Collective Actuation

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DPR & Claytronics Teams

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Background: Intel Lab at Carnegie Mellon

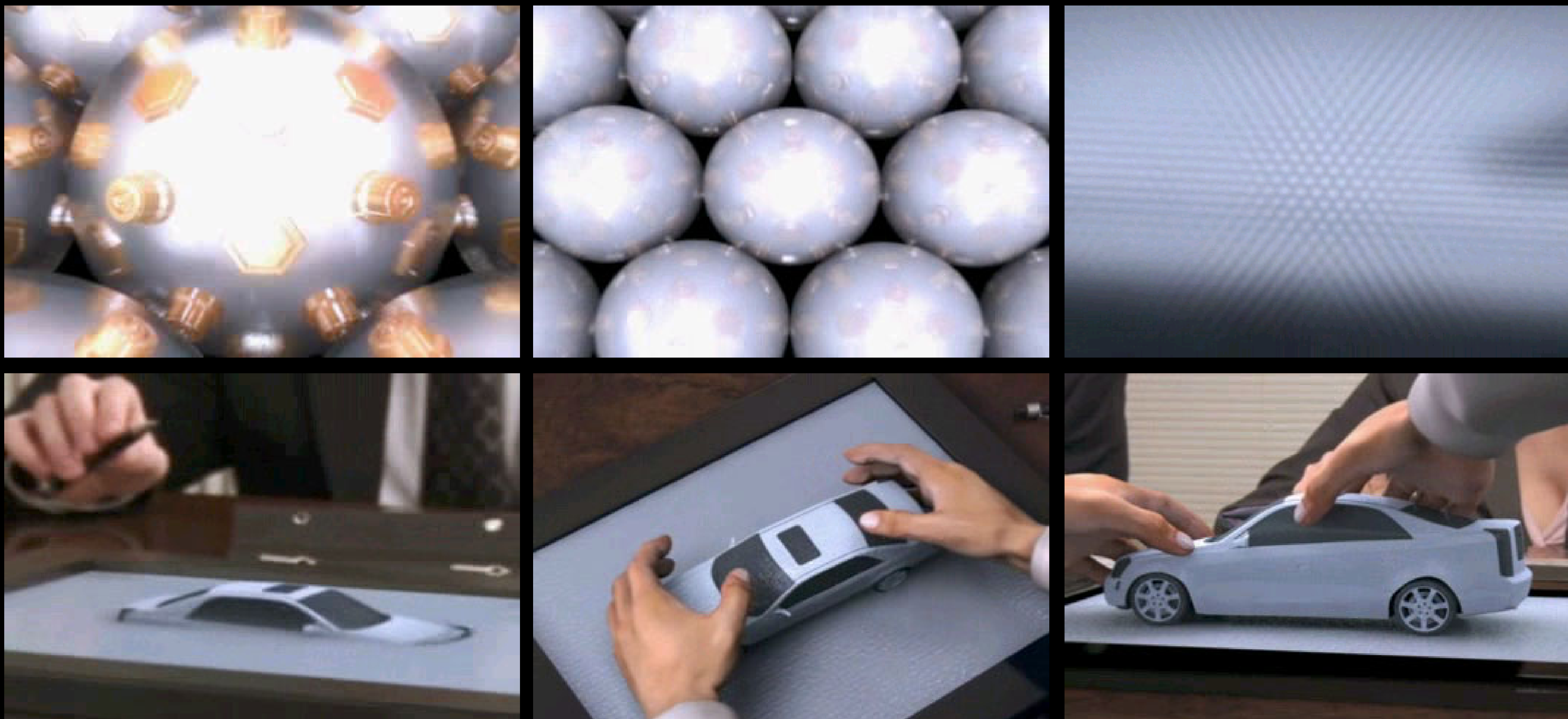
- Located on the 4th floor of the "Collaborative Innovation Center" (CIC) building

Background: DPR (Intel) & Claytronics (CMU)

- Our focus is on *shape-changing ensembles*
- Envision sub-millimeter modules, used in groups of 10^4 to 10^8 units

Long-term project goals:

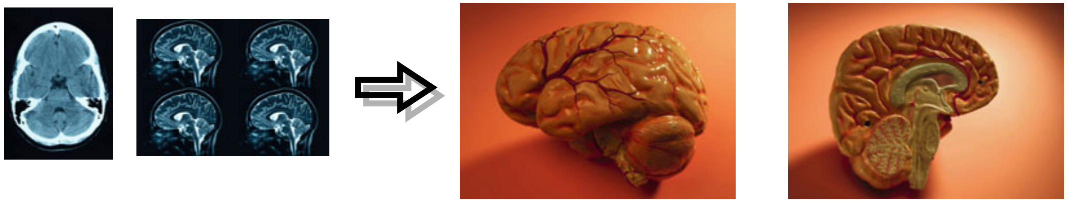
- Scalable software architecture and tools for millions of cooperating agents
- Hardware design (concepts) suitable for integrated photolithographic + self-assembly manufacture



Video: CMU Entertainment Technology Center

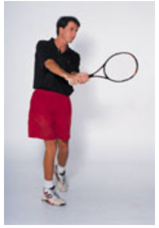
Other Applications

- 3D Visualization & interface (medical, etc.)



- Product design, computer-assisted sculpting

- New forms of telepresence-based human-human communication


- Shape-shifting antennas
- Variable form-factor computing devices
- Malleable user interfaces
- 3D facsimile sampling and reproduction

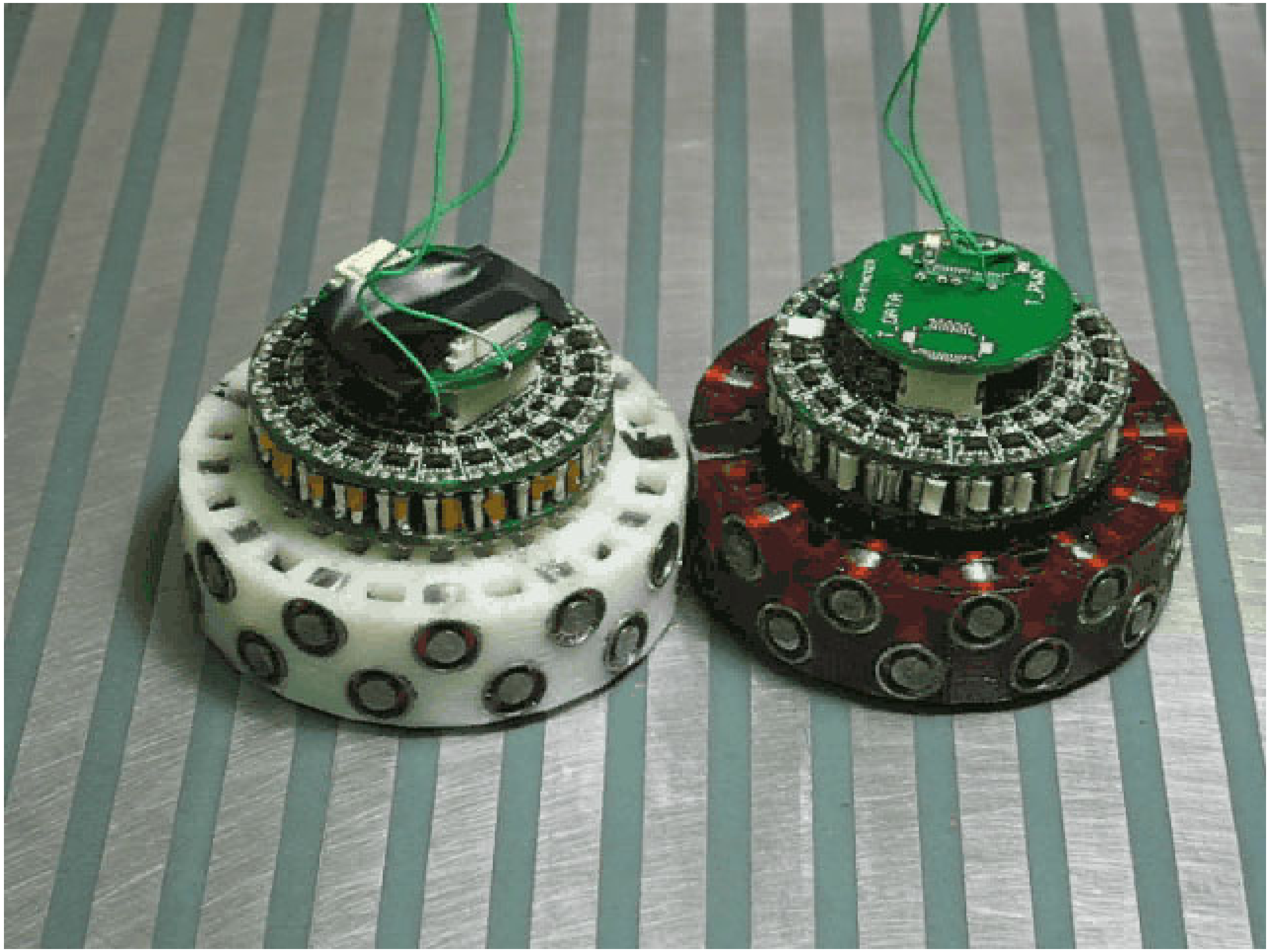
Some Aspects of Shape Control

- Stretchable/shrinkable “lattices”
- Linear actuators, even with spherical modules
- Larger forces than those possible from a pair of modules alone
- ~Millions of cooperating modules
  - Must reduce overall control complexity
  - Need to deal with failures and variability locally
- Likely trade off spatial resolution (module size) vs. increase strength of each module’s actuators

Mesoscale prototype catoms

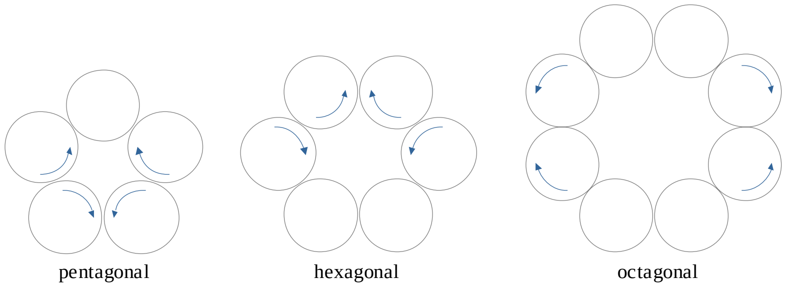
- Cylindrical (~5cm = 2 inch across)
- Electromagnetic actuators/latches

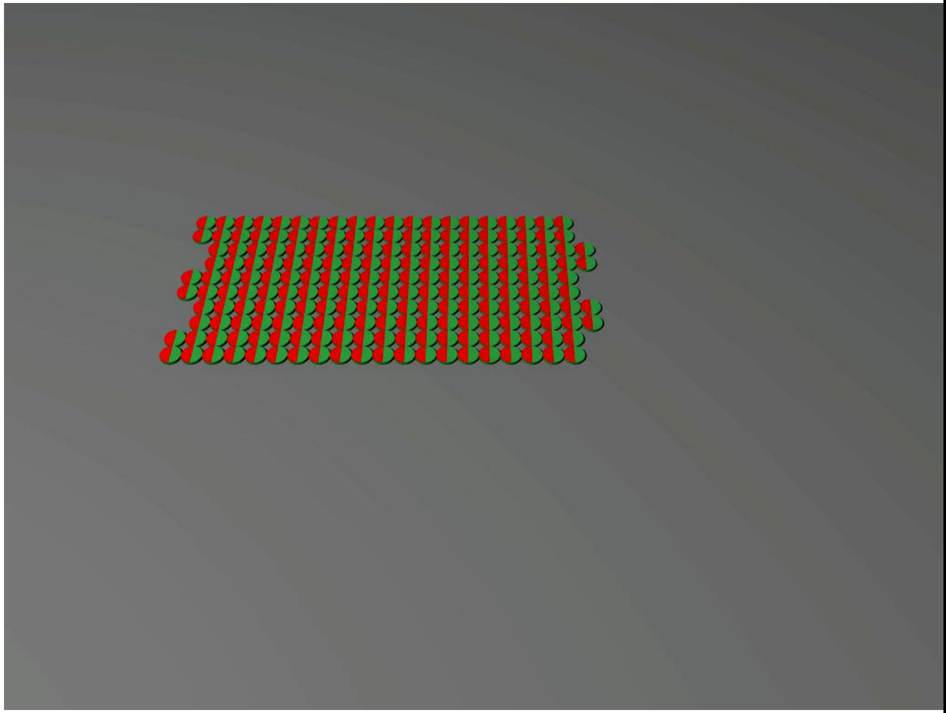
Electromagnetic Rolling Demo



Physical Manipulation Cast as a Software Problem: “Collective Actuation”

Compose groups of catoms where
the outside dimensions change via internal rolling



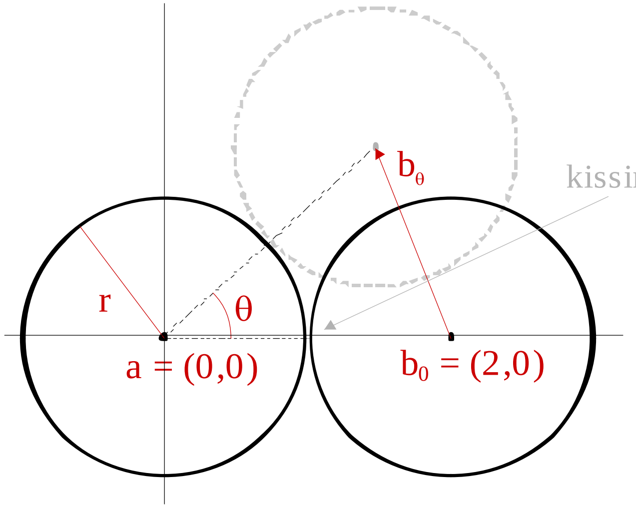


Related Work

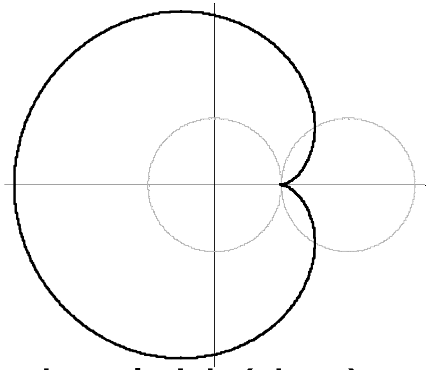
- Parallel Manipulators [Luntz97] [Böhringer]
- Atron chains [Christensen06]
- Rolling locomotion for chain-style MRRs [Atron, Polybot, Superbot]

Kinematics of Module Rolling

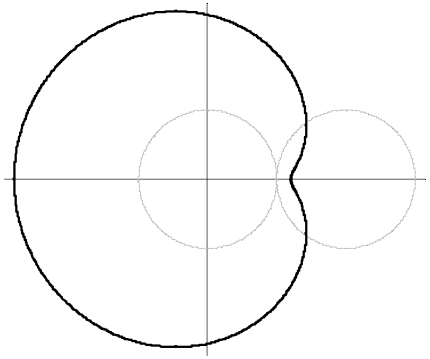
- Treat one module as static, the other as moving
- Center of the moving module traces a circle centered on the static module



- Points outside the center of the moving module trace epitrochoids (or epicycloids for d=r)

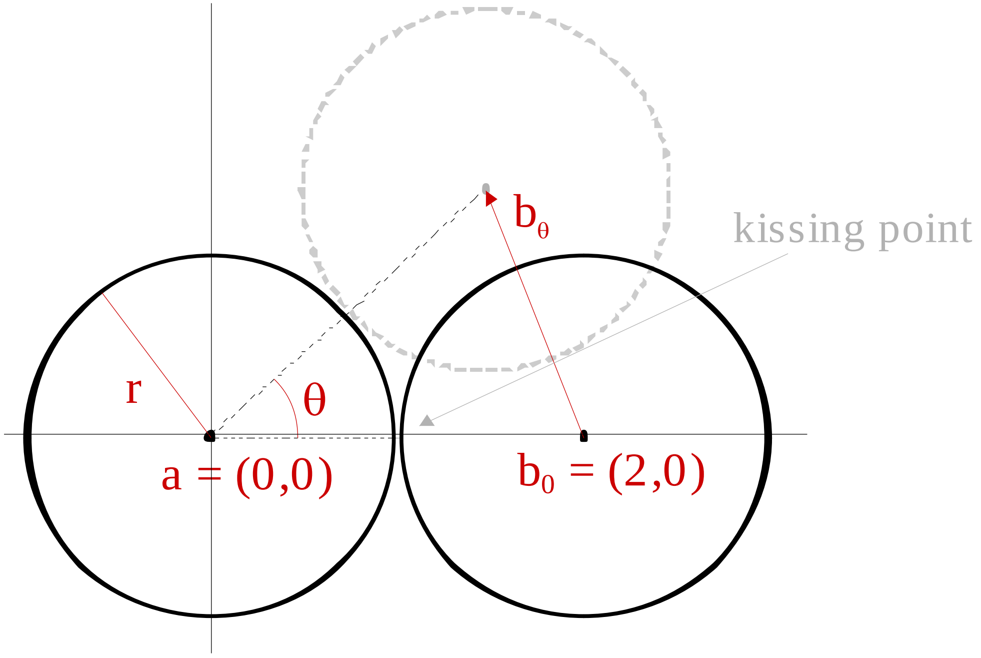


epicycloid (d=r)

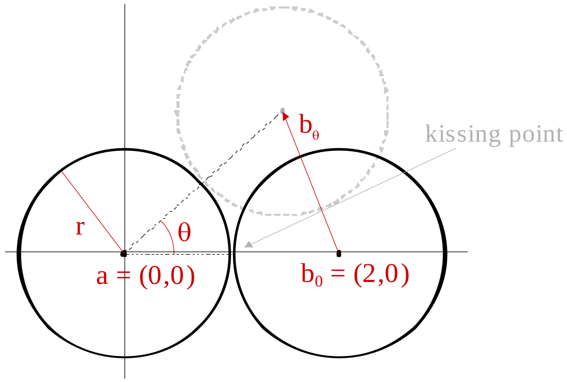


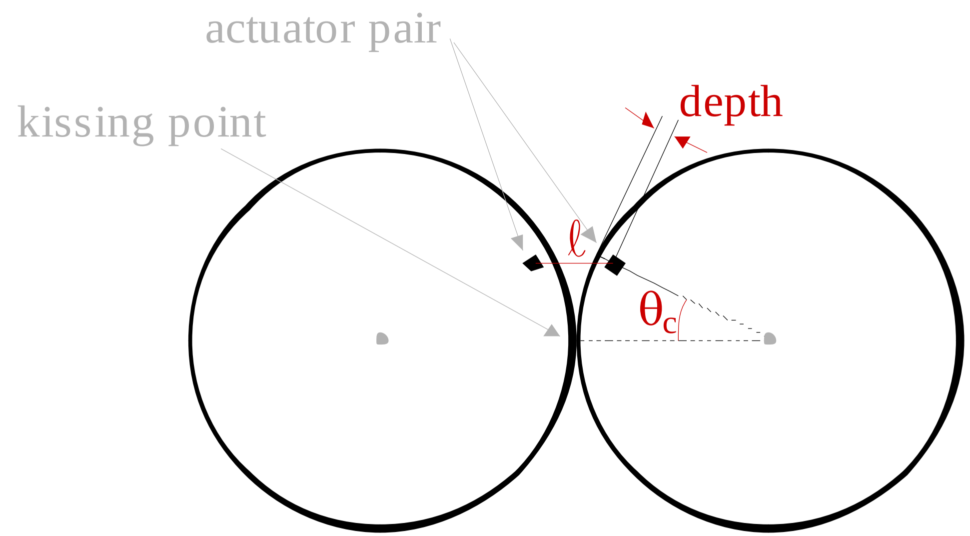
eiptrochoid (d<r)

Motion model: Rolling circular modules

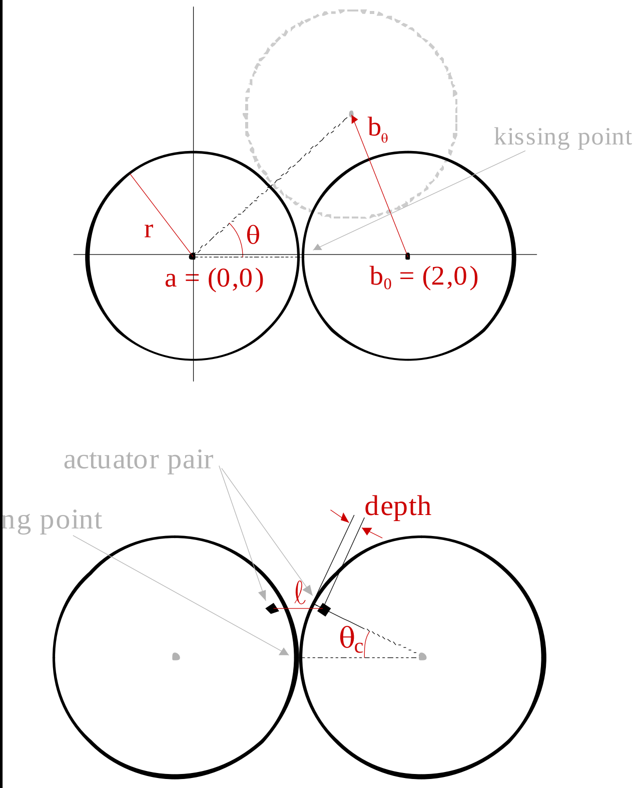


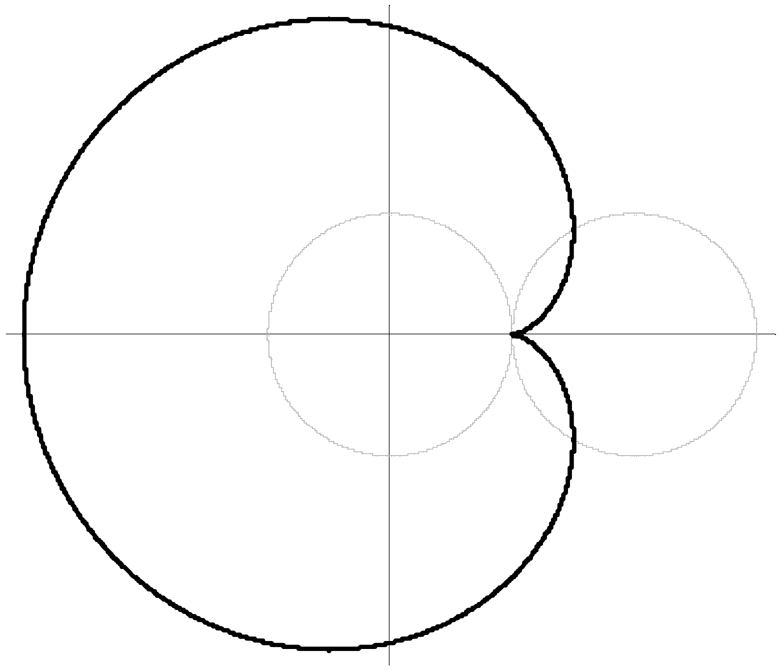
Actuator locations





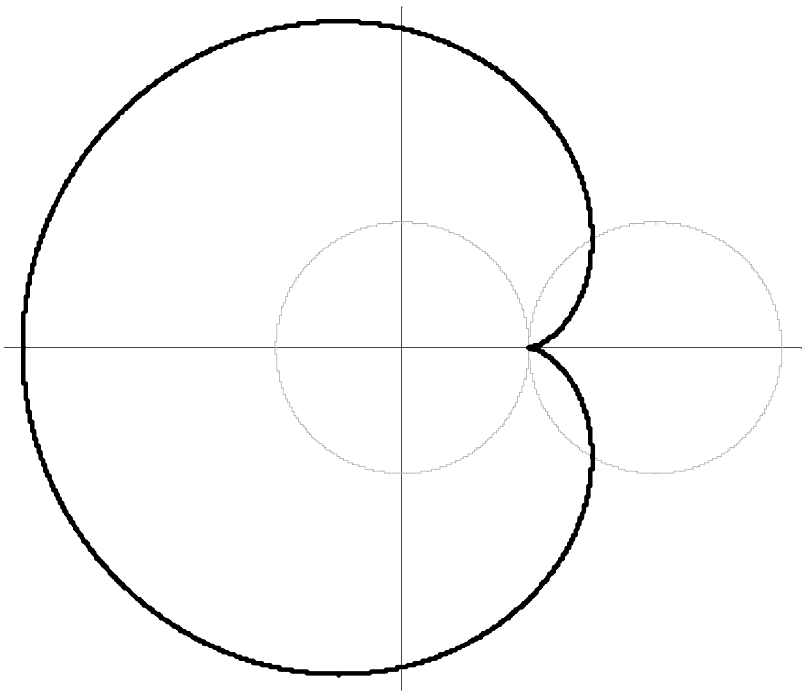
Path of one actuator relative to the other



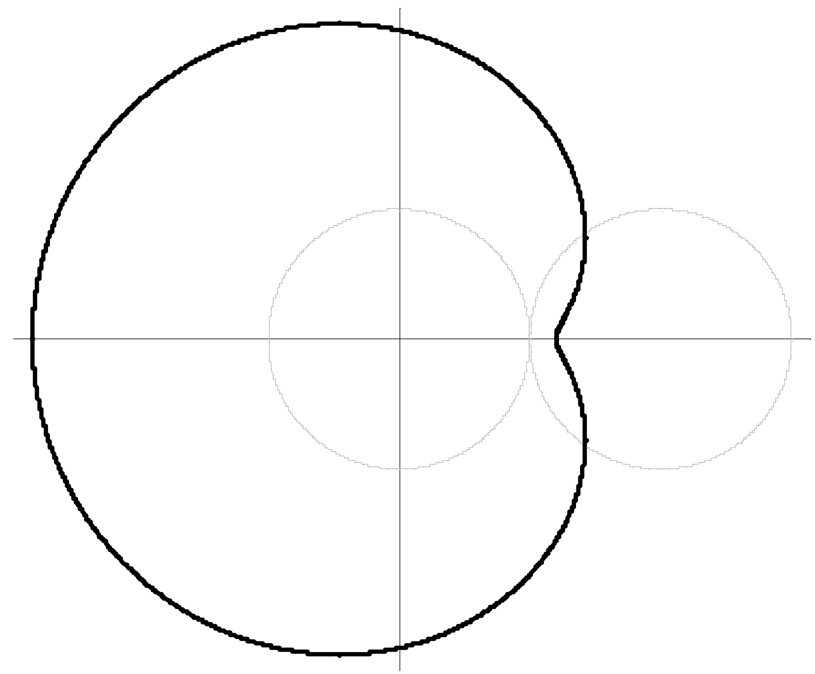


Epicycloid & Epitrochoid

(depth=0)

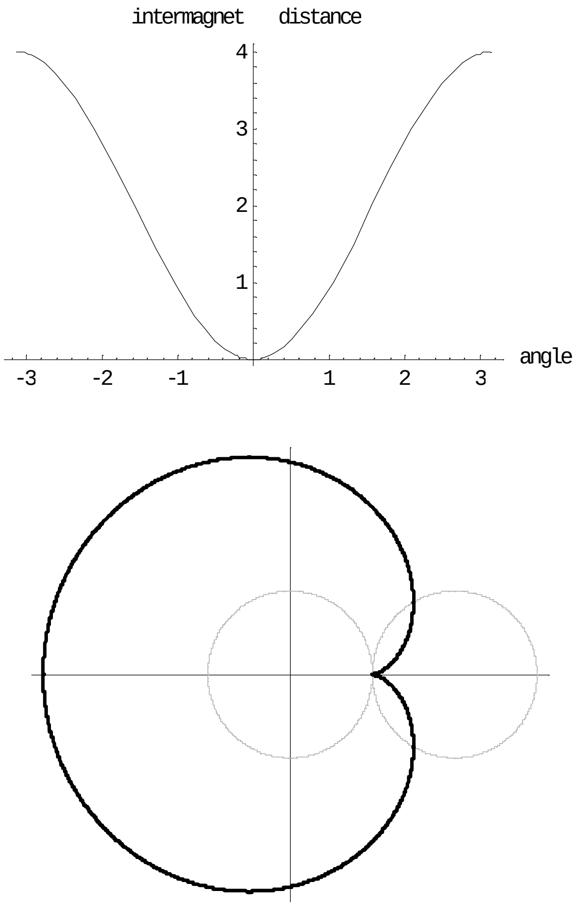


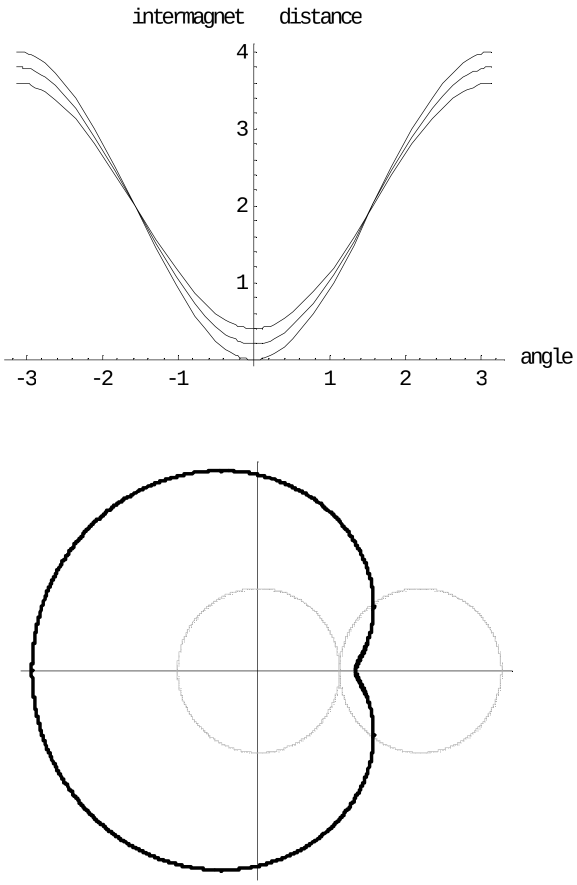
(depth>0)



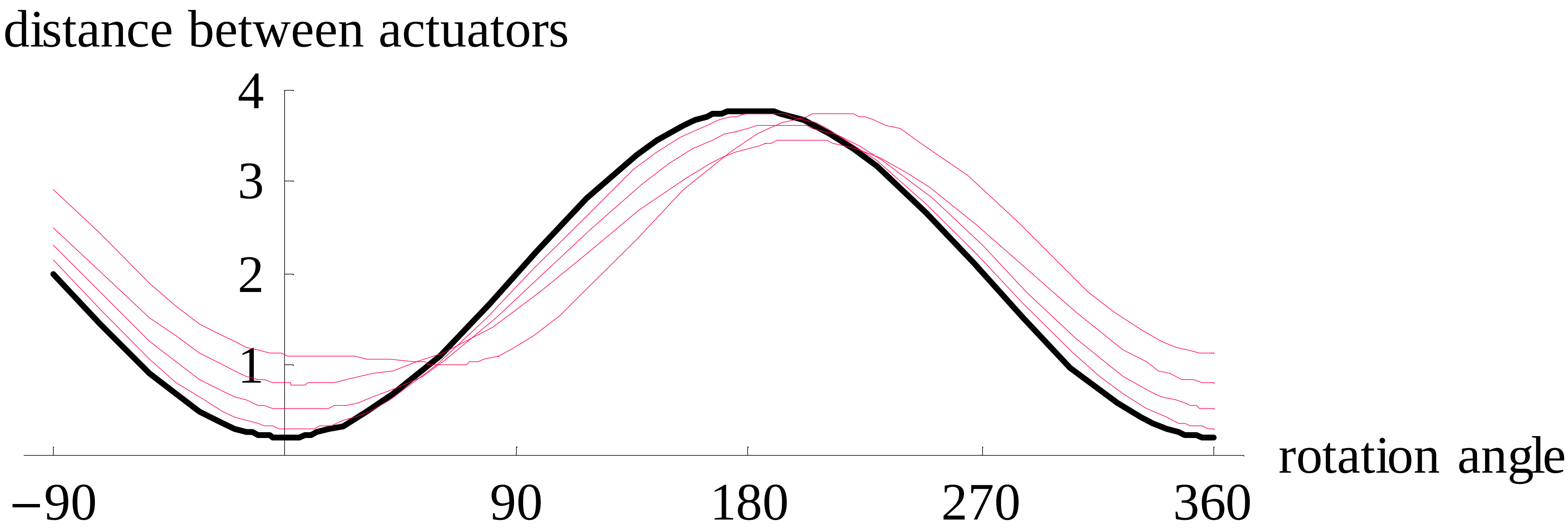
Epicycloid & Epitrochoid

(act. depth=0) (act. depth>0)

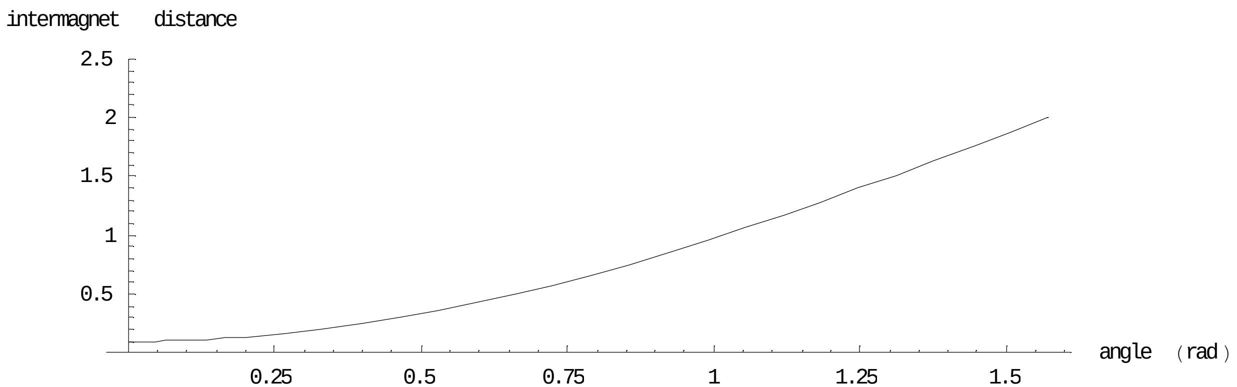




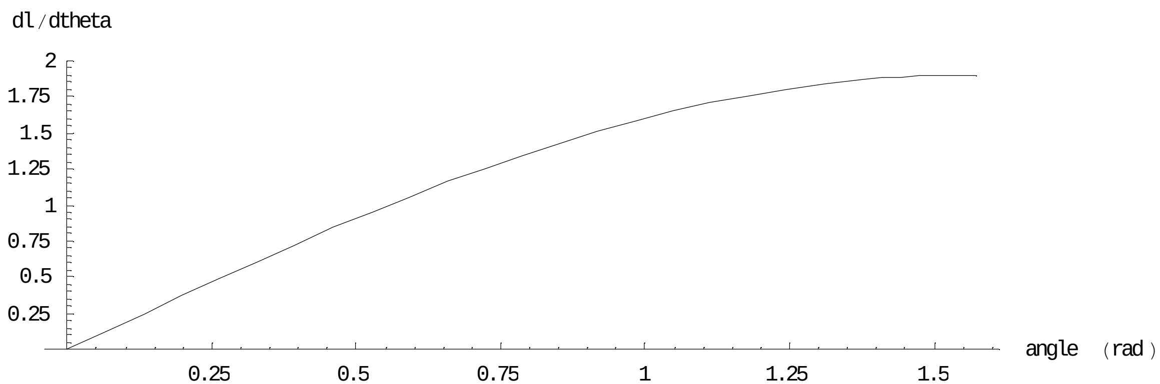
A sinusoidal approximation is close, even for out of phase actuators



Based on the intercatom geometries, we get a varying "lever arm" (i.e., mechanical advantage)



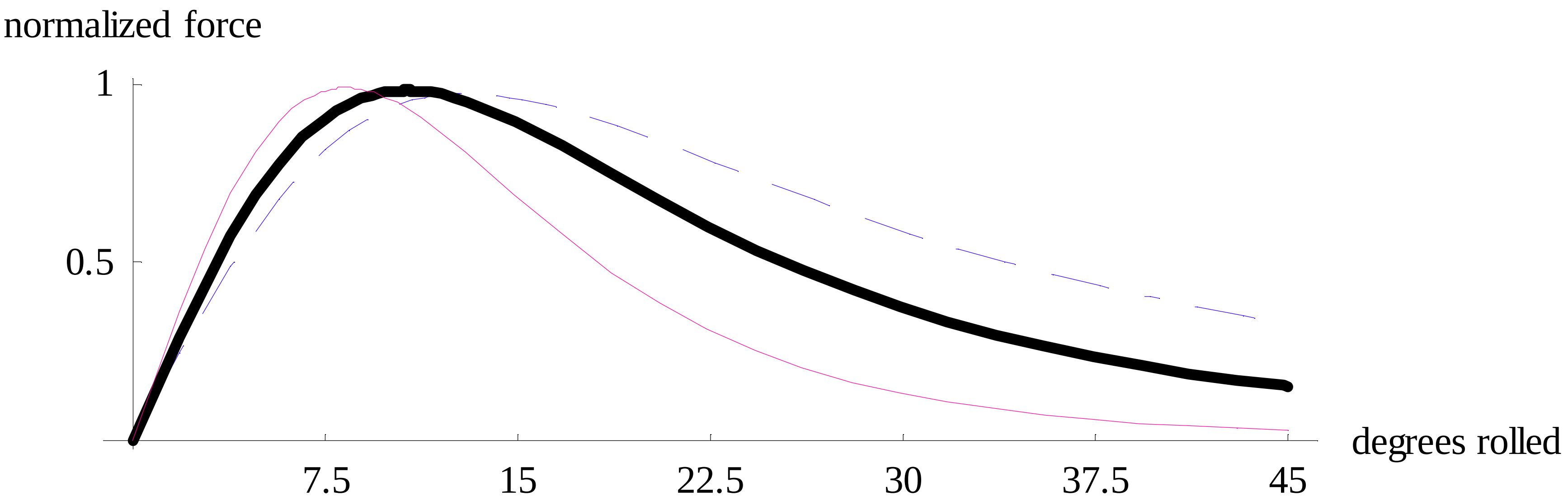
distance between actuators



mechanical advantage

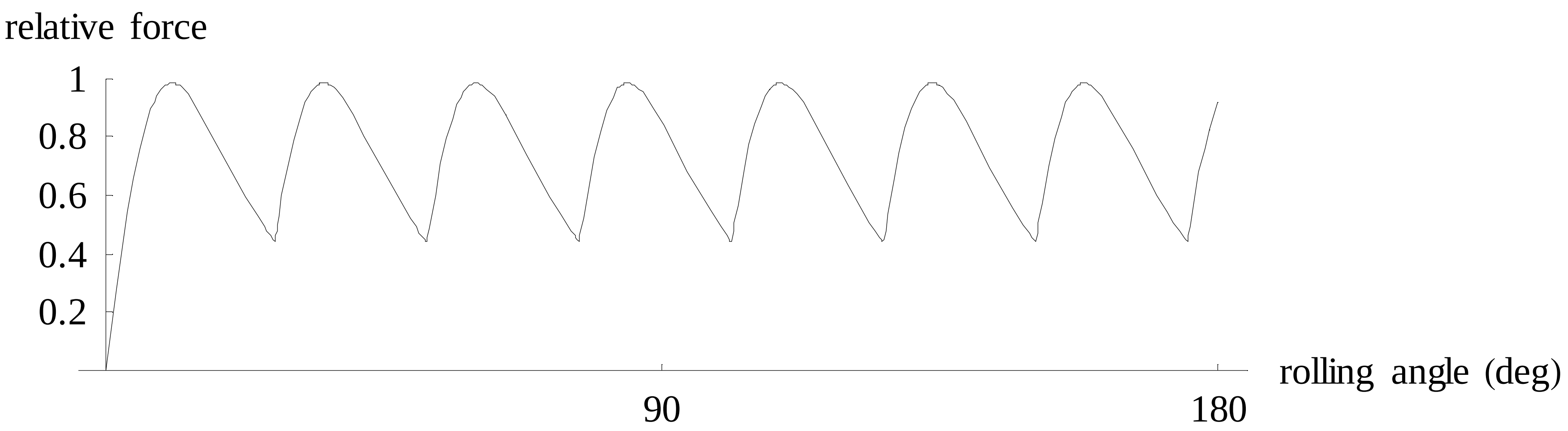
0 angle 180

Combining the effects of lever arm and force law (inverse square, etc.)



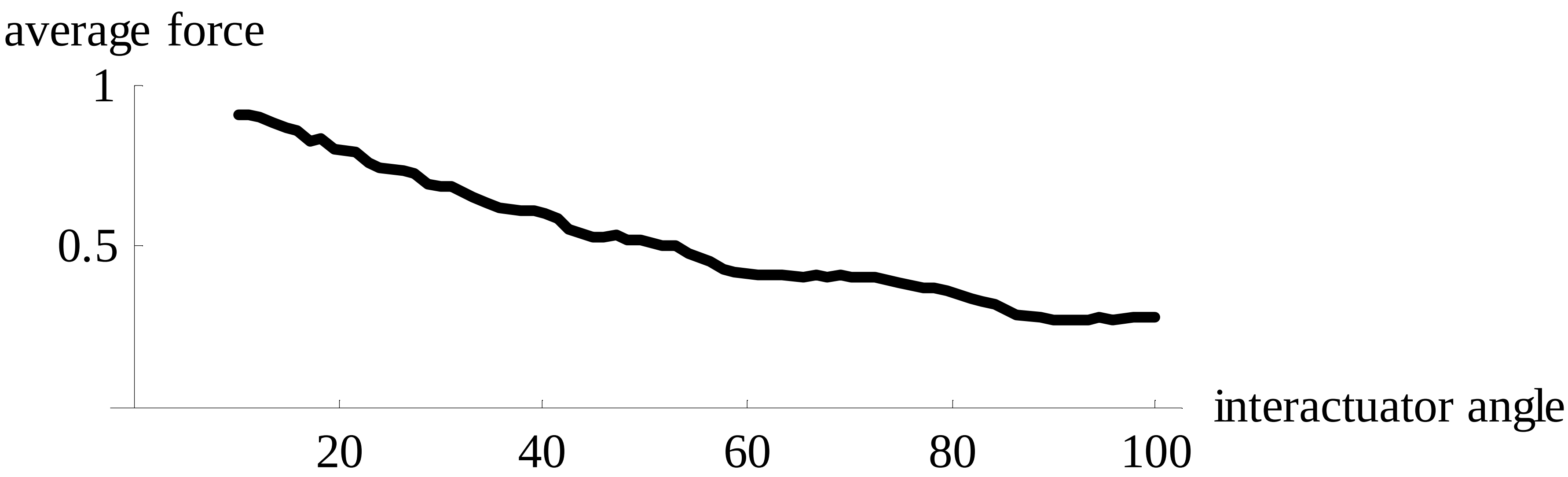
red = inverse cube
black = inverse square
blue = inverse semilog

Composing multiple actuators



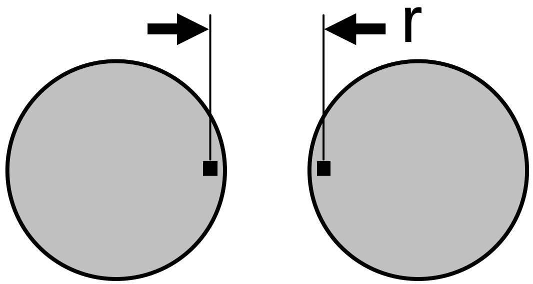
actuator spacing = 25°, d=5%, inverse square law, only one pair of actuators is active at any given time

mean vs peak force over varying interactuator angles



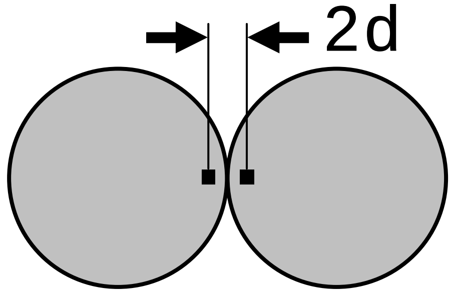
Quantifying actuator force in our unitless analysis

"unit" force



f_m

max force



f_{max}

Math (see the paper for details)

$$b = \begin{bmatrix} 2r\cos\theta \\ 2r\sin\theta \end{bmatrix} \qquad \frac{db}{d\theta} = \begin{bmatrix} -2r\sin\theta \\ 2r\cos\theta \end{bmatrix}$$

$$\ell = \begin{bmatrix} (1-d)r - 2r\cos\phi + (1-d)r\cos 2\phi \\ -2r\sin\phi + (1-d)r\sin 2\phi \end{bmatrix} = \begin{bmatrix} -2r(\cos\phi)(1+(d-1)\cos\phi) \\ -2r(1+(d-1)\cos\phi)\sin\phi \end{bmatrix}$$

$$|\ell| = 2r + (2rd - 2r)\cos\phi$$

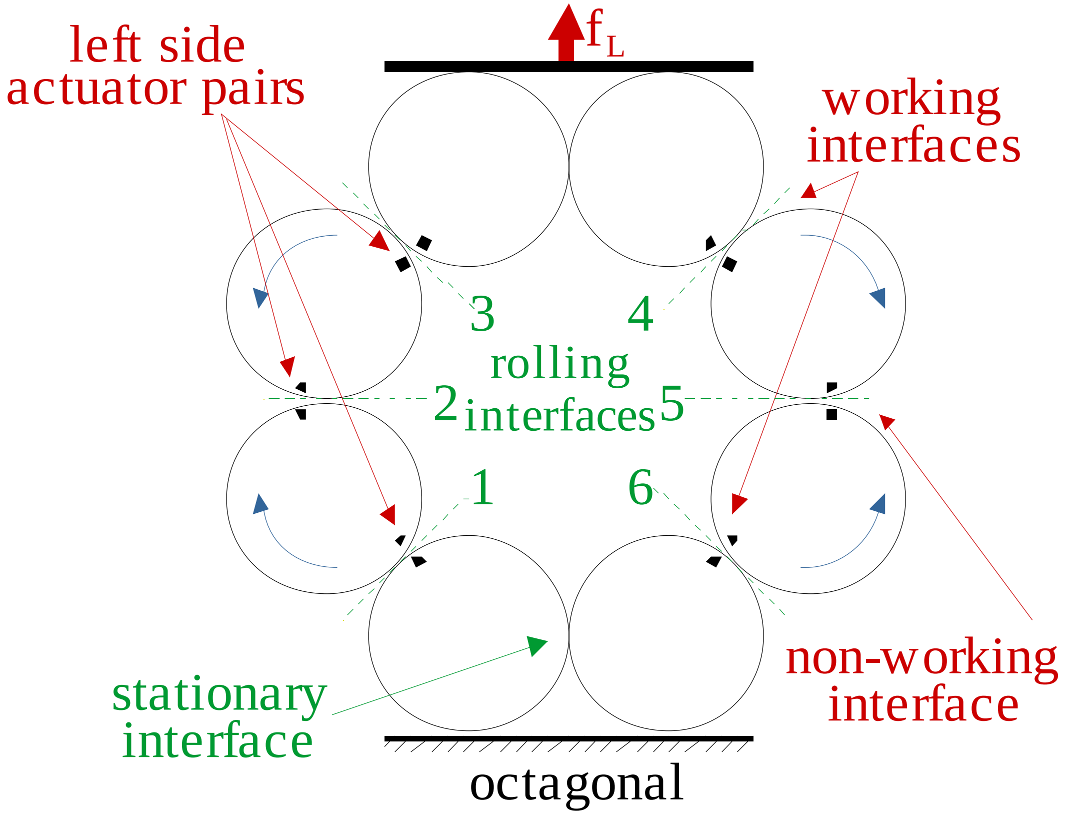
$$\frac{d|\ell|}{d\phi} = 2r(1-d)\sin\phi$$

$$\frac{db}{d|\ell|} = \frac{db}{d\theta}\cdot\frac{d\theta}{d|\ell|} = \begin{bmatrix} -2r\sin\theta \\ 2r\cos\theta \end{bmatrix}\cdot\frac{1}{2r(1-d)\sin(\theta_c-\theta)} = \frac{\csc(\theta_c-\theta)}{d-1}\begin{bmatrix} \sin\theta \\ -\cos\theta \end{bmatrix}$$

$$q = \frac{db}{d|\ell|}\ell^{\gamma} = \frac{\csc(\theta_c-\theta)(2r-(2r-2d)\cos(\theta-\theta_c))^{\gamma}}{d-1}\begin{bmatrix} \sin\theta \\ -\cos\theta \end{bmatrix}$$

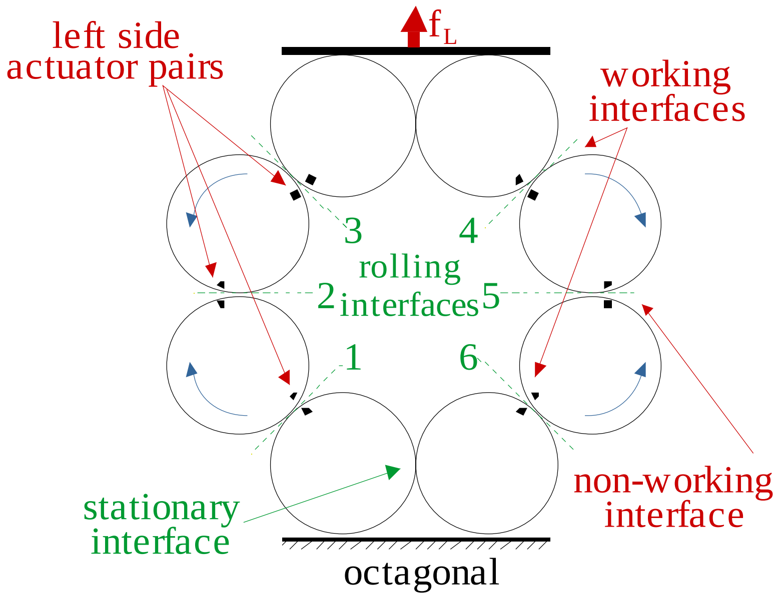
$$f_L = 2\left(\frac{3}{2}\right)\left(\frac{1}{q\bullet\begin{bmatrix} 0 \\ 1 \end{bmatrix}}\right)f_m = \frac{-3(d-1)\cos\theta}{\csc(\theta_c-\theta)(2r-(2r-2d)\cos(\theta-\theta_c))^{\gamma}}f_m$$

Lifting force for an octagonal cell

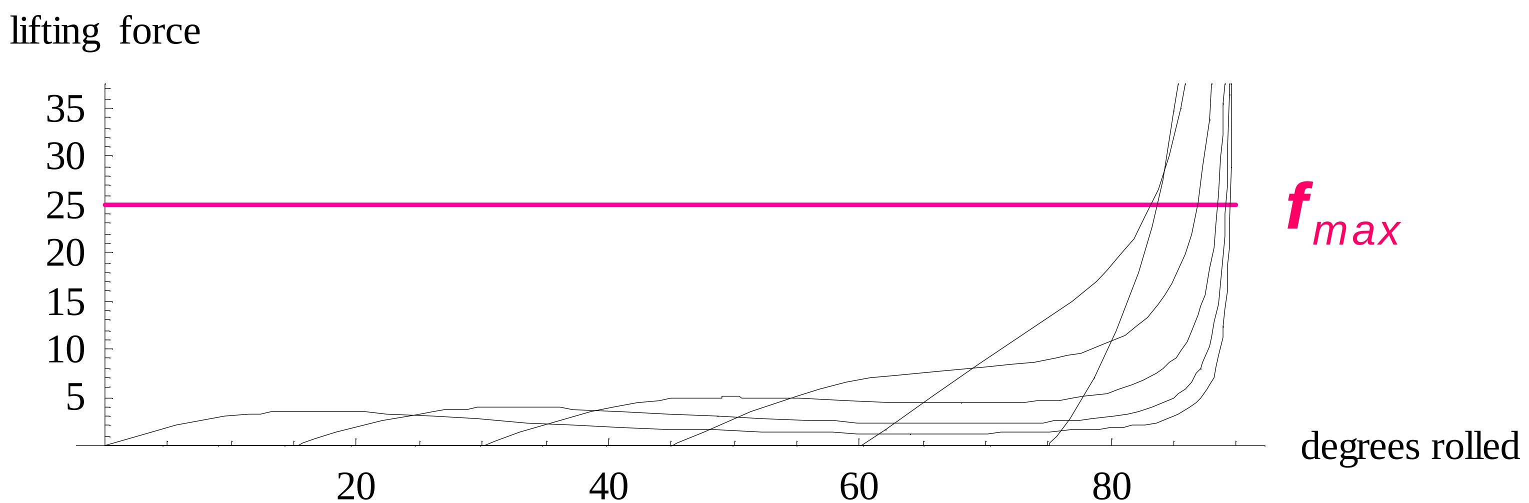


Lifting force for an octagonal cell

$$f_L = 2\left(\frac{3}{2}\right)\left(\frac{1}{q \bullet \begin{bmatrix} 0 \\ 1 \end{bmatrix}}\right) f_m = \frac{-3(d-1)\cos\theta}{\csc(\theta_c - \theta)(2r - (2r - 2d)\cos(\theta - \theta_c))^{\gamma}} f_m$$

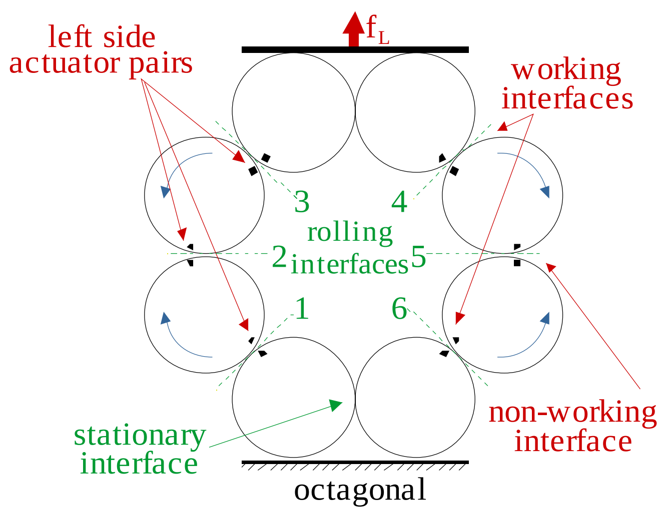


Lifting force for an octagonal cell

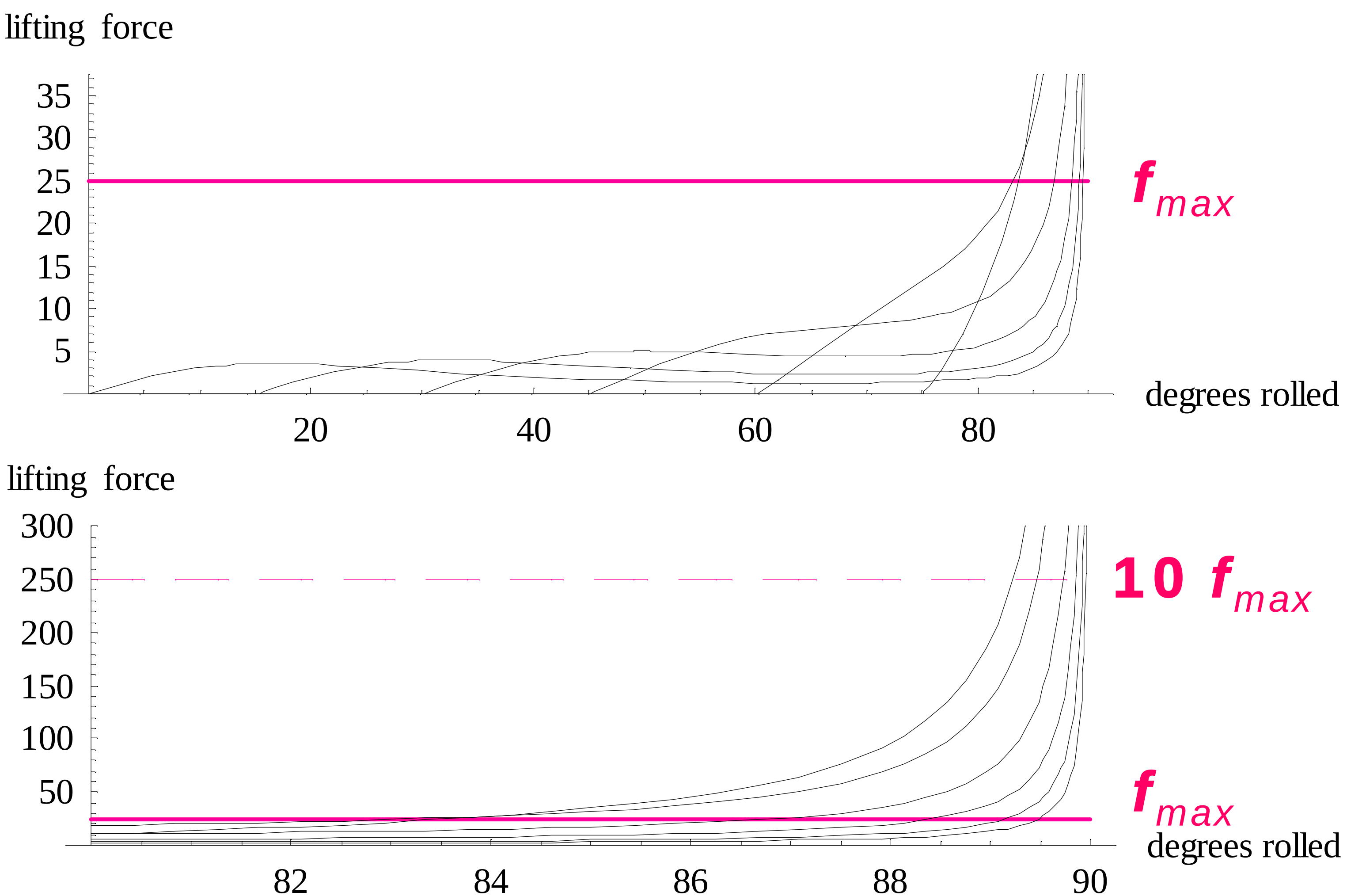


(d=10%, inverse square law)

$$f_L = 2\left(\frac{3}{2}\right)\left(\frac{1}{q \bullet \begin{bmatrix} 0 \\ 1 \end{bmatrix}}\right) f_m = \frac{-3(d-1)\cos\theta}{\csc(\theta_c - \theta)(2r - (2r - 2d)\cos(\theta - \theta_c))^{\gamma}} f_m$$

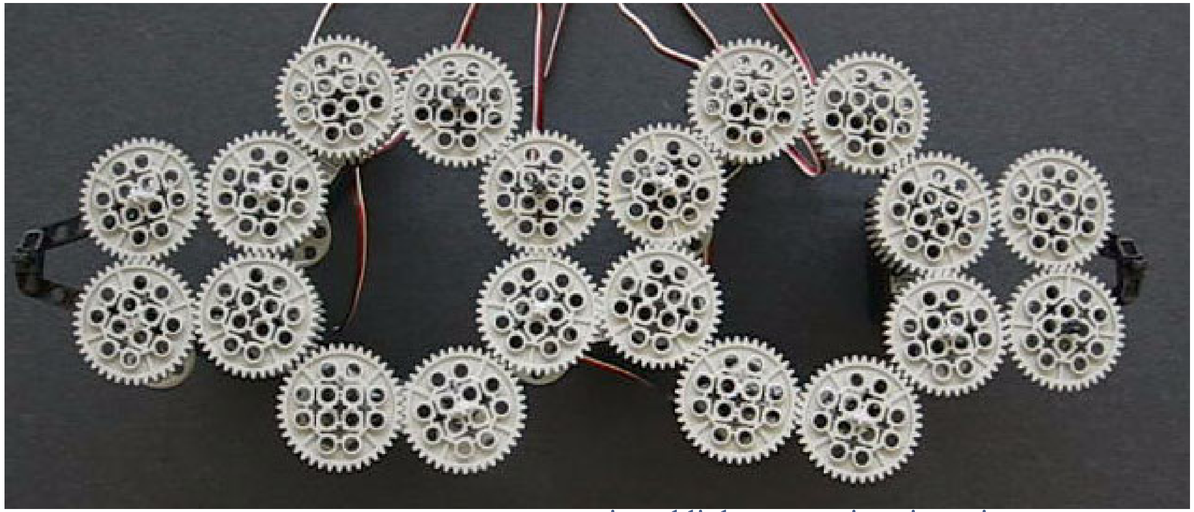


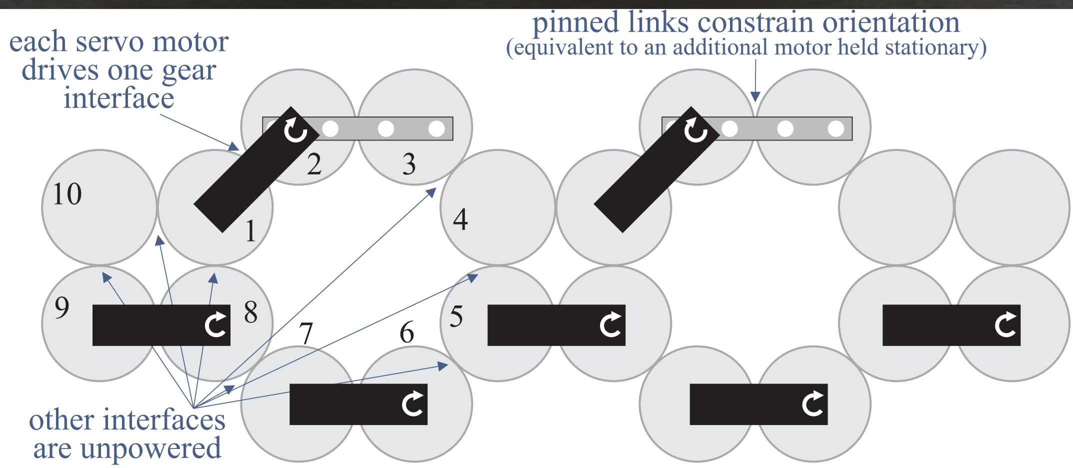
Lifting force for an octagonal cell



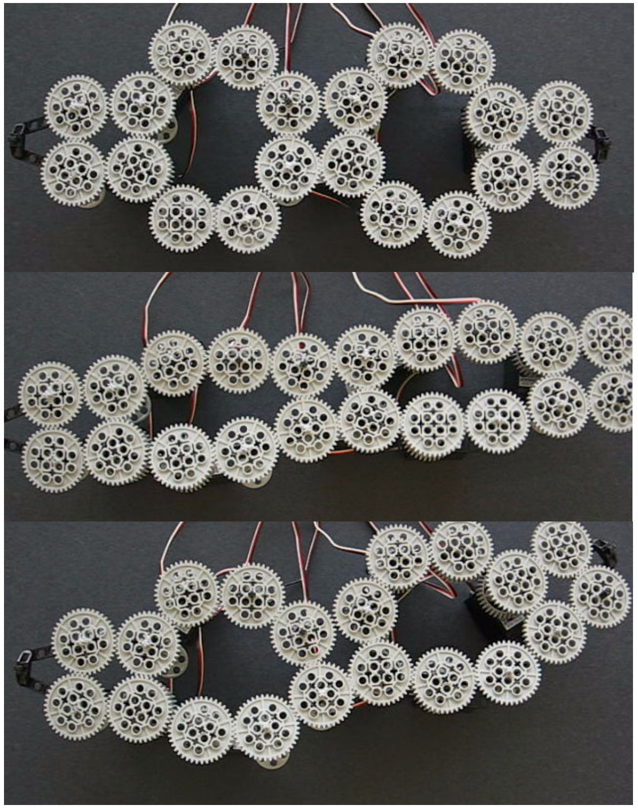
d=10%, inverse square law

Experiment: Self-Articulating Structures

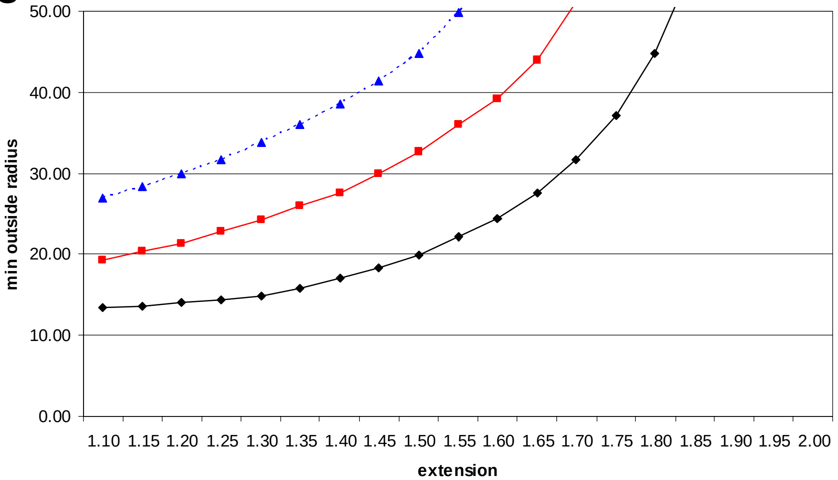




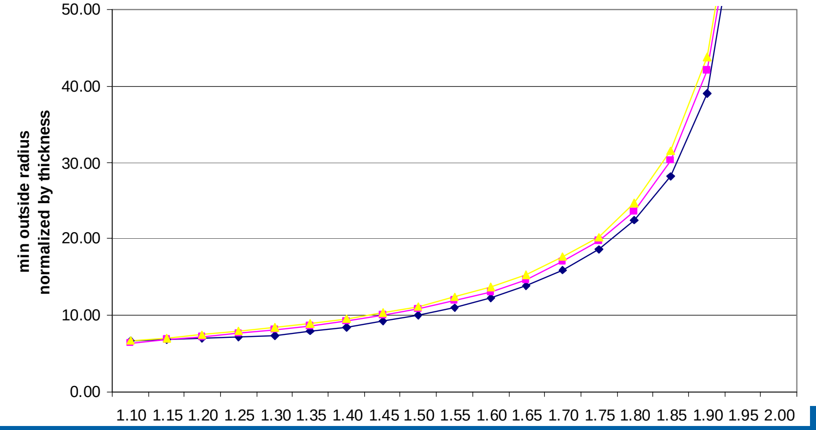
Experiment: Self-Articulating Structures



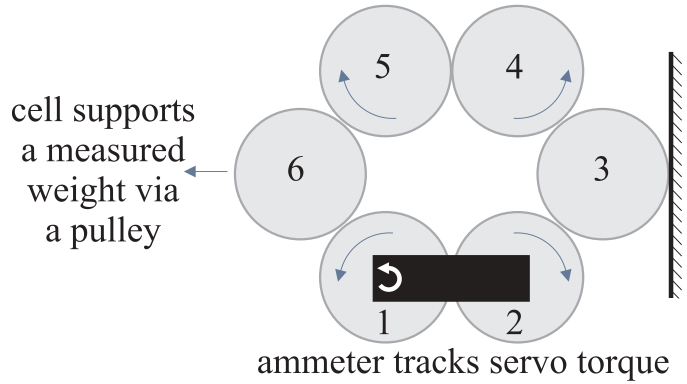
tightest curvature achieved vs extension

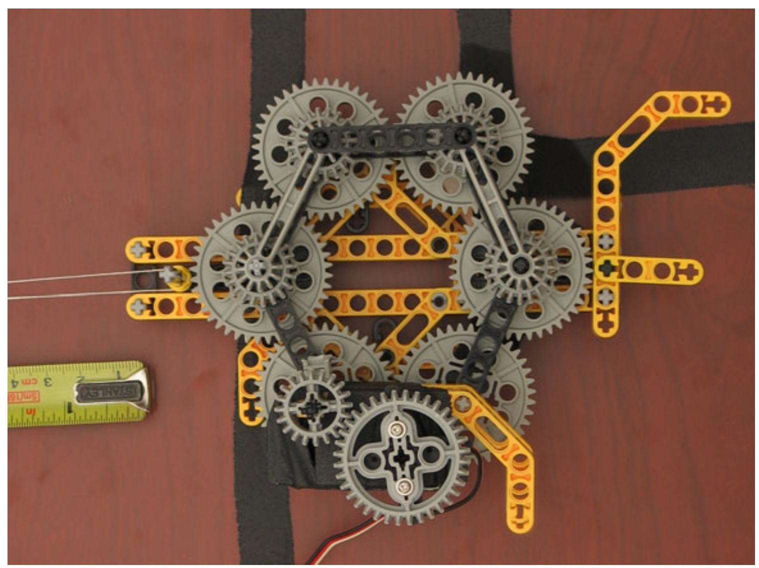


curvature normalized to beam thickness



Experiment: Force Test Cell





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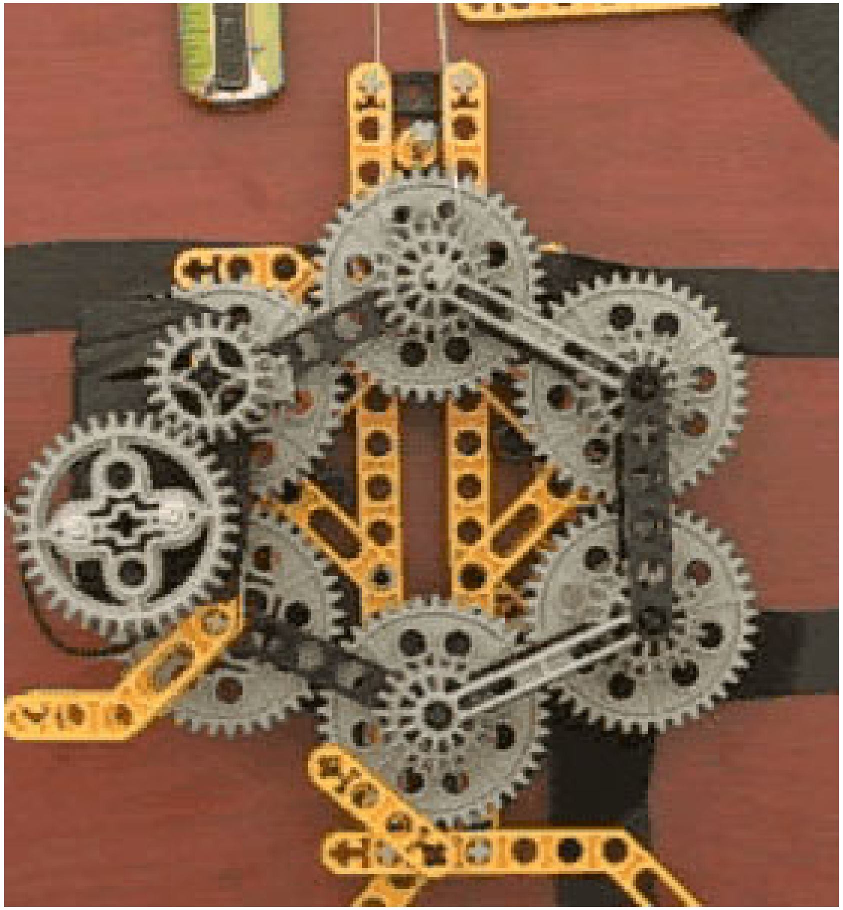
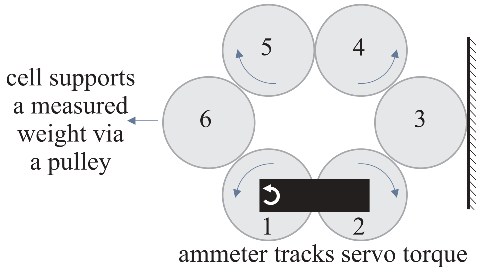
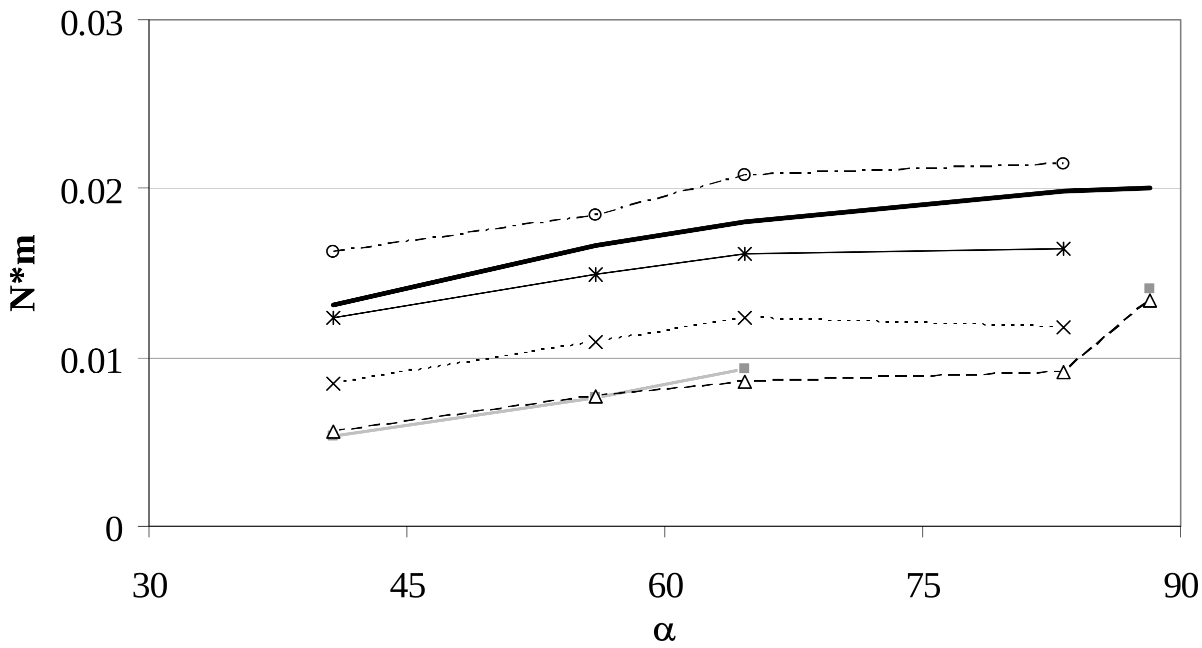
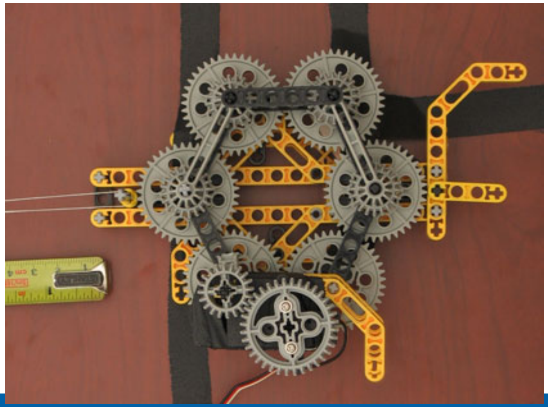


Experiment: Force Test Cell

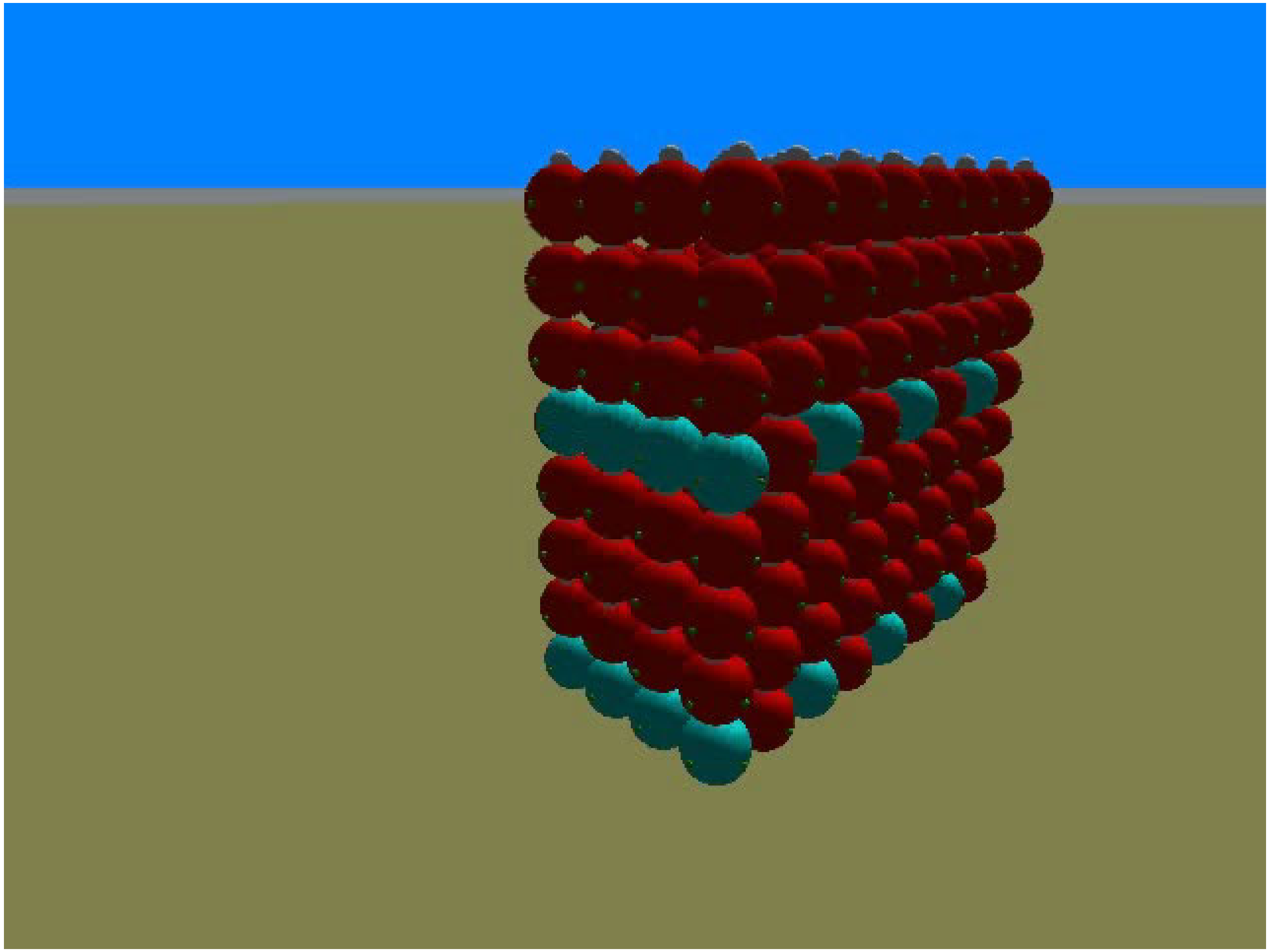






Pinned gears + Servos

3D Simulation



Control Complexity / Bandwidth Observations

- **Reduced DOF**: Collective Actuation cells offer a reduced degree-of-freedom means of commanding the structure
- **Potential for Aggregation**: Depending upon the shape, adjacent cells may be combined into single logical entities for control purposes
- **Scalability**: Arrays of cells can control large structures with control complexity proportional to the number of desired degrees of freedom in the shape

What works

- **Kinematic Simulation**: octohedral & hexahedral cells in 2D; octohedral in 3D
- **Kinematic Prototypes**: Pinned 2D cells using toothed gears & servos
- **Force-at-distance Driven Prototypes**: Magnetically-retained/driven 2D versions using permanent magnets (illustrate force curves around fixed operating points)

Selected Unsolved Problems

- Stability of rolling modules, particularly in 3D
- Hardware: Robustness of our current force-at-distance actuators is low – so far our electromagnet prototypes don't work sufficiently reliably to test this technique
- Distributed Control Algorithm (see future work by Ram Ravichandran)
- Dynamics
- Exploit nonuniform failure modes: It is possible to predict which bonds will break when a cell is overloaded – use this property to strengthen cells or detect and respond to failures

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