Manipulation: Mechanisms, Grasping and Inverse Kinematics

RSS Lectures 14 & 15

Monday & Wednesday, 1 & 3 April 2013

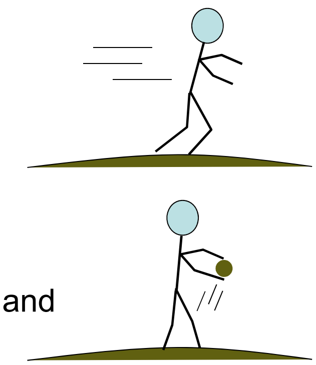
Prof. Seth Teller

Overview

- Mobility and Manipulation
  - Manipulation Strategies
- Mechanism Analysis
  - Instantaneous Center
  - Reuleaux's Method
- Multi-Finger Manipulation
  - Grasp Analysis
  - Grasp Synthesis
  - Forward Kinematics
  - Inverse Kinematics
  - Grasp Planning
- Lab 7 Preview

Mobility / Manipulation Duality

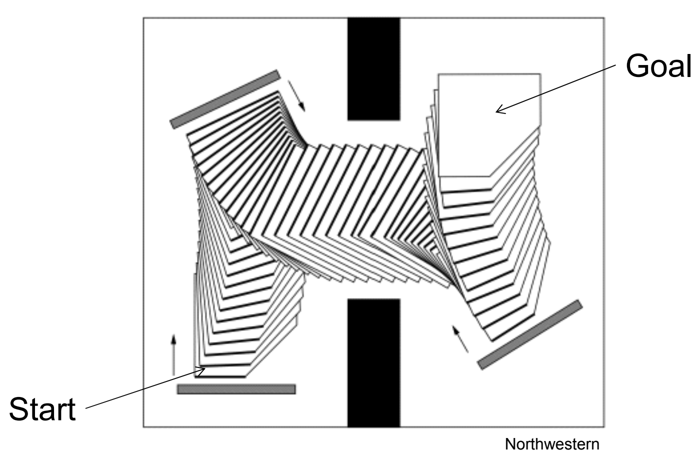
- Mobility:
  - Earth is fixed
  - Legs apply forces to earth
  - Reaction forces move body
- Manipulation:
  - Body is fixed to earth
  - Arms apply forces to manipuland
  - Forces move manipuland



- Goal of Field: Mobile Manipulation
  - Use of *coordinated whole-body motion* to effect desired manipulation of manipuland, environment
  - Examples: Lifting a sandbag, throwing a baseball, shoveling snow, replacing a ceiling smoke detector

Manipulation by Pushing

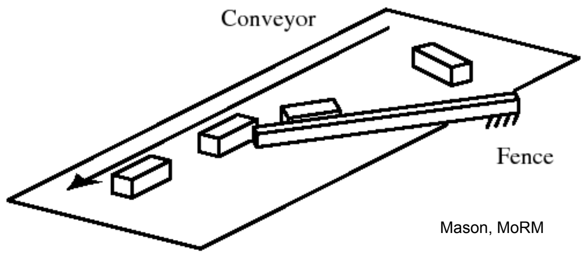
- Stable push:
  - Motions that keep object in *line* contact w/ manipulator



  - Motion planning, but with additional constraints

Fixturing

- Use of designed pegs, surfaces, prior knowledge of manipuland geometry to achieve desired pose

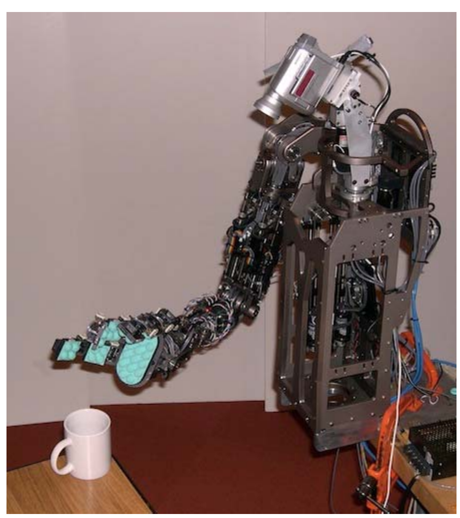


Mason, MoRM

- Goldberg's "part squeezer" (Try it!)

Soft-finger Manipulation

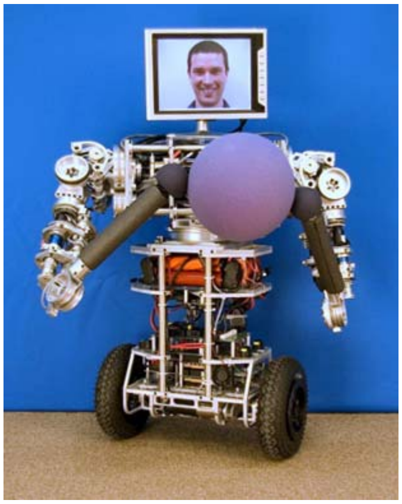
- Can exploit visual/tactile sensing & feedback



Obrero / MIT

Mobile, Two-handed Manipulation

- Challenges: mass distribution; uncertainty



uBot / UMass Amherst

End Effectors

- The component that usually comes into intentional contact with the manipuland
- Often attached interchangeably to robot arm
  - … like a human hand picking up a specialized tool
- Many designs (here ordered roughly by time)

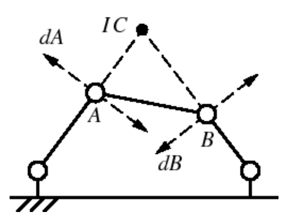
Manipulation Challenges

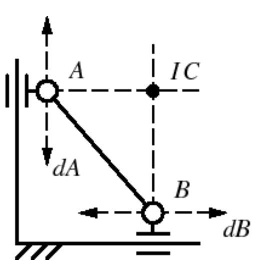
CMU robot "Herb" (Home Exploring Robot Butler, also after Herb Simon)

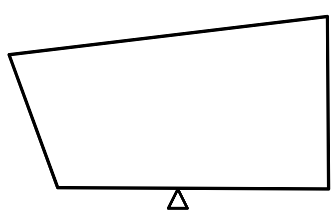
How can the robot *perceive* the object's type and pose?
How can the robot *reach for* the object?
How can the robot *grasp* the object?
How can the robot *move* the object where desired?
… Today we'll focus on grasping.

Mechanism Analysis

- Given some set of constraints, how can the motion of an object be characterized?
  - Rotating links
  - Sliding links
  - Point contacts



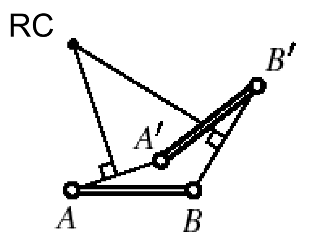




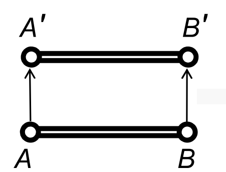
Figures from Mason, MoRM

Rotation Center (RC)

- Consider *finite* planar displacement of rigid object
  - Some point in the plane is left fixed by displacement
  - This point is called the "rotation center" (RC)
- What if the displacement is a pure translation?
  - Where is the RC?

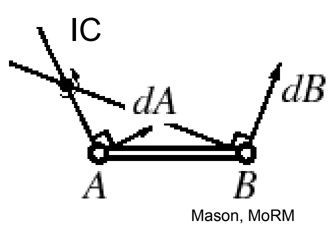


Mason, MoRM

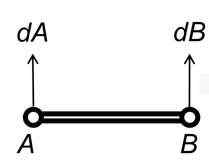


Instantaneous Center (IC):

- Consider a *differential* displacement (i.e. velocity)
  - Displacement still has a fixed point; where is it?
- What if the displacement is a pure translation?
  - Where can the IC lie?

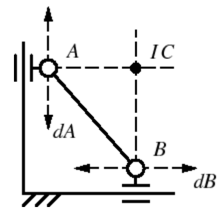


Mason, MoRM

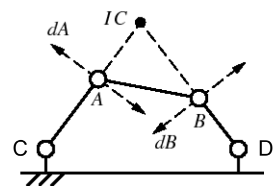


Use of IC for Mechanism Analysis

- Example four-bar linkage:
  - Base link
  - Two sliding+rotating links A, B
  - Coupler link connecting AB



- Example four-bar linkage:
  - Base link
  - Four rotating links A, B, C, D
  - Coupler link connecting AB

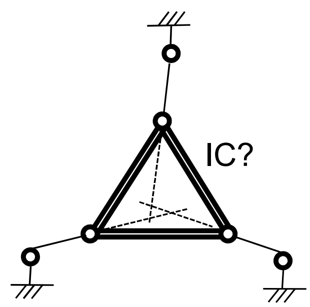


- Constraints on A, B dictate coupler motion
- IC completely determined; characterizes linkage

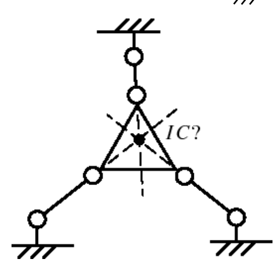
Figures from Mason, MoRM

IC for Mechanism Analysis (cont.)

- Consider this mechanism:
  - IC is



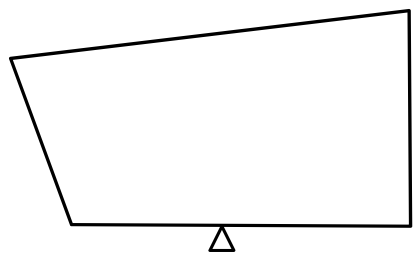
- Another possibility:
  - “False instantaneous center”



Mason, MoRM

Unilateral constraints

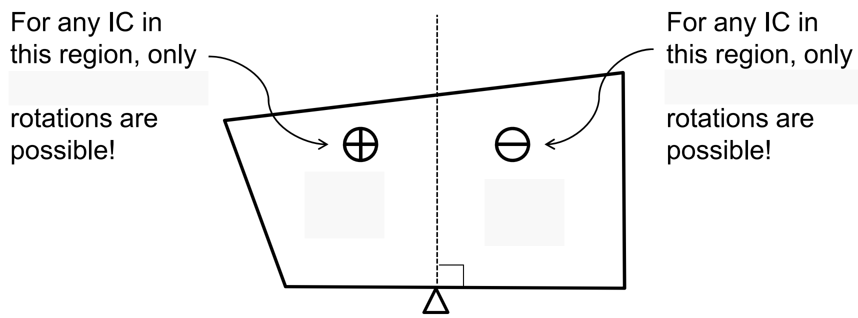
- Point contact with boundary of manipuland
- Manipuland cannot *violate* constraint
  (but it can *separate* from it: thus "unilateral")



- How does this point contact constrain
  the possible motions of the manipuland?

Reuleaux's method (1876)

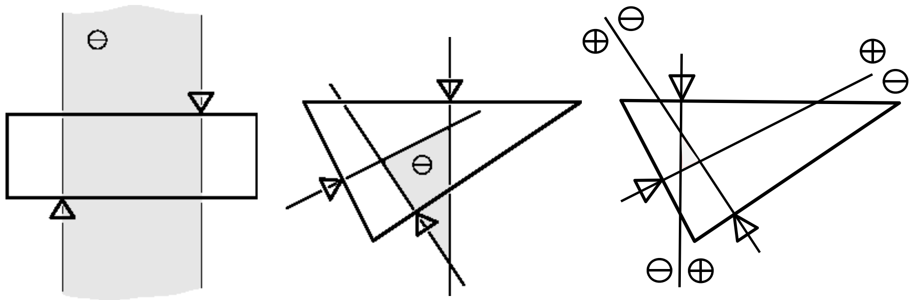
- Each unilateral constraint partitions space of ICs into regions left, right and on *line of contact normal*



- Why is the "line of contact normal" key to analysis?
  - Along it, differential rotation of either sign is possible
    (for now, we are assuming frictionless point contacts)

Reuleaux's method (cont.)

1. Construct line of for each contact
2. Label plane regions as w.r.t. this constraint



3. Each remaining region with
   is a locus of possible instantaneous centers

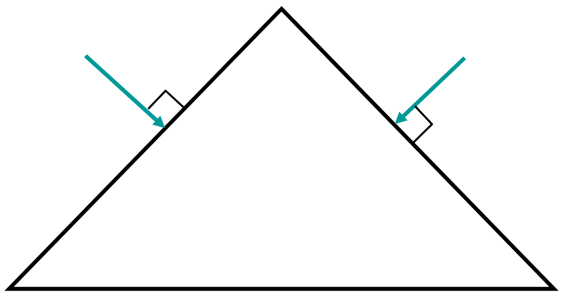
→ Can the IC locus become *empty*? If so, how?

Multi-Finger Manipulation

- Frictionless contacts
- Force-direction closure
- Torque closure
- Contacts with friction

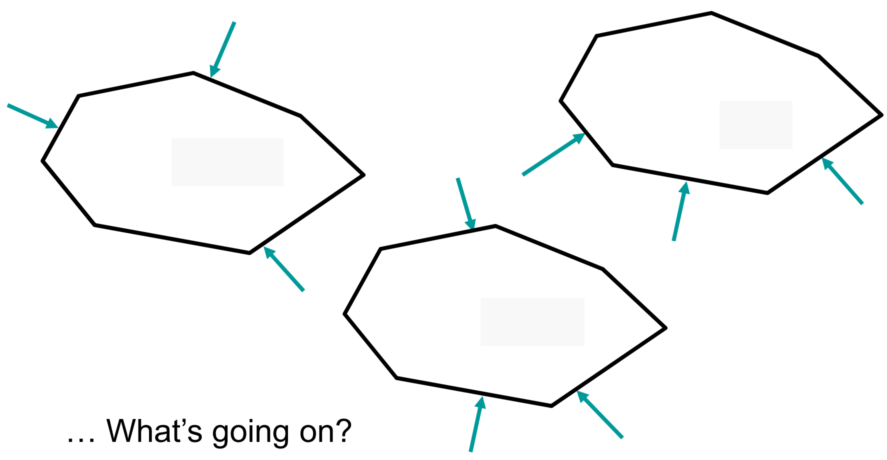
Frictionless Point Contacts

- Force must be normal to object boundary (why?)
- Force must point into object's interior (why?)



Force-Direction Closure

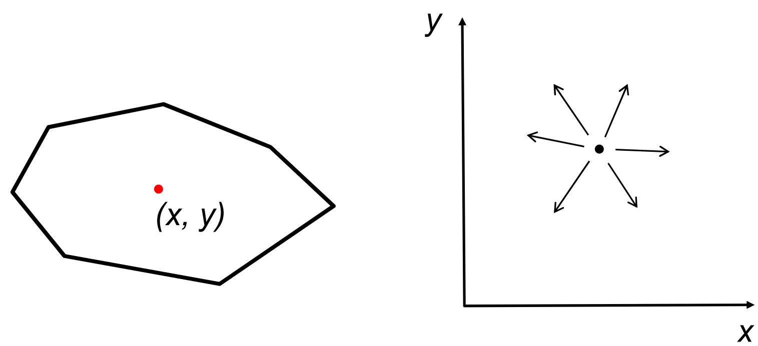
- Under what conditions will a set of point contact forces resist arbitrary planar *translation*?



… What's going on?

How many contacts are needed?

- Analyze situation in c-space with DOF argument
  - First: how many c-space DOFs for object origin?

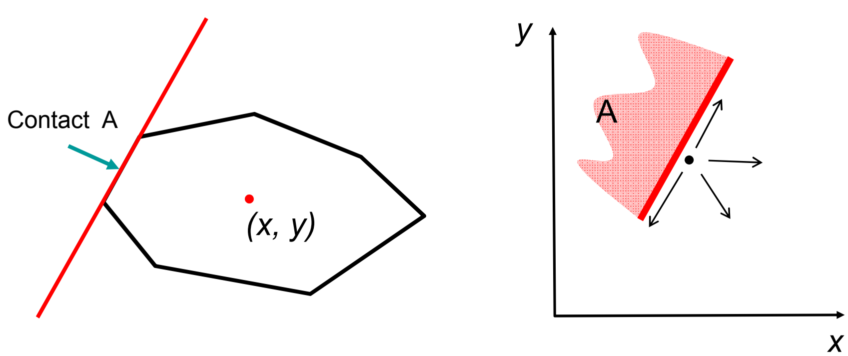


Cartesian space

Configuration space

How many contacts are needed?

- Analyze situation in c-space with DOF argument
  - What does a Cartesian point contact imply in c-space?



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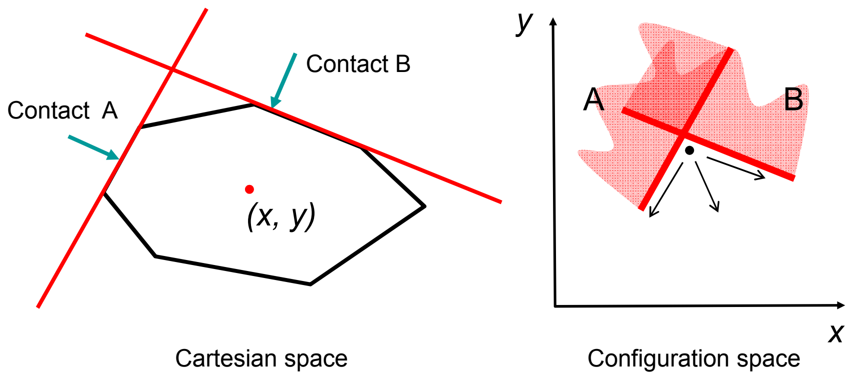

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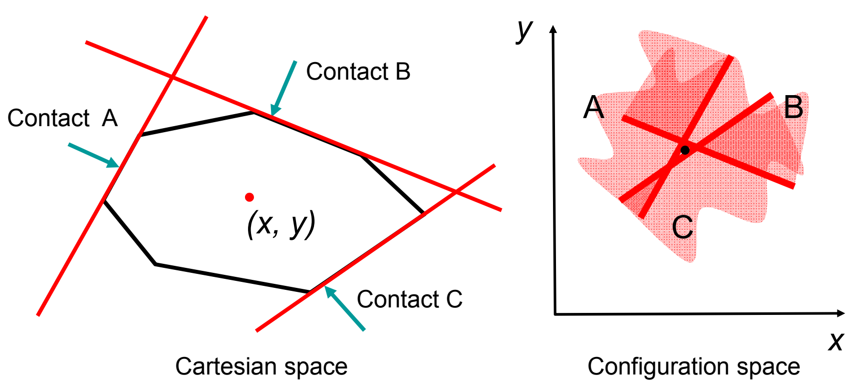
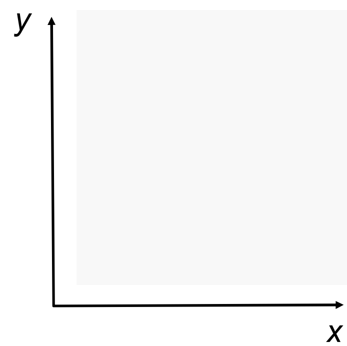


DOF Counting for Translation

- Conclude that contacts are needed in general
  - Are there situations in which more are required?



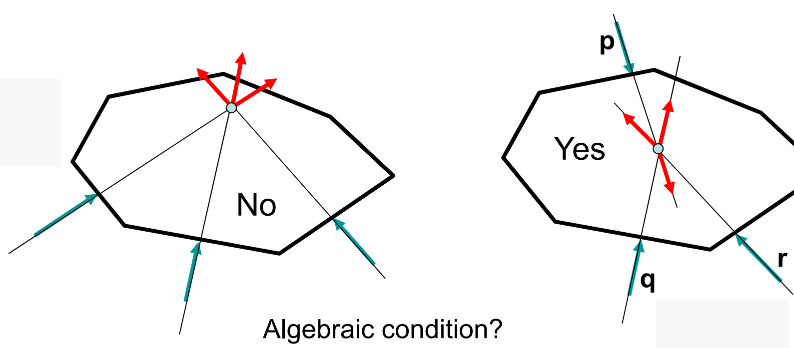
Cartesian space

Configuration space

  - Example of

Conditions for Force-Direction Closure

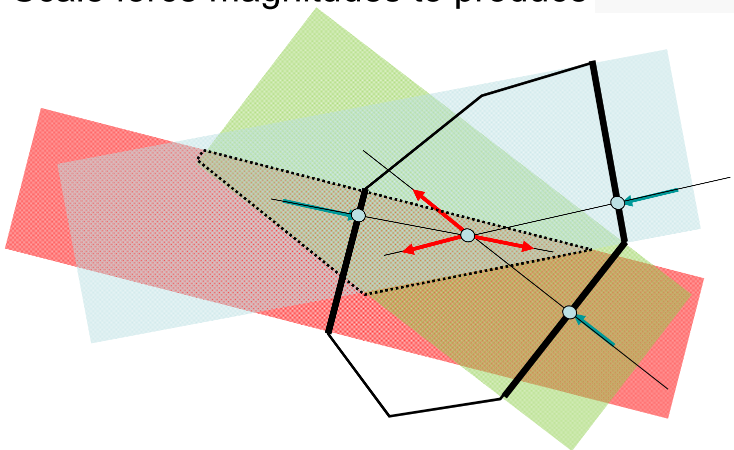
- Force vectors must
- Some positive combination of forces



Algebraic condition?
For force vectors **p**, **q**, **r**,
there must exist $\alpha, \beta, \gamma > 0$
s.t.

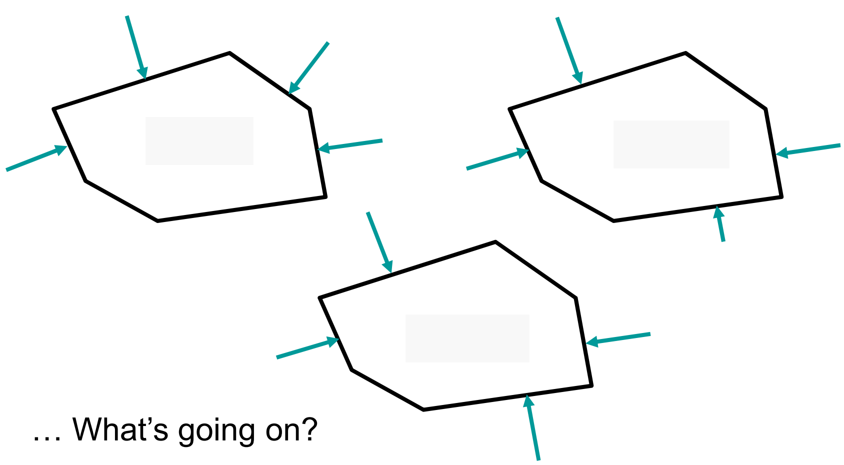
Synthesizing a Force-Direction Grasp

1. Choose admitting a
2. Project onto per-edge
3. Scale force magnitudes to produce



Torque Closure

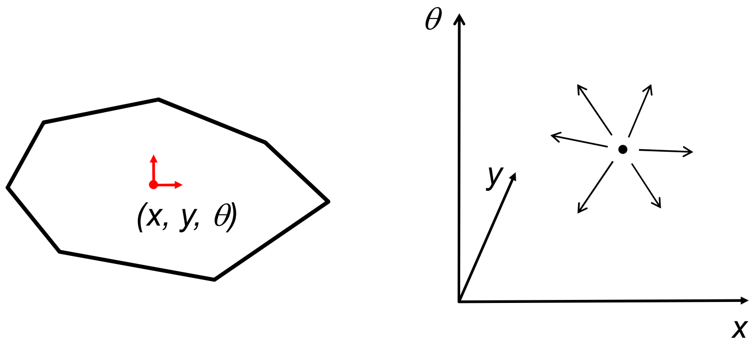
- Under what conditions will a set of point contact forces resist arbitrary planar *rotations*?



… What's going on?

How many contacts to "pin" rotation?

- Use analogous DOF argument in c-space
  - First: how many c-space DOFs for object pose?

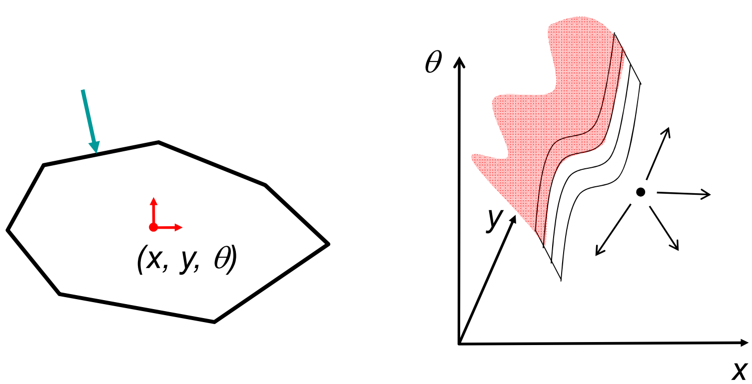


Cartesian space

Configuration space

How many contacts to pin rotation?

- Introduce point contact in Cartesian space
  - Implies c-space constraint with 2D manifold boundary



Cartesian space

Configuration space

How many contacts to pin rotation?

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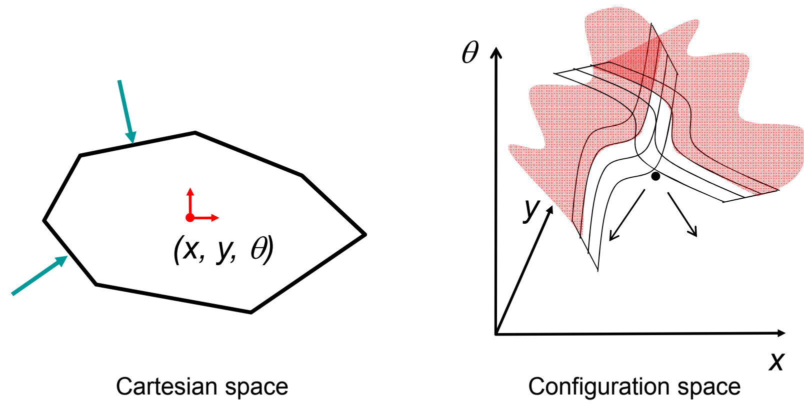
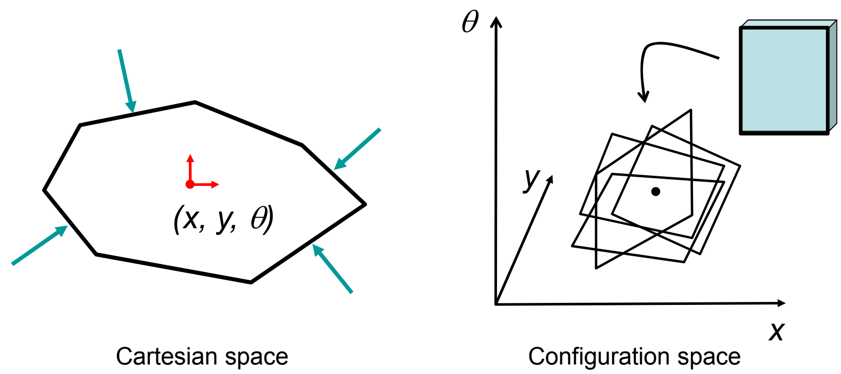


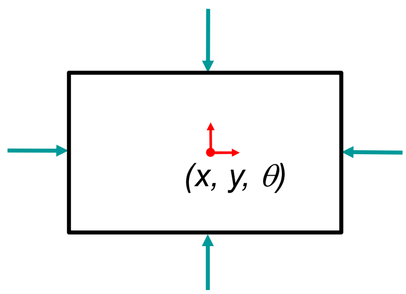
How many contacts to pin rotation?

- Locally, each constraint has a planar boundary
  - … So, how many *halfspaces* needed to pin point?



Are There Degeneracies?

- Polygon with sides not in general position…
- Might we need more? What about ?



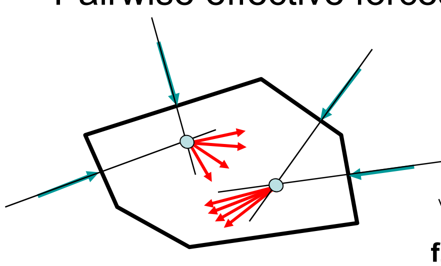
Cartesian space

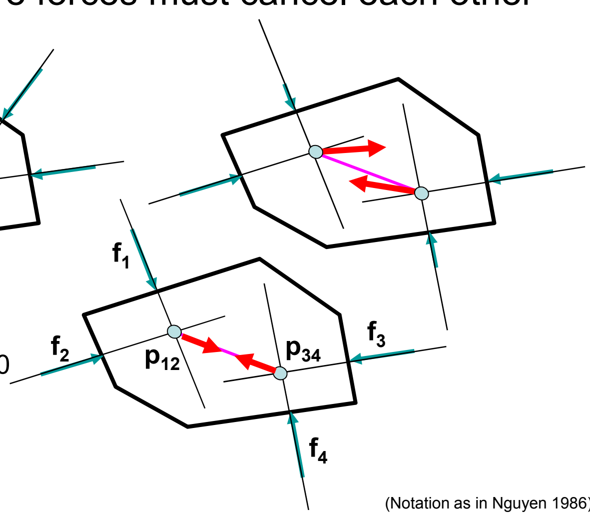
Cartesian space

- For polyhedra in 3D: need
  - *Frictionless* contacts cannot pin

Conditions for Torque Closure

- Each normal cone must contain the other's apex
- Pairwise effective forces must cancel each other





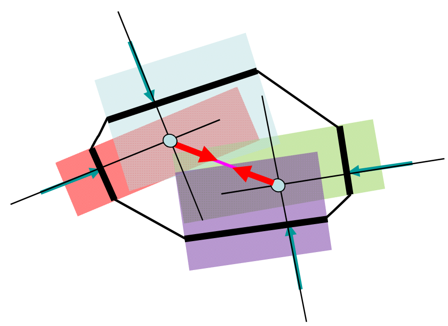
Algebraic condition? For force vectors $\mathbf{f}_1$, $\mathbf{f}_2$, $\mathbf{f}_3$, $\mathbf{f}_4$, there must exist $\alpha, \beta, \gamma, \delta > 0$ s.t.

(Notation as in Nguyen 1986)

Synthesizing a Torque-Closure Grasp

1. Choose two edge pairs* admitting force centers
2. Choose centers inducing mutual normal cones
3. Project centers to respective edge contact points
4. Scale forces to produce alignment, cancellation

*Edge pairs need not be contiguous

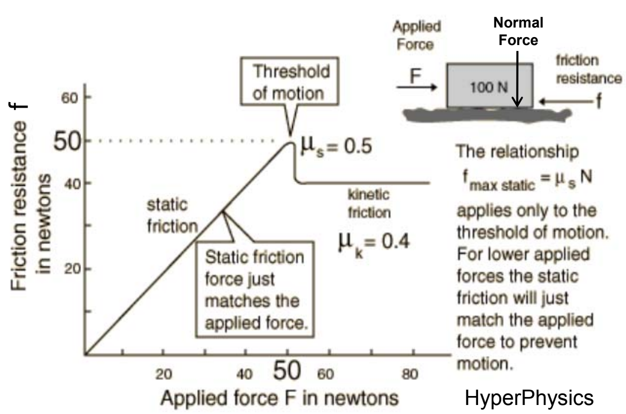


Does rotation closure imply translation closure?

Kinetic and Static Friction (“Stiction”)

$F_f <= \mu_s * F_n$ (at rest): coefficient of *static* friction μ_s

$F_f <= \mu_k * F_n$ (moving): coefficient of *kinetic* friction μ_k

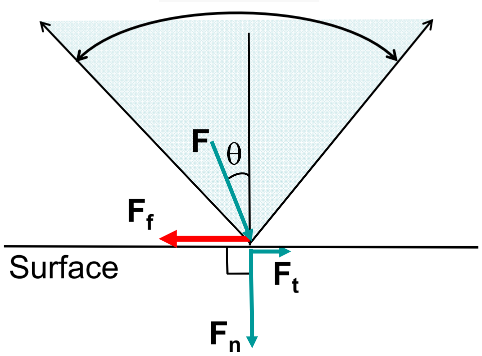


HyperPhysics

(Stiction makes things difficult both for humans and robots. Why?)

Point Contact with Friction

- Consider a point contact exerting force **F** at an angle θ to the surface normal. What happens?



For contact at rest,

$|\mathbf{F_t}| < |\mathbf{F_f}| = \mu\, |\mathbf{F_n}|$

At critical angle θ_{crit},

$|\mathbf{F_t}| =$

Substituting gives

$|\mathbf{F}| \sin \theta_{crit} =$

Which yields

$\mu =$

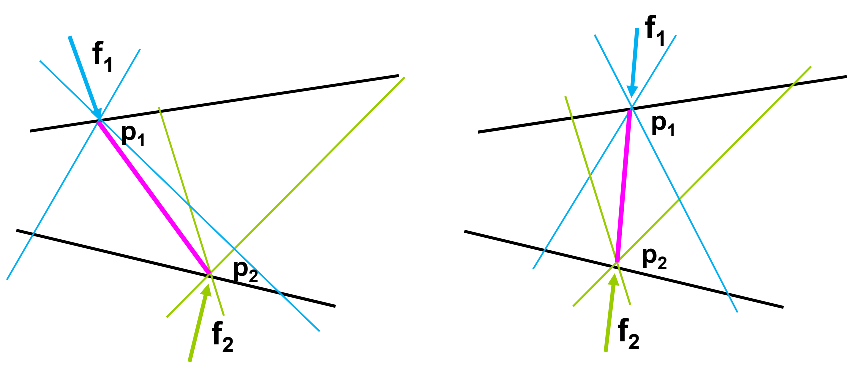
So that

$\theta_{crit} =$

- Produces of directions, s.t. point will not when **F** is applied

Grasp Analysis With Friction

Consider forces $\mathbf{f_1}$, $\mathbf{f_2}$ at frictional contacts $\mathbf{p_1}$, $\mathbf{p_2}$



When can $\mathbf{f_1}$, $\mathbf{f_2}$ oppose one another without sliding?

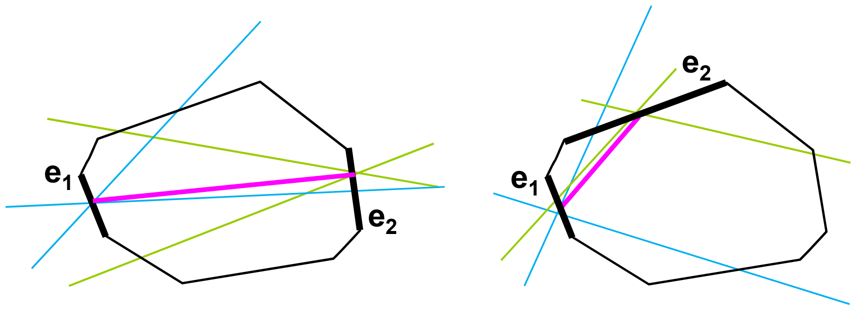
Each force must

Point $\mathbf{p_1}$ (resp. $\mathbf{p_2}$) must

Grasp Synthesis With Friction

Choose a *compatible* pair of edges $\mathbf{e_1}$, $\mathbf{e_2}$

Intuition? Using what data? How to choose?

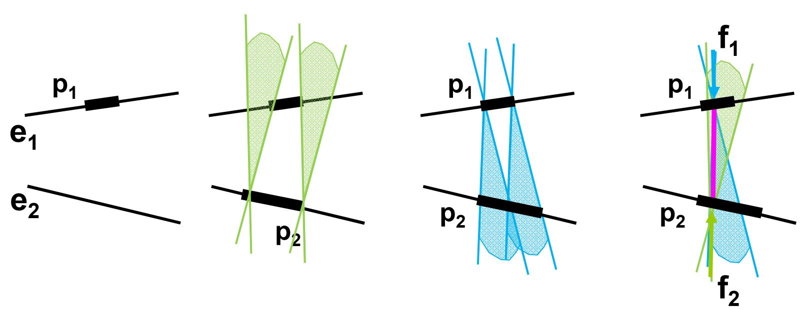


Grasp Synthesis With Friction

Choose target region for contact point $\mathbf{p_1}$

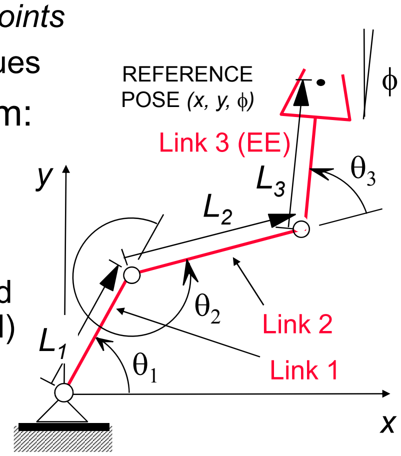
Determine feasible target region for contact $\mathbf{p_2}$

Orient and scale $\mathbf{f_1}$, $\mathbf{f_2}$ so as to cancel along $\overline{\mathbf{p_1 p_2}}$



Forward and Inverse Kinematics

- So far, have cast computations in Cartesian space
- But manipulators controlled in *configuration space:*
  - Rigid *links* constrained by *joints*
  - For now, focus on joint values
- Example 3-link mechanism:
  - Joint coordinates θ_1, θ_2, θ_3
  - Link lengths L_1 , L_2 , L_3
- End effector coordinates
  - "Reference pose" described by *x*, *y*, and ϕ (w.r.t. vertical)
- How can we relate EE to configuration variables?

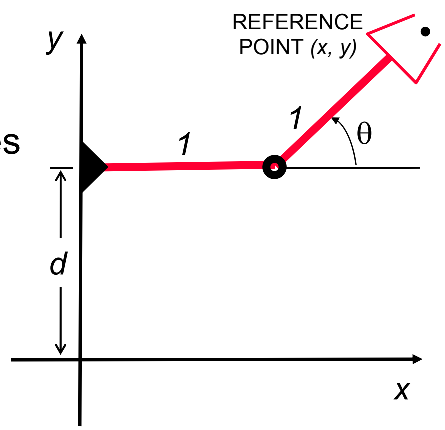


Forward Kinematics

- Given mechanism description and joint values, express end effector pose in Cartesian coordinates
  - Example: two-link arm with one sliding, one rotating joint
- Configuration variables:
  - Joint coordinates *d*, θ
  - Link lengths (both 1)
- End effector coordinates
  - "Reference point" (*x*, y)
- Challenge: express as

  $x = x\,(d, \theta) =$

  $y = y\,(d, \theta) =$



Inverse Kinematics

- Given end effector pose in Cartesian coordinates, identify the joint values that *yield* the desired pose
- Challenge: solve for joint values in terms of pose

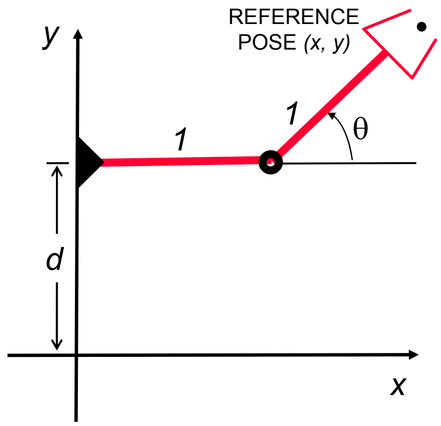
$\theta = \theta(x, y)$

$=$

$d = d(x, y)$

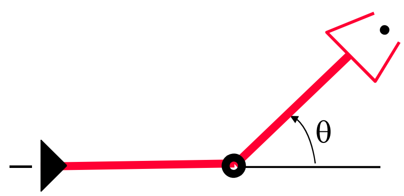
$=$

Hints:



Why is IK difficult?

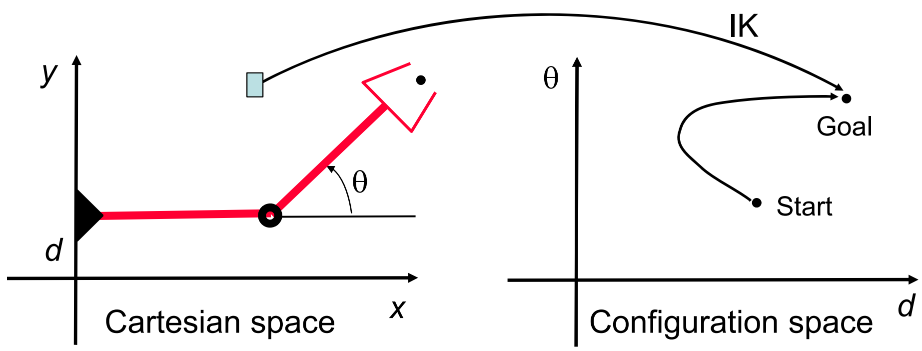
- Nonlinear
  - Revolute joints → inverse trigonometry



- Multi-valued
  - Often multiple solutions for a single Cartesian pose
- Discontinuities and singularities
  - Can lose one or more DOFs in some configurations
- Possibly over-constrained (no exact solution)
  - Use of approximation and iterative algorithms
- Dynamics
  - In reality, want to apply forces and torques (while respecting physical constraints), not just move arm!

Putting it All Together: Grasping

- Input workspace, obstacles, and manipuland:
  - Determine a feasible grasp (set of contact points)
  - Use IK to solve for target end-effector pose in c-space
  - Plan a collision-free reach to the computed pose
  - Control end-effector along desired trajectory



What have we swept under the rug?

- Sensing
  - Shape, pose of target object, accessibility of surfaces
  - Classification of material type from sensor data
  - Freespace through which grasping action will occur
- Prior knowledge
  - Estimation of mass, moments, friction coefficients from material
  - Internal, articulated, passive vs. active degrees of freedom
- Uncertainty & compliance
  - Tolerate noise inherent in sensing and actuation
  - Ensure that slight sensing, actuation errors won't cause damage
  - Handle soft fingers making contact over a finite area (not a point)
- Dynamics
  - All of the above factors may be changing in real time

Confidence vs. Arrogance

Confident:

Having strong belief, firm **trust**, or
sure expectation. [OED]

From Latin *com-* (intensive prefix) + *fidere* “to trust”

Arrogant:

Making or implying strong or **unwarrantable** claims to dignity, authority or knowledge. [OED]

From Latin *arrogare* “to claim for oneself, assume”