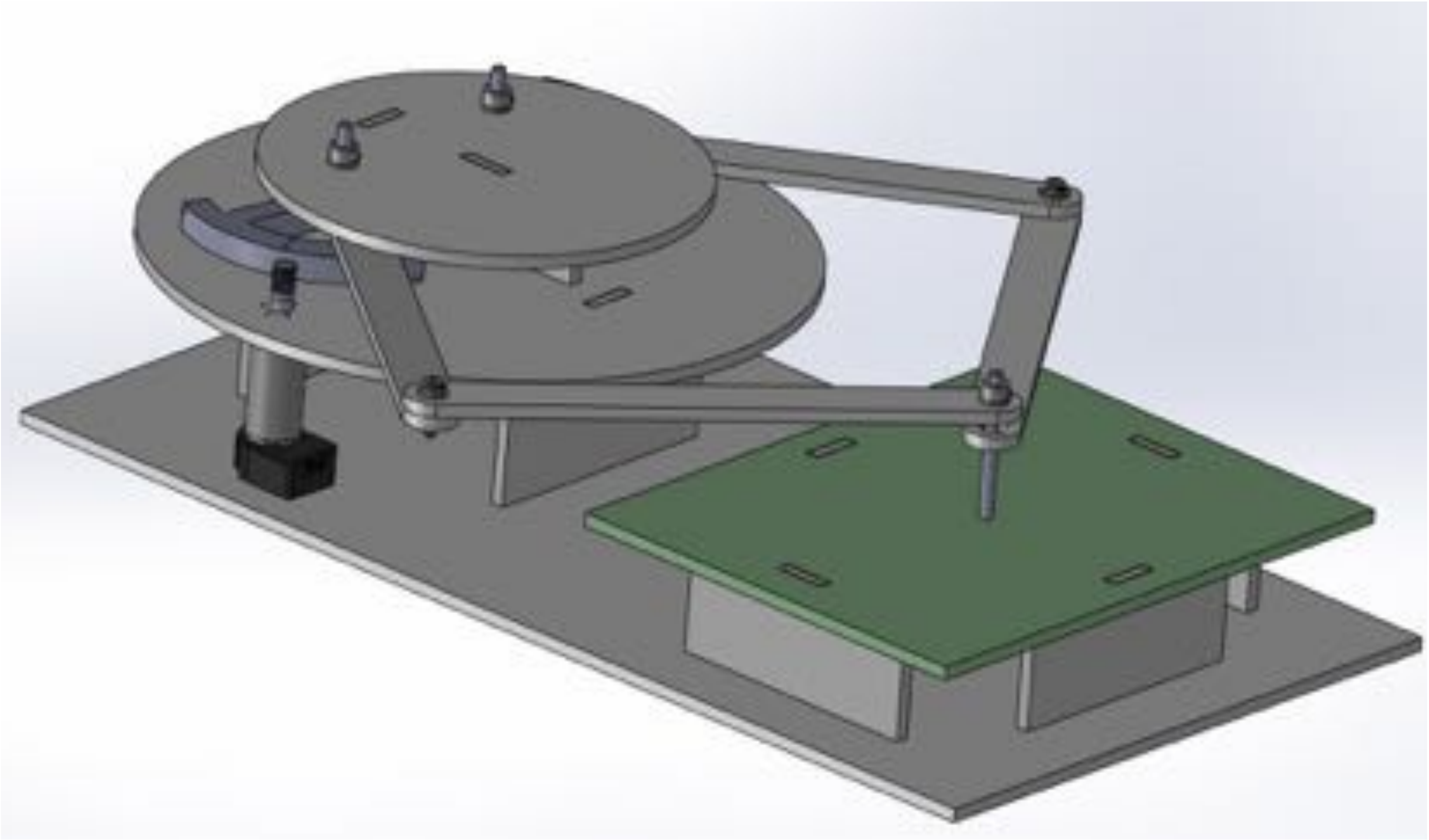
pantograph haptic device

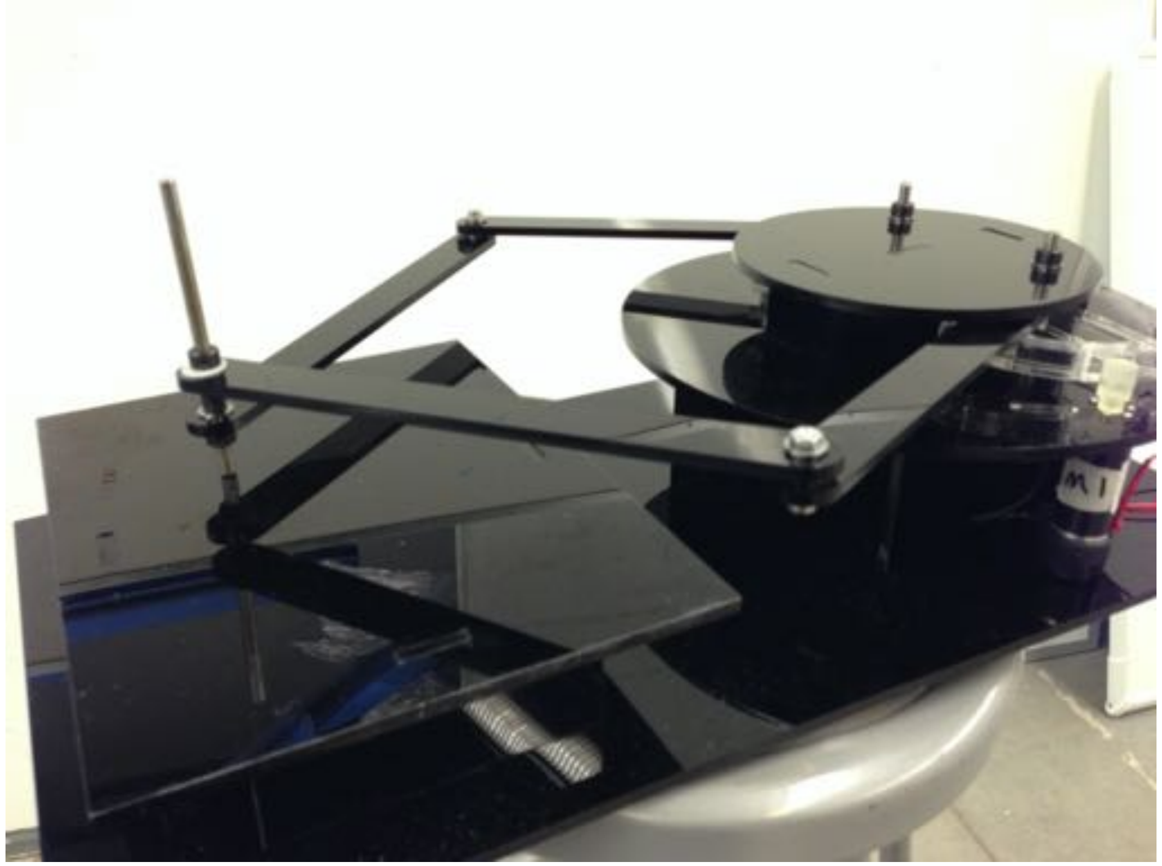




Xiyang Yeh, ME 327 2012
http://charm.stanford.edu/ME327/Xiyang

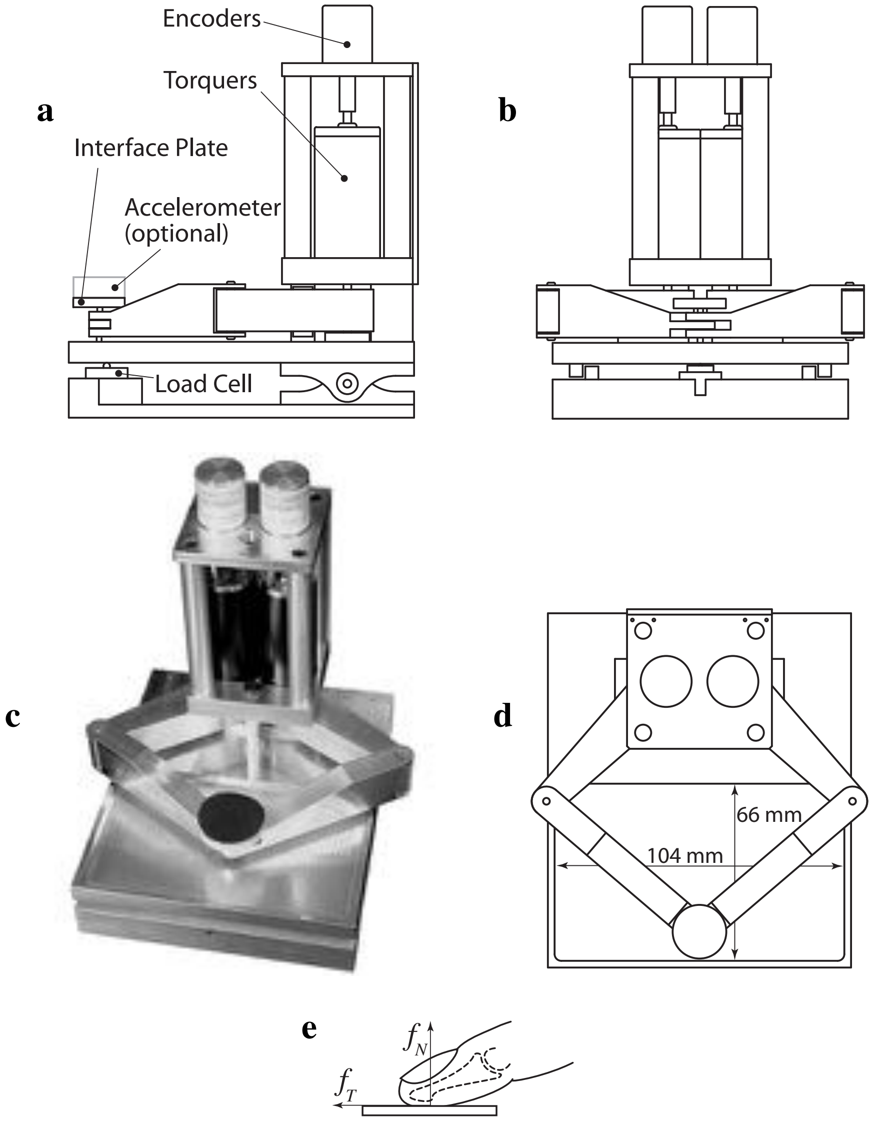
pantograph haptic device

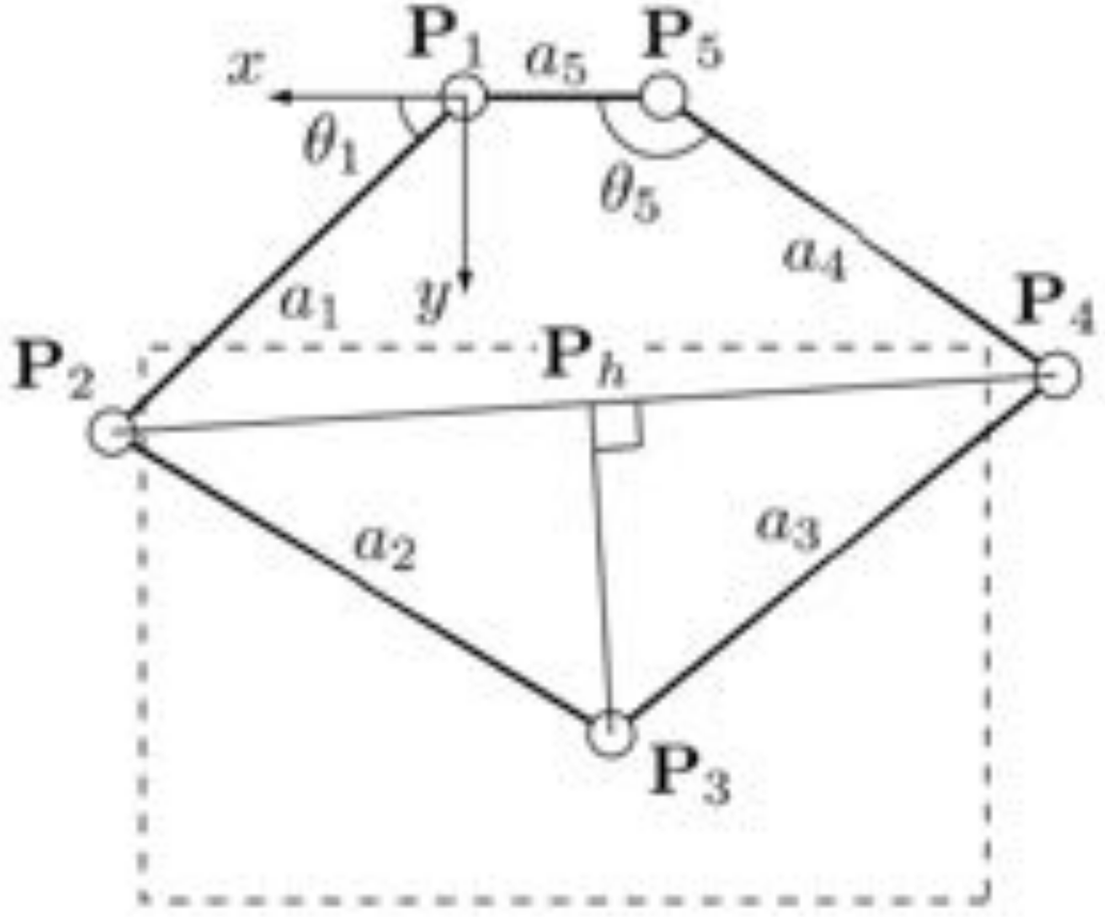




Sam Schorr and Jared Muirhead, ME 327 2012
http://charm.stanford.edu/ME327/JaredAndSam

pantograph haptic device

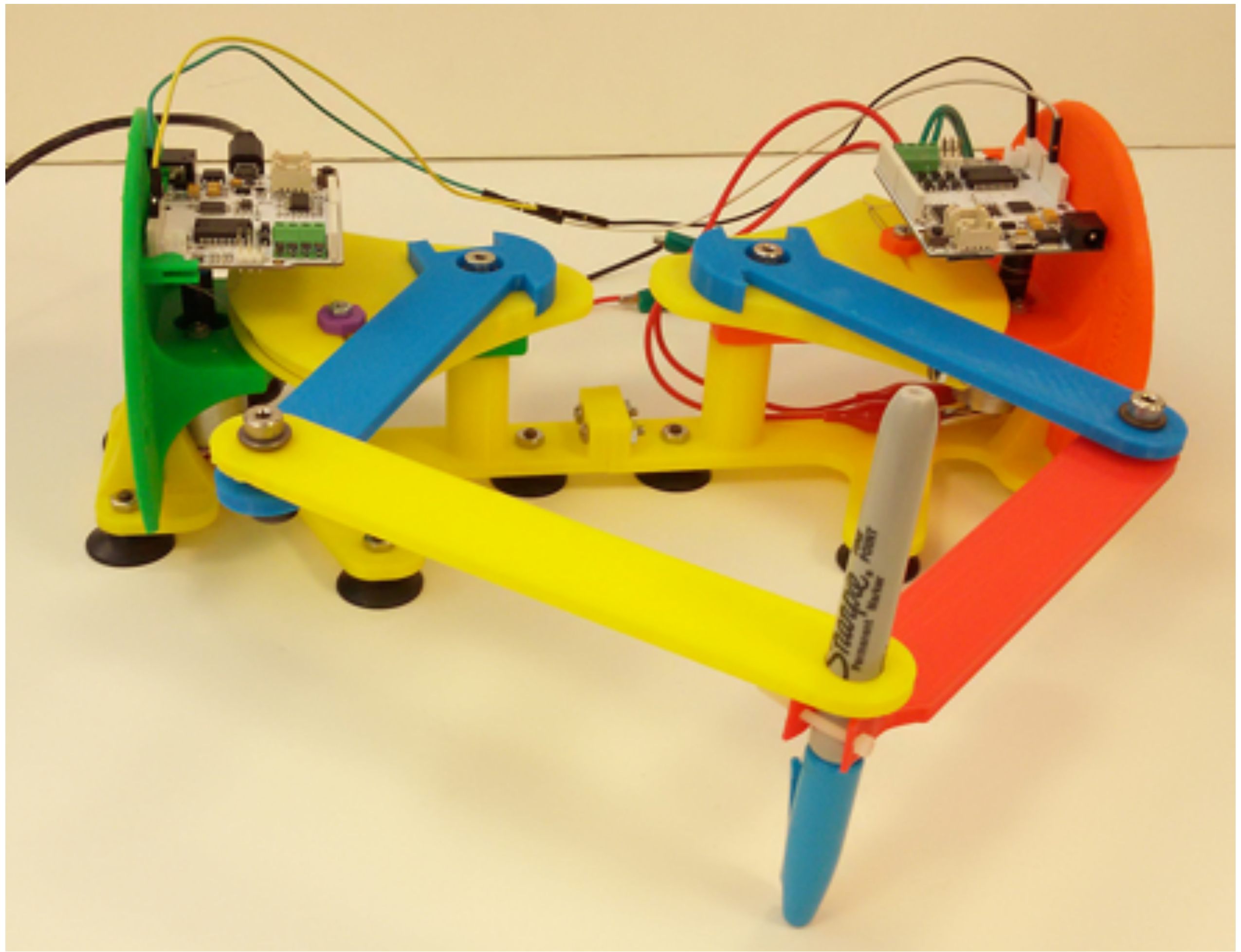




Campion and Hayward, IROS 2005

http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1545066

graphkit



2 x hapkit +

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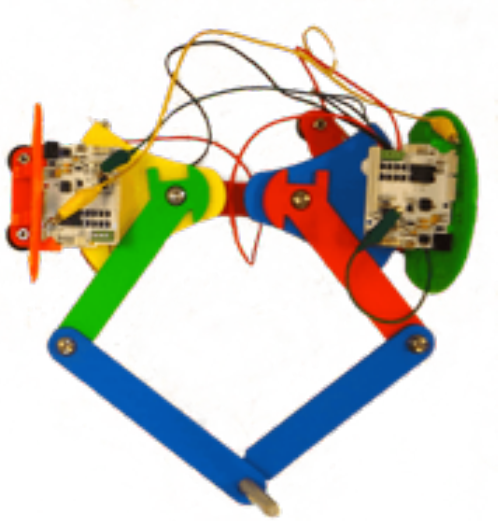
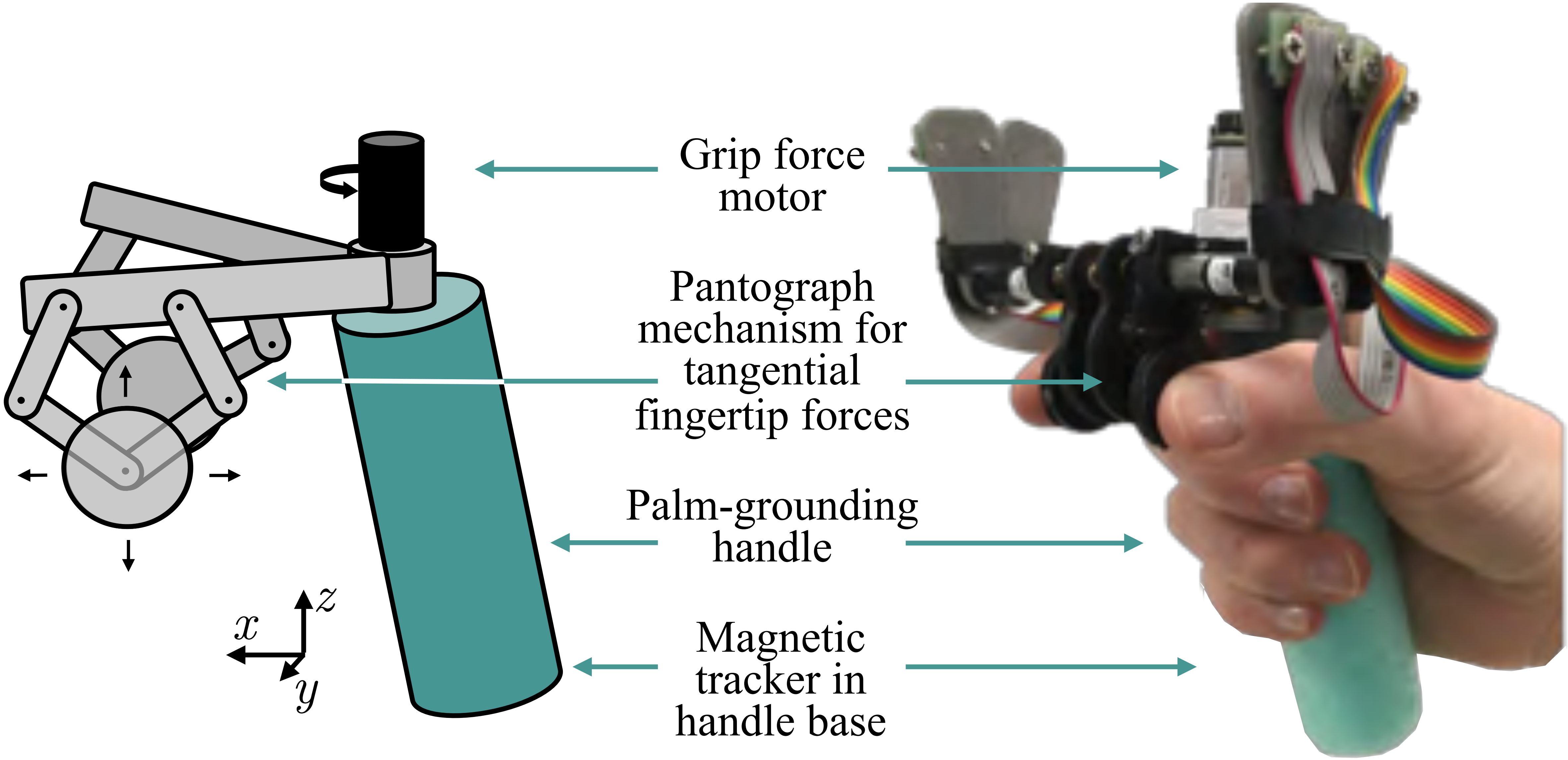


Design by Tara Gholami and Joey Campion
http://hapkit.stanford.edu/twoDOF.html

Fingertip Pantographs



Grip force motor

Pantograph mechanism for tangential fingertip forces

Palm-grounding handle

Magnetic tracker in handle base

Julie Walker 2020

https://arxiv.org/abs/1903.03150

Holdable Haptic Device for 4-DOF Motion Guidance

Julie M. Walker, Nabil Zemiti,
Philippe Poignet, and Allison M. Okamura