KTH ROYAL INSTITUTE
OF TECHNOLOGY

Introduction to Robotics

DD2410

Lecture 6 - Control, Grasping

Schedule - Lectures

Aug 29 - 1. Intro, Course fundamentals, Topics, What is a Robot, History Applications.

Aug 30 - 2 Manipulators, Kinematics
(Aug 31 - 3 ROS Introduction)
Sep 03 - 4. Differential kinematics, dynamics
Sep 04 - 5. Actuators, sensors I (force, torque, encoders, ...)
Sep 10 - 6. Grasping, Motion, Control

Sep 11 - 7. Behavior Trees and Task Switching
Sep 17 - 8. Planning (RRT, A*, ...)

Sep 18 - 9. Mobility and sensing II (distance, vision, radio, GPS, ...)
Sep 24 - 10. Localisation (where are we?)
Sep 27 - 11. Mapping (how to build the map to localise/navigate w.r.t.?)
Oct 01 - 12. Navigation (how do I get from A to B?)

Syllabus

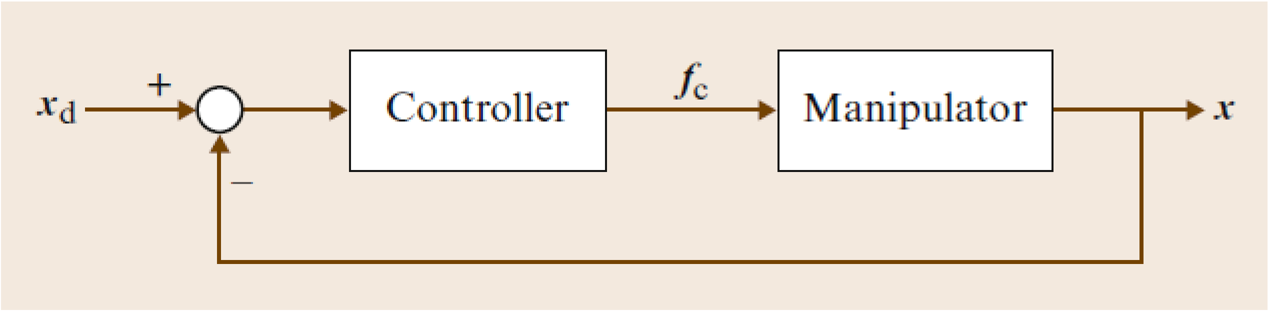
JJ Craig: 9,10,11
RH: A6, A7, C28

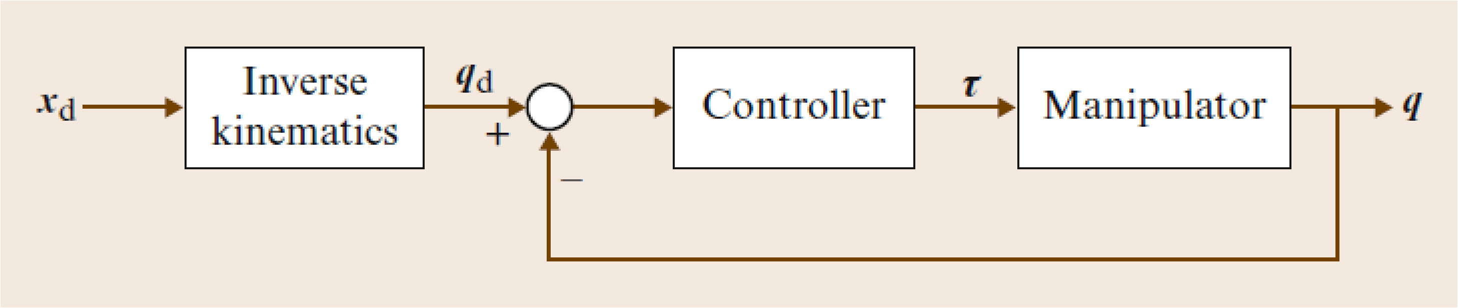
- Control
  - Joint level vs full system
  - Position control
  - Velocity control, CTC
  - practical considerations
- Grasping
  - Definitions
  - Examples

Control

- Motion control
  - The system state $\mathbf{x(t)}$ should follow a desired state $\mathbf{x_d(t)}$ with as small errors as possible
  - Trajectories can be generated as a set of waypoints that are interpolated, or be generated by advanced planners (see later lecture).

- Control domain
  - Joint space or cartesian?

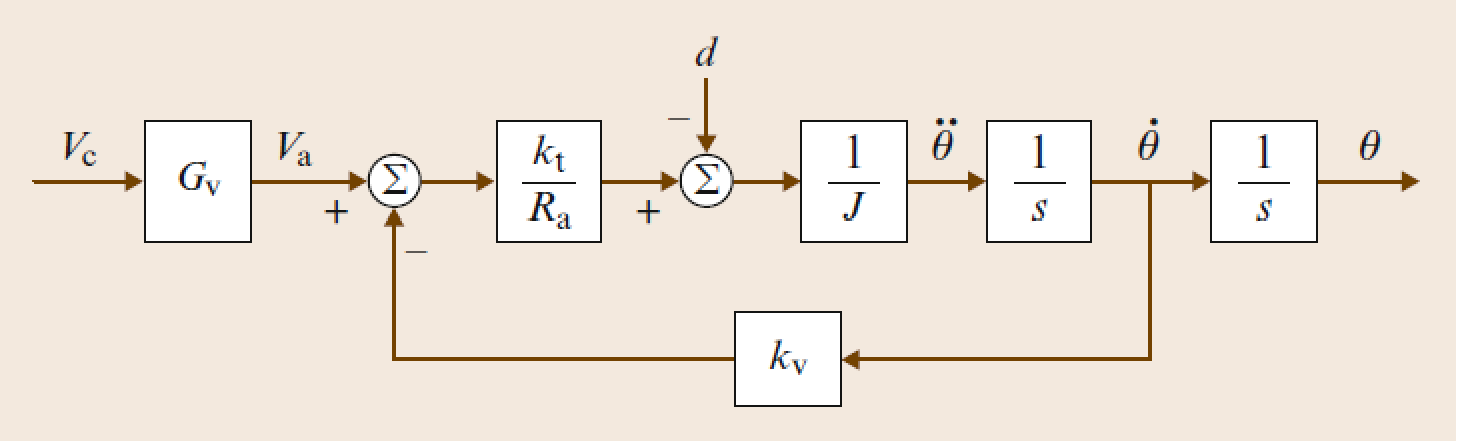




Independent joint control

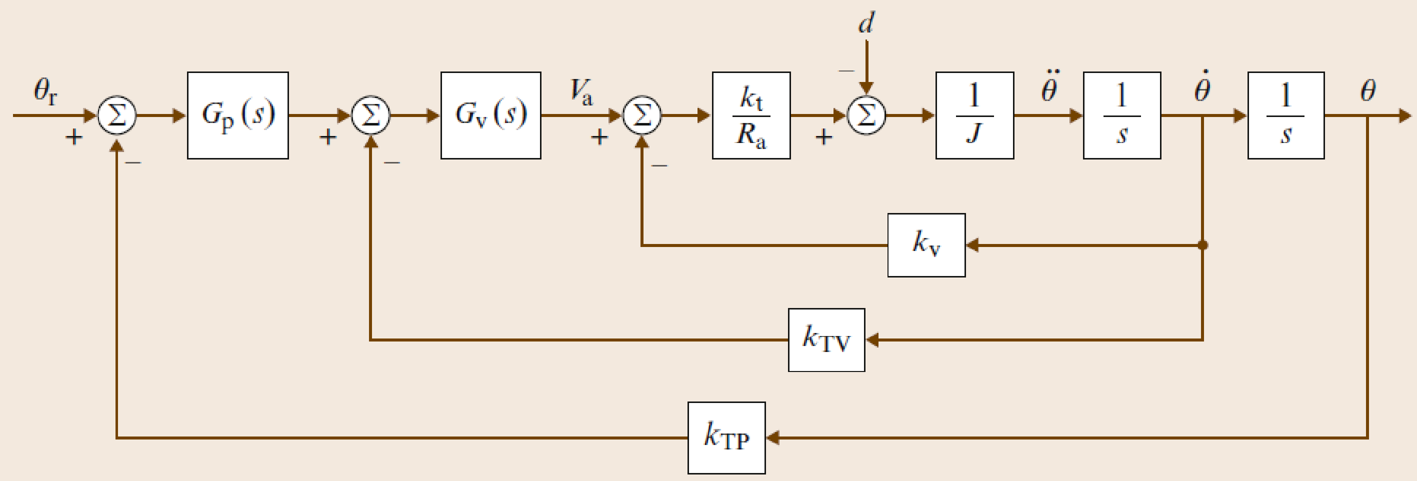
- Each joint is controlled individually
- The dynamic effects of other joints are treated as disturbances
- Easy to implement, non-expensive computation
- Large errors when working close to dynamic limits

Independent joint control - model of a single joint



- V_c, V_a - Input and amplifier voltage
- k_t, k_v - torque and motor constants
- d - disturbance
- J - link inertia as seen from the motor

Independent joint control - feedback control



- G_p - Position controller (P)
- G_v - Velocity controller (PI)
- k_{TV}, k_{TP} - transducer constants

$$G_p(s) = K_P\,, \qquad G_v(s) = K_V \frac{1 + sT_V}{s}\,,$$

Full manipulator control

- Given the system dynamics notation:

$$H(q)\ddot{q} + C(q, \dot{q})\dot{q} + \tau_g(q) = \tau \, ,$$

- PID control can be used to reach a given setpoint, without explicit knowledge of system dynamics

$$\tau = K_P(q_d - q) + K_I \int f(q_d - q)\,dt - K_V \dot{q}$$

- Integrator part will correct static effects of gravity
- Gains will be good for local regions around a configuration
- Poor performance for highly dynamic actions

Full manipulator control

- Given the system dynamics notation:

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + \tau_g(q) = \tau \; .$$

Full manipulator control

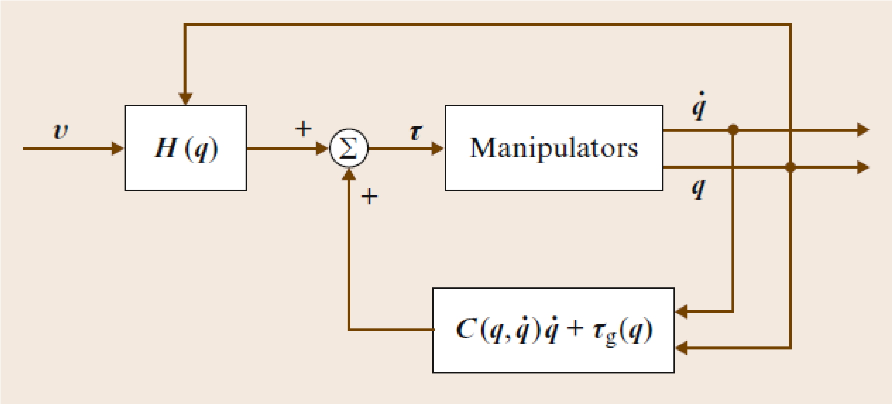
$$\boldsymbol{H}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{\tau}_{\mathrm{g}}(\boldsymbol{q}) = \boldsymbol{\tau} \ ,$$

Computed Torque Control - CTC

$$\boldsymbol{H}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{\tau}_{\mathrm{g}}(\boldsymbol{q}) = \boldsymbol{\tau} \; ,$$

Computed Torque Control - CTC

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + \tau_{\mathrm{g}}(q) = \tau$$



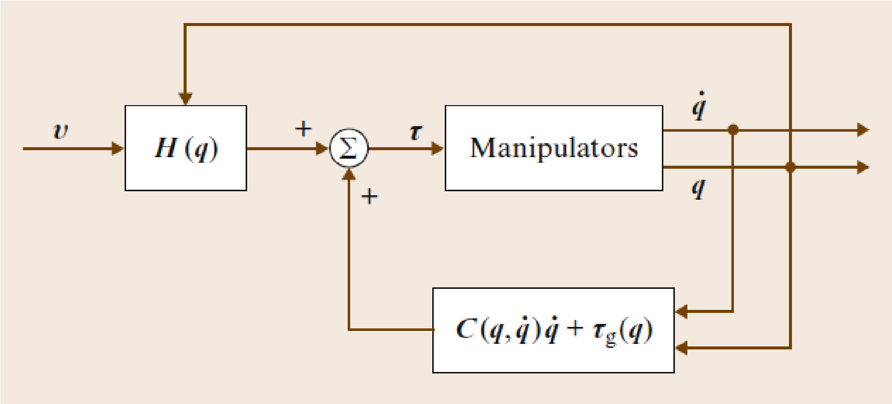
- Assume the control signal $\ddot{q} = v$
  and we get a decoupled system where we can directly assign the desired accelerations

- A dynamically well-performing tracker can be given as

$$v = \ddot{q}_{\mathrm{d}} + K_{\mathrm{V}}\dot{e}_{\mathrm{q}} + K_{\mathrm{P}}e_{\mathrm{q}}$$,where e_q is the error

Computed Torque Control - CTC

$$\boldsymbol{H}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{\tau}_{\mathrm{g}}(\boldsymbol{q}) = \boldsymbol{\tau}\ .$$



- In practice, modelling errors will have to be treated by an extra term, see RH A6.6 for details

$$\boldsymbol{v} = \ddot{\boldsymbol{q}}_{\mathrm{d}} + \boldsymbol{K}_{\mathrm{V}}\dot{\boldsymbol{e}}_{\mathrm{q}} + \boldsymbol{K}_{\mathrm{P}}\mathrm{e}_{\mathrm{q}} + \Delta\boldsymbol{v}$$

Force Control

- Assuming that we can measure forces/torques, we can define controllers that track a desired force $\mathbf{F_d(t)}$

$$\boldsymbol{H}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{J}^T \boldsymbol{f} = \boldsymbol{\tau}$$

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$$\boldsymbol{\tau} = \boldsymbol{g}(\boldsymbol{q}) - \boldsymbol{K}_v\dot{\boldsymbol{q}} + \boldsymbol{J}^T\left[\boldsymbol{f}_d - k_I\int_0^t(\boldsymbol{f} - \boldsymbol{f}_d)d\tau\right]$$

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0 for static forces

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0 for static forces

- Note that forces and position (velocity) can typically not be tracked independently!

- Given the above schemes, it is possible to realize velocity controlled robots, by setting $\mathbf{x}_d(\mathbf{t})$ to be the integrated target velocity
- Velocity controllers allow us to implement a range of reactive robot behaviors
- Industrial manipulators that do not expose their internal controls can be seen as velocity controlled

Force/position Control

- Velocity control for other controllers, assuming force measurements:
  - Virtual spring around x_0

$$f_d = -k(x - x_0)$$

$$v_d = \alpha(f - f_d)$$

Force/position Control

- Velocity control for other controllers, assuming force measurements:
  - Admittance control, as virtual damping

$$f_d = -k(\dot{x})$$

$$v_d = \alpha(f - f_d)$$

- Velocity control for other controllers, assuming force measurements:
  - Virtual fixture

$$v_d = k f$$

where k projects on fixture

- Velocity control for other controllers, assuming force measurements:
  - Full impedance (mass, damper, spring)

- Assuming a robot with several degrees of freedom, different control strategies can be used in different subspaces:
  - position in (**x**,**y**), force in **z**
  - admittance control in (**x,y,z**), fixed orientation
  - trajectory following in **pose,** obstacle (singularity) avoidance in nullspace.

- Grasping
  - Definitions, taxonomy
  - Grippers

- Grasping
  - Form closure
  - Force closure
  - Caging

- Form closure

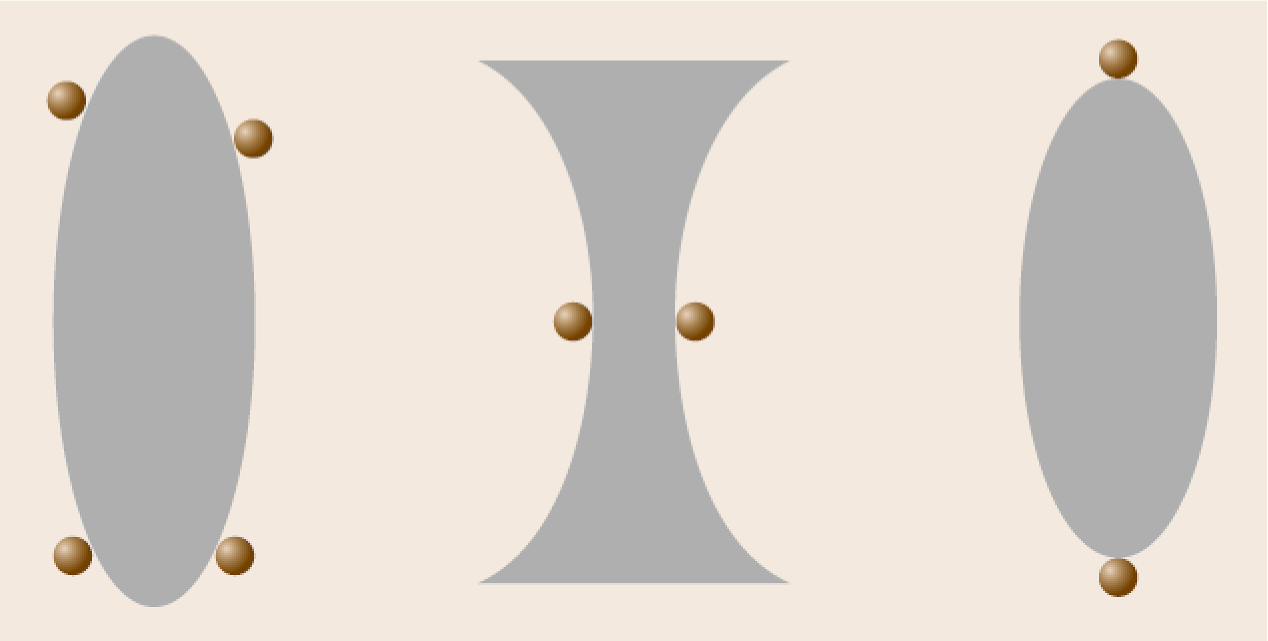


Fig. 28.8 Three planar grasps: two with form closure of different orders and one without form closure

- Gap function is distance between hand and object

$$\psi_i(\boldsymbol{u}, \boldsymbol{q})$$

  - ***u*** is object pose, ***q*** is hand configuration
  - at all contact points,

$$\psi_i(\bar{\boldsymbol{u}}, \bar{\boldsymbol{q}}) = \boldsymbol{0} \quad \forall\, i = 1, \ldots, n_c$$

  - A grasp has form closure **iff** the following implication holds:

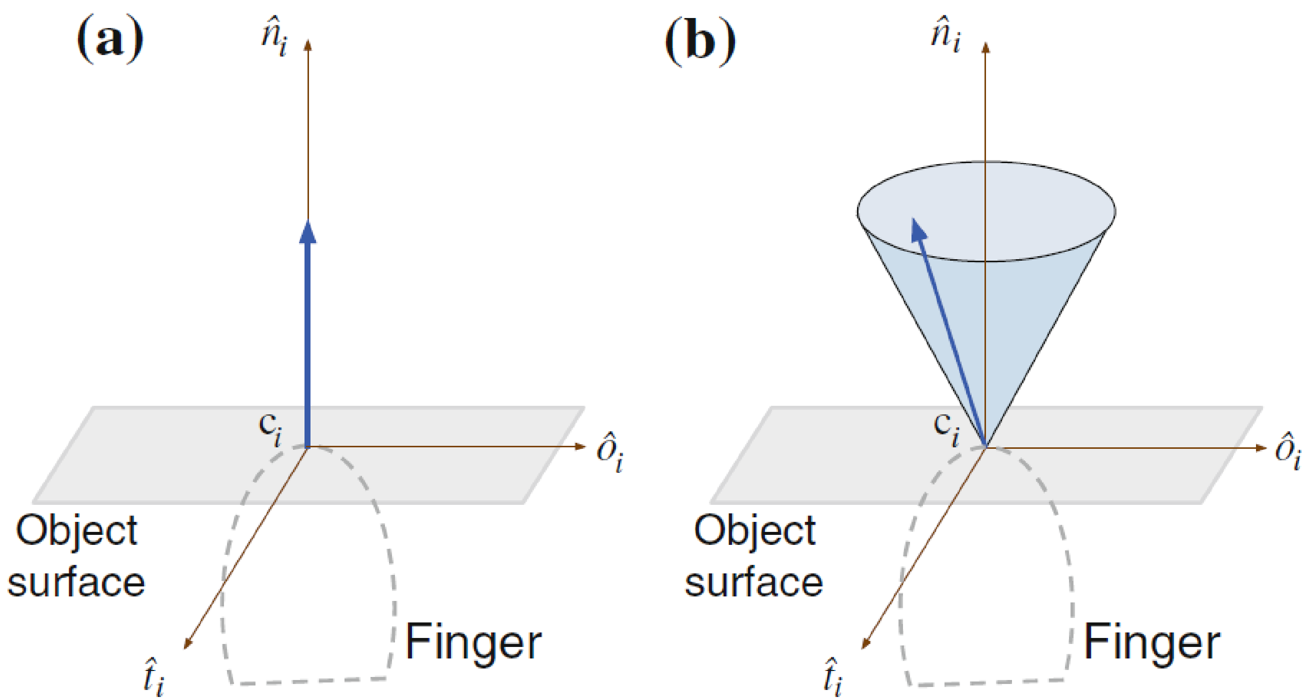
$$\boldsymbol{\psi}(\bar{\boldsymbol{u}} + \mathrm{d}\boldsymbol{u}, \bar{\boldsymbol{q}}) \geq \boldsymbol{0} \Rightarrow \mathrm{d}\boldsymbol{u} = \boldsymbol{0}$$

that is, there is no possible motion that increases gap

Grasping - force closure

- Contact types

Frictionless | With friction

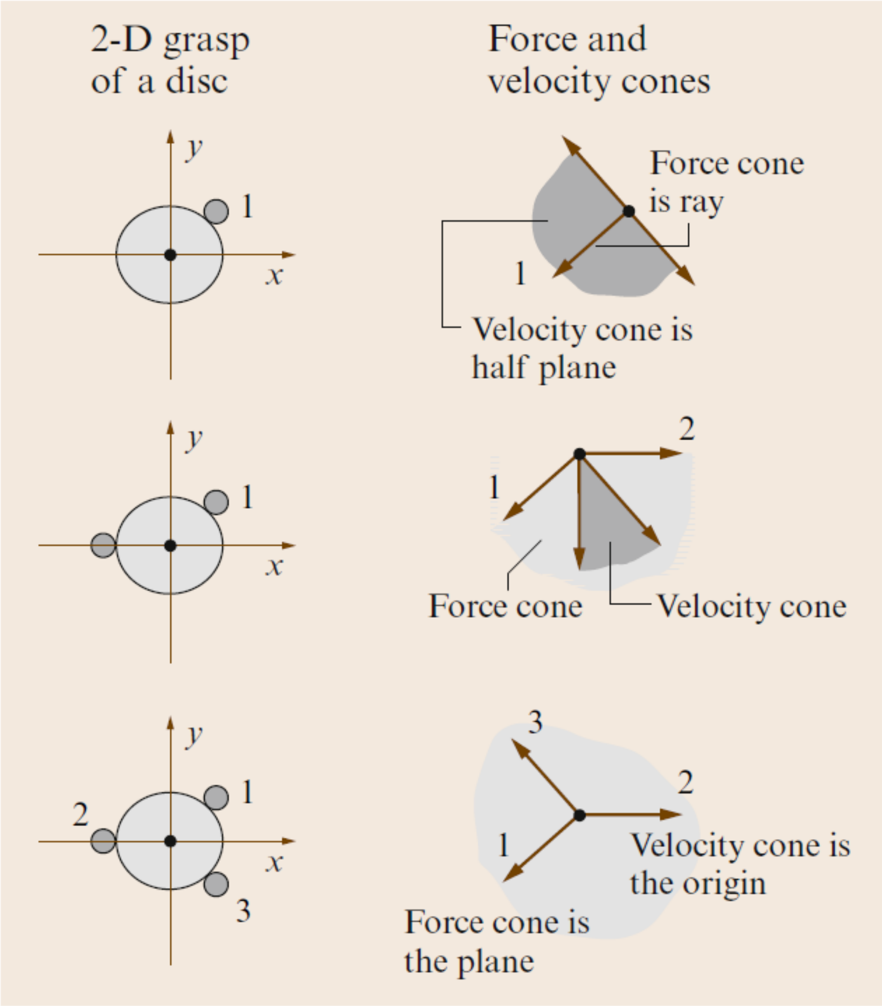


B. León et al., *From Robot to Human Grasping Simulation*, Cognitive Systems Monographs 19, DOI: 10.1007/978-3-319-01833-1_2, © Springer International Publishing Switzerland 2014

Grasping - force closure

- A grasp is in force-closure if the fingers can apply, through the set of contacts, arbitrary wrenches on the object, which means that any motion of the object can be resisted by the contact forces.

  right: frictionless case



B. León et al., *From Robot to Human Grasping Simulation*, Cognitive Systems Monographs 19, DOI: 10.1007/978-3-319-01833-1_2,

- friction case

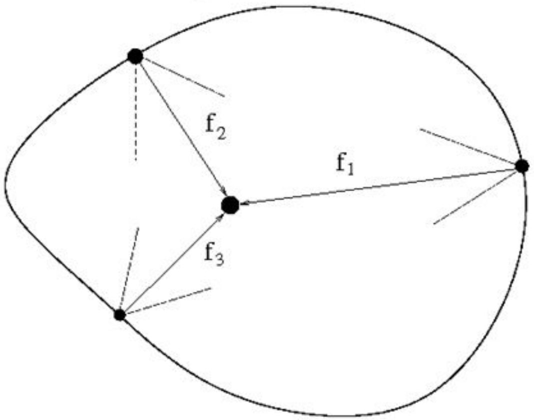
Force Closure

Need balanced forces or else object twists

2 fingers – forces oppose: $\bar{f}_1 + \bar{f}_2 = 0$

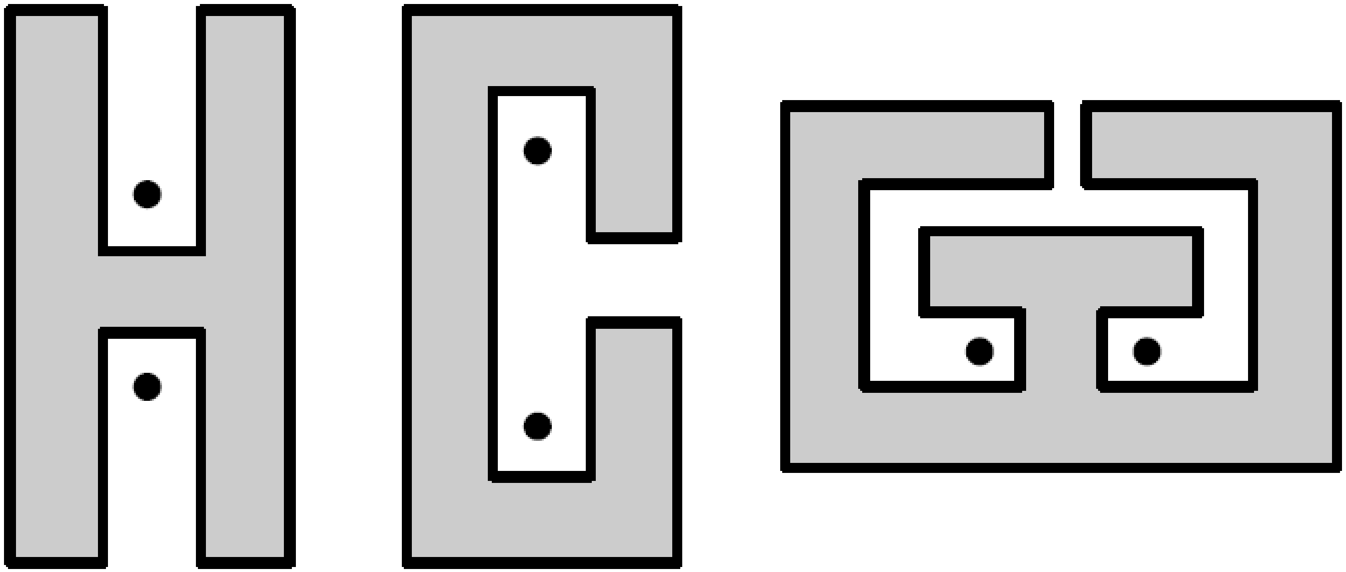
3 fingers – forces meet at point: $\bar{f}_1 + \bar{f}_2 + \bar{f}_3 = 0$

Force closure: point where forces meet lies within 3 friction cones otherwise object slips



Olivia Fox: "Kinematics & Grasping Need to know: Representing mechanism geometry Standard configurations Degrees of freedom Grippers and graspability conditions Goal"

- Caging



(a) (b) (c)

Alberto Rodriguez, Matt Mason, and Steve Ferry. "From Caging to Grasping" Proceedings of Robotics: Science and Systems, 2011, Los Angeles, CA, USA

"Let P be a polygon in the plane, and let C be a set of n points in the complement of the interior of P. The points capture P if P cannot be moved arbitrarily far from its original position without at least one point of C penetrating the interior of P."

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c.f. form closure:

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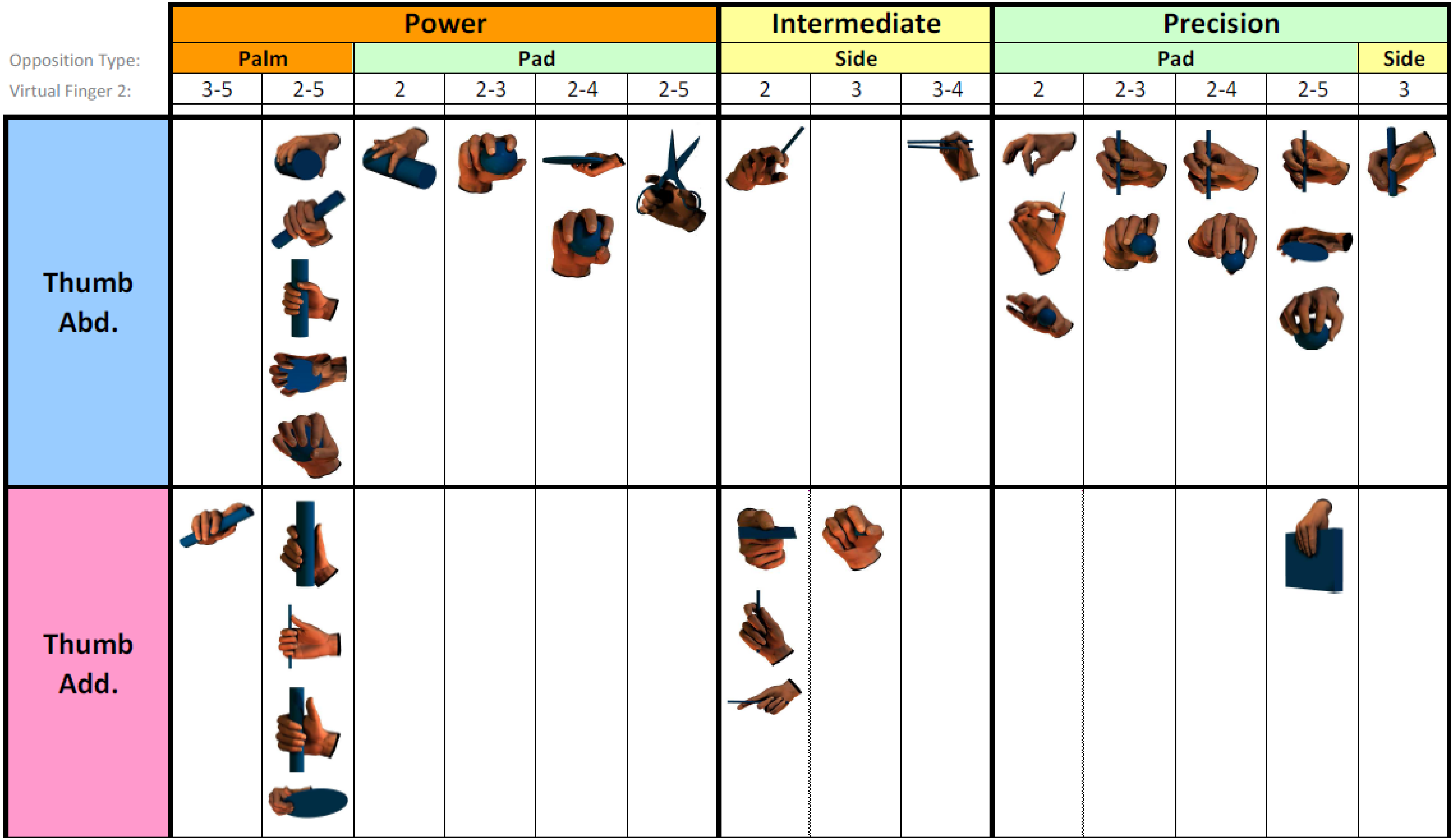
c.f. form closure:

$$\boldsymbol{\psi}(\bar{\boldsymbol{u}} + \mathrm{d}\boldsymbol{u}, \bar{\boldsymbol{q}}) \geq \mathbf{0} \Rightarrow \mathrm{d}\boldsymbol{u} = \mathbf{0}$$

$$\Psi\left(\bar{u}+du, \bar{q}\right) \geq 0 \Rightarrow du \; bounded$$

Alberto Rodriguez, Matt Mason, and Steve Ferry. "From Caging to Grasping" Proceedings of Robotics: Science and Systems, 2011, Los Angeles, CA, USA

Grasping taxonomy



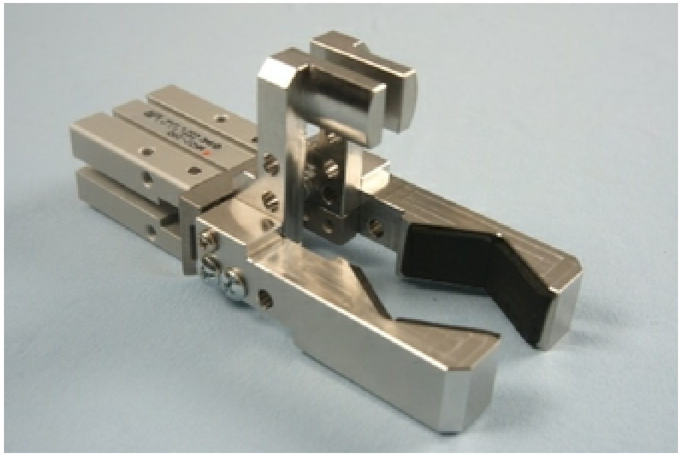
T Feix, R Pawlik, H Schmiedmayer, J Romero, D Kragic, "A comprehensive grasp taxonomy", RSS 2009

Industrial grasping

- parallell grippers

Industrial grasping

- Custom grippers



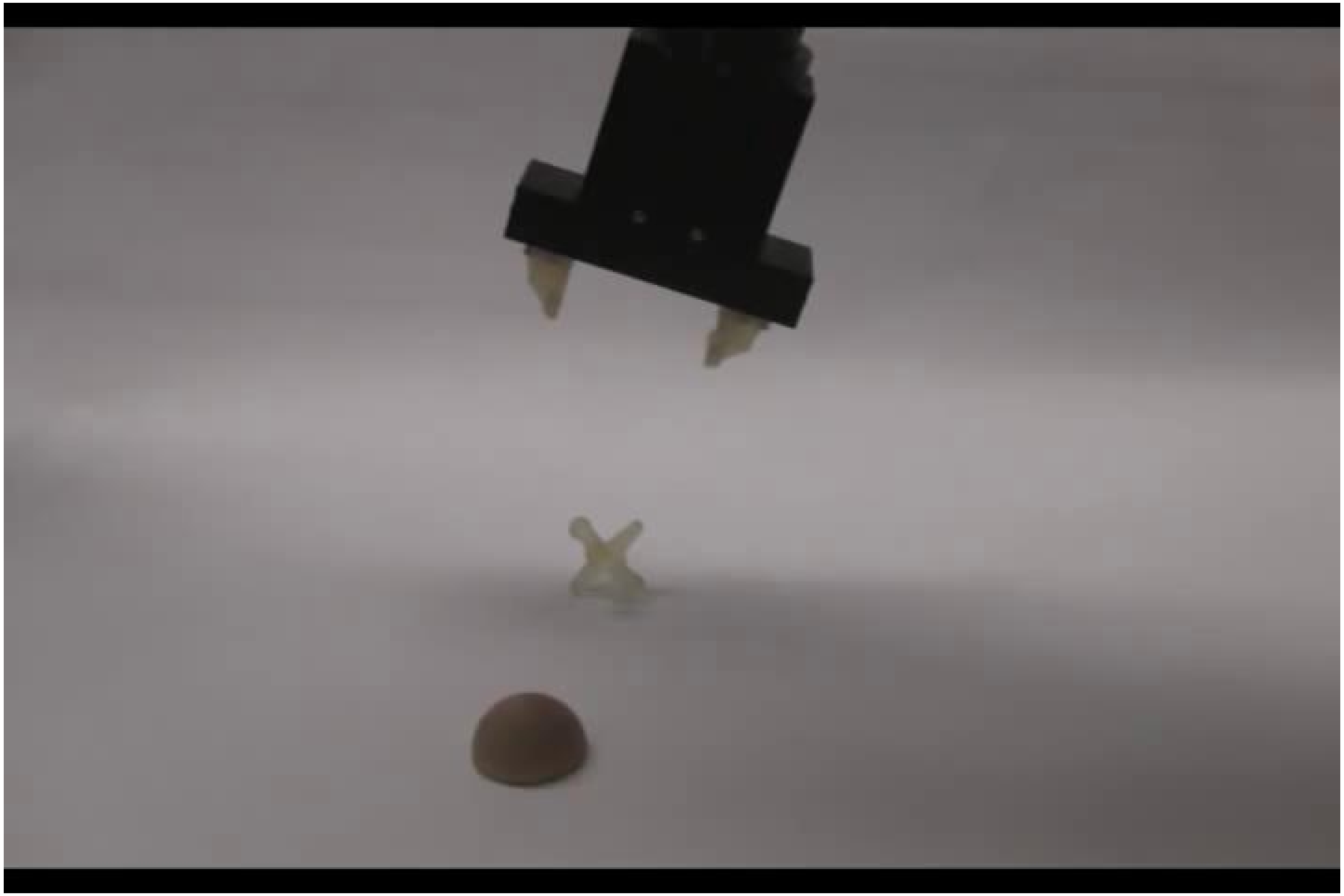
Industrial grasping

- Underactuated grippers

Industrial grasping

- Suction, magnets

Industrial grasping



credit: Cornell Creative Machines Lab