Robotic grasping

Master SIIA
IMT Atlantique
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Introduction

Course objectives

- **Understand the problems** underlying manipulation
- Overview of **hardware and software tools** for robotic manipulation
- **Bibliographical references** for further reading
- Practice session: manipulation inside a simulator using ROS
- Active domain of research. Not all the answers are available.
  You can contribute! Interested in a PhD in RAMBO?

References

Course based on the books:

- **Modern Robotics** (K. Lynch, F. Park, 2017)
- **Handbook of robotics** (editors B. Siciliano, O. Khatib, 2nd ed. 2017)
- related scientific publications

Questions answered by the course

- What is manipulation?
- What types of grippers exist?
- How many contact points are needed to grasp an object firmly?
- Where should the contacts be placed?
- How are grasps computed?
- How are grasps evaluated and ranked?

What is manipulation?

What is manipulation?

Manipulation: application of motions or forces to purposefully change the state of an object.
Manipulation primitives include:

- **grasping**
- throwing
- catching
- pushing
- kicking
- tapping
- sliding
- rolling
- pivoting
- toppling
- etc.

Manipulation example

Grasping

Complete restraint: prevents loss of contact

Desired: grasp maintenance against unknown disturbing forces and moments applied to the object (inertia forces, gravity)

Prevent:

- contact separation
- unwanted contact sliding

Closure grasps

Grasps that can be maintained for every possible disturbing load.

- **Form closure:** restraint by geometry
- **Force closure:** restraint by contact force and friction

  All form closure grasps are also force closure grasps.

Gripper types

Gripper types

- Linear
- Jaw
- Passive compliant
- Flexible soft
- Anthropomorphic
- Granular jamming
- Suction cup
- Magnetic

Gripper types

LINEAR GRIPPER[*]

Gripper types

JAW GRIPPER[*]

Gripper types

KIRIGAMI GRIPPER[*]

Gripper types

Passive compliant Fin Ray gripper[*]

Gripper types

FLEXIBLE SOFT GRIPPER [*]

Gripper types

ANTROPOMORPHIC HAND [*]

Gripper types

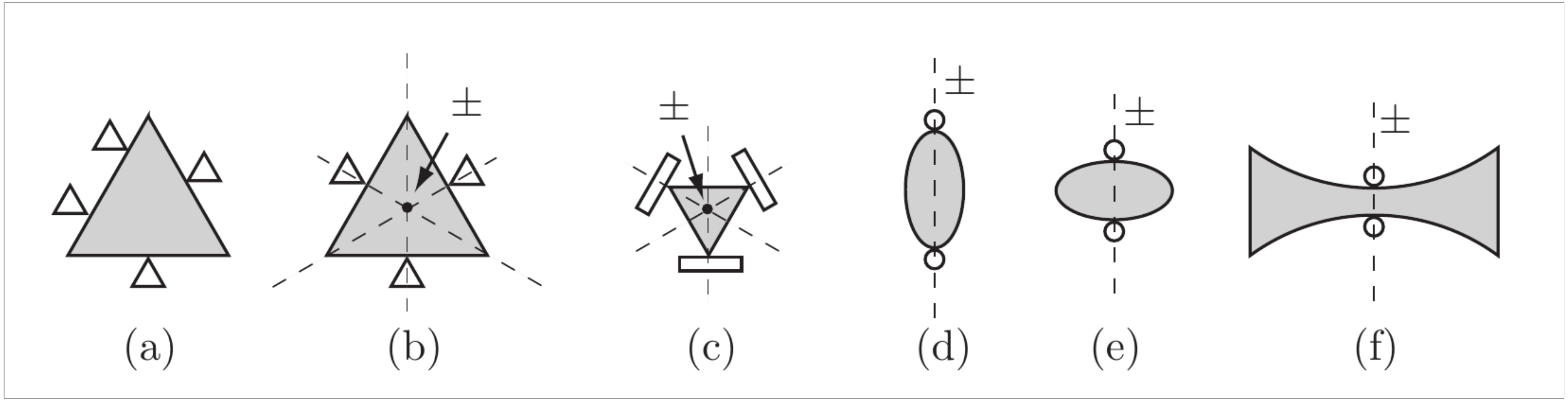
GRANULAR JAMMING GRIPPER [*]

Gripper types

SUCTION CUP VACUUM GRIPPER[*]

Gripper types

MAGNETIC GRIPPER[*]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±
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(a)
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(c)
(d)
(e)
(f)

Contact models

Model	**Rigid-body models**	**Compliant models**
Varieties	• frictionless • frictional	• compliance/stiffness model
Sources of forces	• the constraint of incompressibility and impenetrability between the rigid bodies • surface frictional forces	• derived from the compliance or stiffness model
Advantages	• straightforward to use • computationally efficient • compatible with solid-modeling software systems.	• overcome the static indeterminacy inherent to rigid-body models • predict deformations of grasped/fixtured parts during loading
Disadvantages	• static indeterminacy problem • ignore object deformations	• more complicated

Source: Handbook of Robotics (2016) 37.1.1 Choosing a Contact Model

Contact mechanics (rigid bodies)

influenced by:

- Contact kinematics
- Contact force model
- Rigid body dynamics

Quasi-static assumption: if motions are slow, then velocity and acceleration terms are negligible.
Therefore contact forces and gravity forces must balance.
contact forces + gravity forces = 0

Definitions (recapitulation)

- **Configuration:** a specification of the position of all points of a robot.
- **C-space:** the space of all configurations of a robot.
- **Degrees of freedom (dof):** the dimension of the C-space
  dof = ∑ (#freedom of points) - (# of independent constraints)

Definitions

Twist: combination of angular and linear velocity

$$\mathcal{V} = \begin{bmatrix} w \\ v \end{bmatrix} \begin{matrix} \leftarrow \text{angular velocity (3x1 matrix)} \\ \leftarrow \text{linear velocity (3x1 matrix)} \end{matrix}$$

In which direction object movement is possible?

Wrench: combination of moment and force

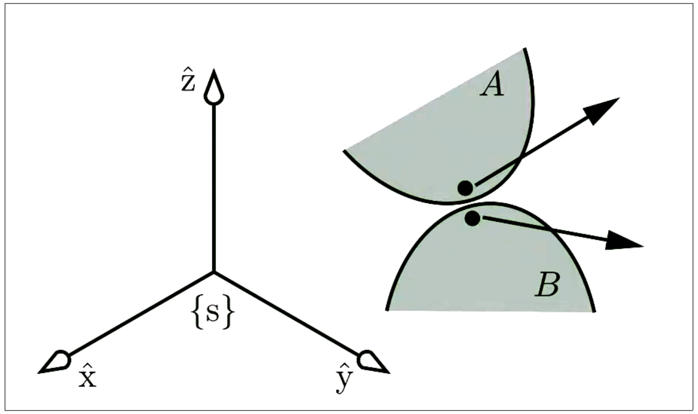
$$\mathcal{F} = \begin{bmatrix} m \\ f \end{bmatrix} \begin{matrix} \leftarrow \text{moment of force (3x1 matrix)} \\ \leftarrow \text{force (3x1 matrix)} \end{matrix}$$

In which direction object movement can be constrained?

The dot product of a **twist** and a **wrench** is **power**.

$$\mathcal{V}^T \mathcal{F} = \text{power}$$

(1/3) Contact Kinematics



$q_1,\ q_2$: rigid body configurations
$q = (q_1^T,\ q_2^T)^T$: composite configuration
$d(q)$: distance between two bodies

- positive when objects are separated
- zero when they are touching
- negative when objects penetrate each other

Source: Modern Robotics (Video supplements) **12.1.2. Contact Types: Rolling, Sliding, and Breaking**

(1/3) Contact Kinematics

FIRST-ORDER ANALYSIS OF A SINGLE CONTACT

d	$\dot{d}$	$\ddot{d}$	$\ldots$	
> 0				no contact
< 0				infeasibile (penetration)
$= 0$	> 0			in contact, but breaking free
$= 0$	< 0			infeasibile (penetration)
$= 0$	$= 0$	> 0		in contact, but breaking free
$= 0$	$= 0$	< 0		infeasibile (penetration)

etc.

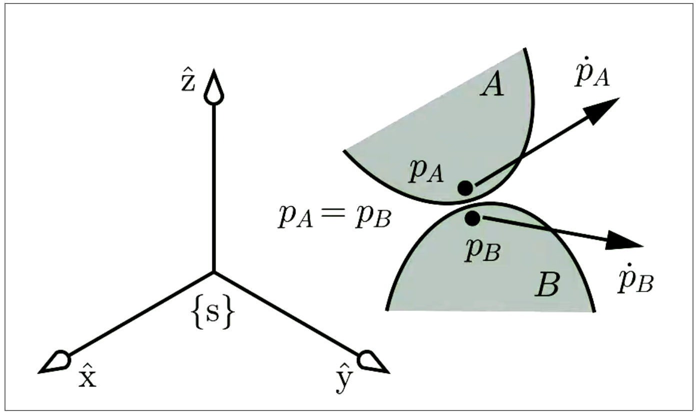
Contact is maintained only if all time derivatives are zero.

(1/3) Contact Kinematics

$$\dot{d} = \left(\frac{\partial d}{\partial q}\right)^T \dot{q}$$

$$\ddot{d} = \dot{q}^T \left(\frac{\partial^2 d}{\partial q^2}\right)^T \dot{q} + \left(\frac{\partial d}{\partial q}\right)^T \ddot{q}$$

(1/3) Contact Kinematics



$A, \ B$ are two bodies in contact in space-frame {s}

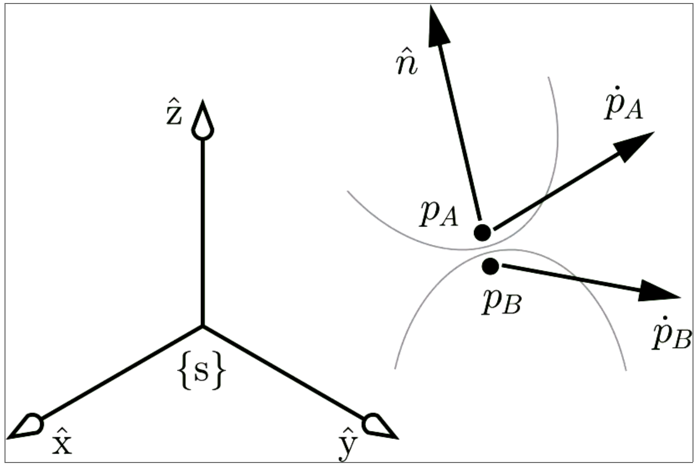
$p_A, \ p_B$ are contact points on the two bodies

$p_A = p_B$ at contact

$\dot{p}_A, \ \dot{p}_B$ = velocities of contact points on bodies A and B

Source: Modern Robotics (Video supplements) **12.1.2. Contact Types: Rolling, Sliding, and Breaking**

(1/3) Contact Kinematics



$\hat{n}$ = contact normal pointing into body A

$\mathcal{V}_A = \begin{bmatrix} w_A \\ v_A \end{bmatrix},\ \mathcal{V}_B = \begin{bmatrix} w_B \\ v_B \end{bmatrix}$ are the twists of bodies A and B

$\dot{p}_A,\ \dot{p}_B$ = velocities of contact points on bodies A and B

$$\dot{p}_A = v_A + w_A \times p_A$$

Source: Modern Robotics (Video supplements) **12.1.2. Contact Types: Rolling, Sliding, and Breaking**

Contact types

ROLLING, SLIDING, AND BREAKING FREE

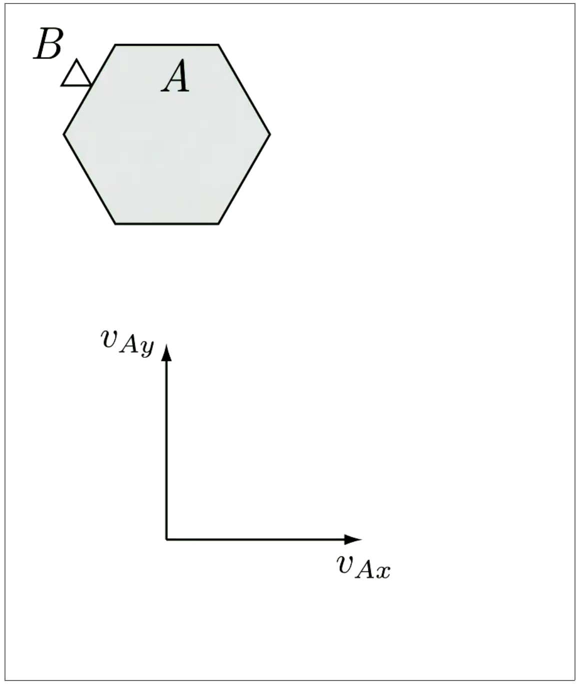
Two bodies maintaining a single-point contact during motion undergo a **roll-slide motion**.

impenetrability	$\hat{n}^T(\dot{p}_A - \dot{p}_B) \geq 0$
first-order roll-slide	$\hat{n}^T(\dot{p}_A - \dot{p}_B) = 0$
first-order rolling	$\dot{p}_A - \dot{p}_B = 0$

Source: Modern Robotics (Video supplements) **12.1.2. Contact Types: Rolling, Sliding, and Breaking**

Contact types

EXAMPLE 1



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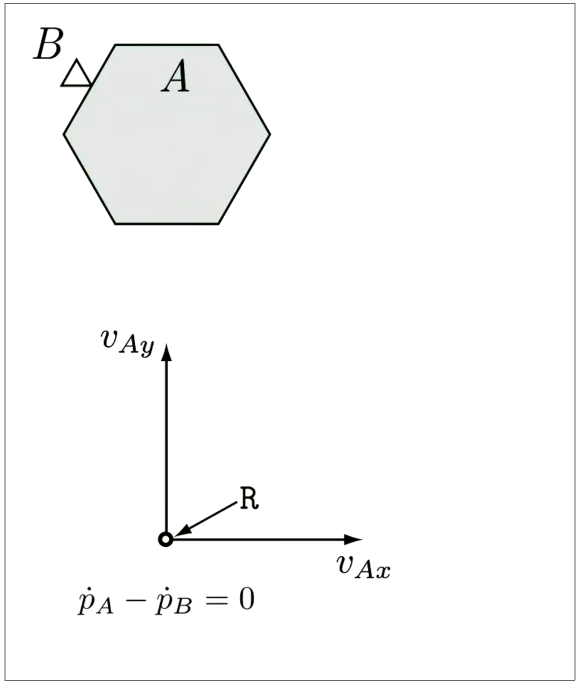

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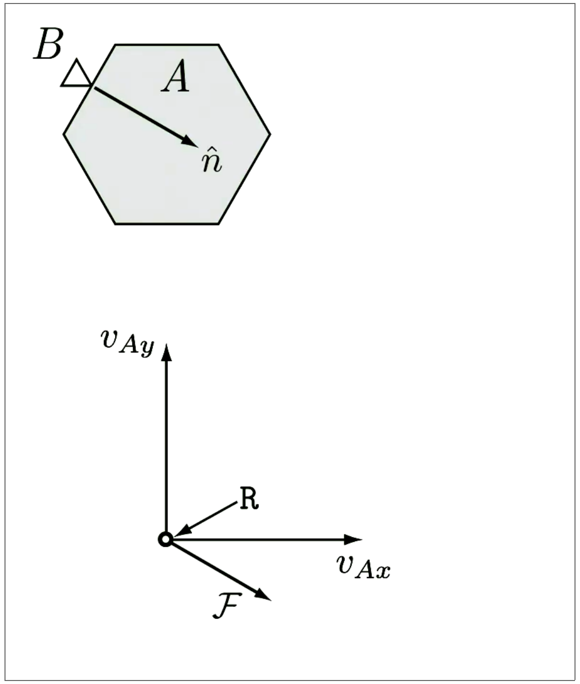

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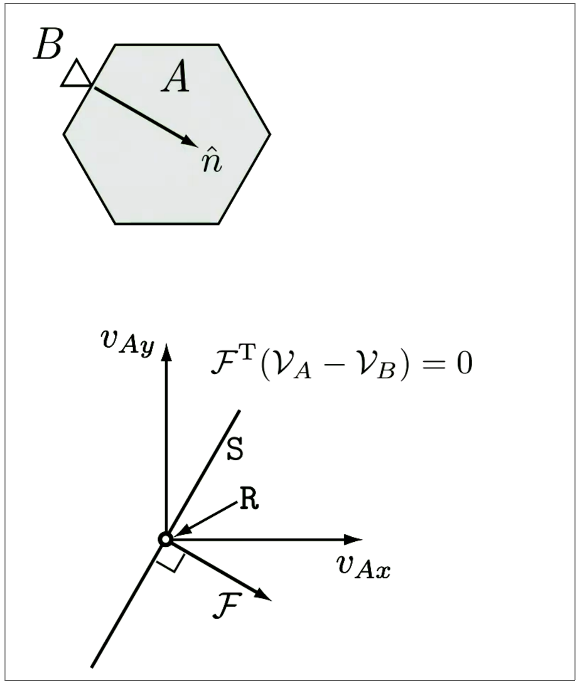

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Contact types

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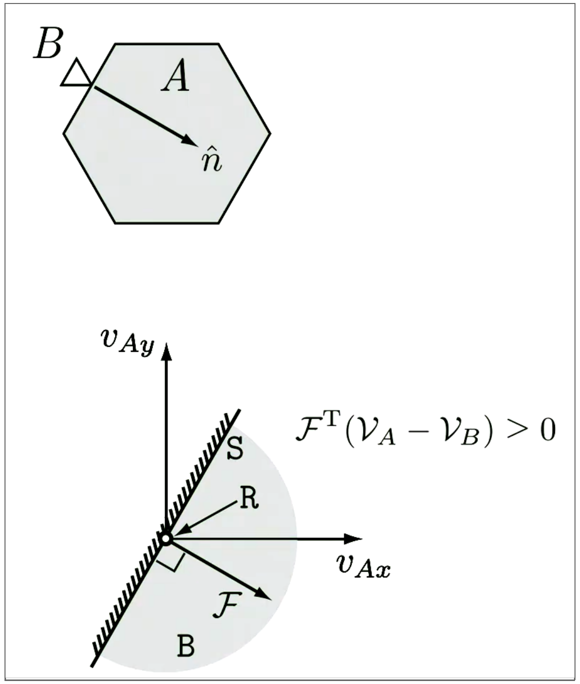
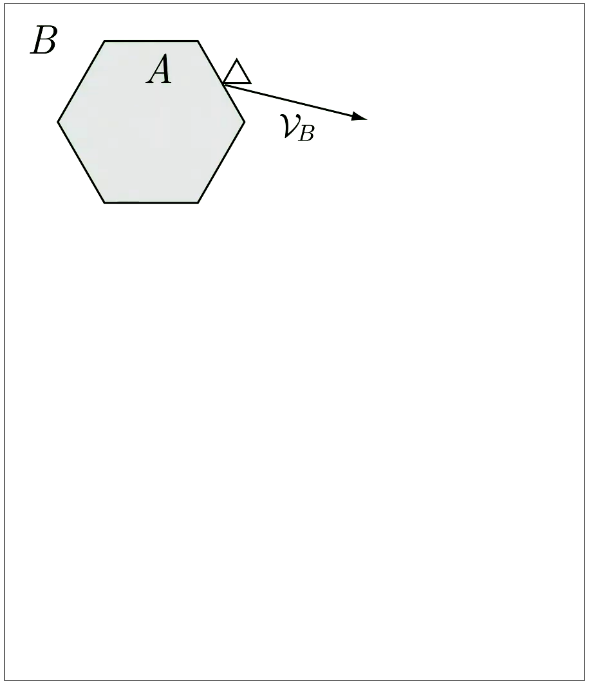


Source: Modern Robotics (Video supplements) **12.1.2. Contact Types: Rolling, Sliding, and Breaking**

Contact types

EXAMPLE 2



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Contact types

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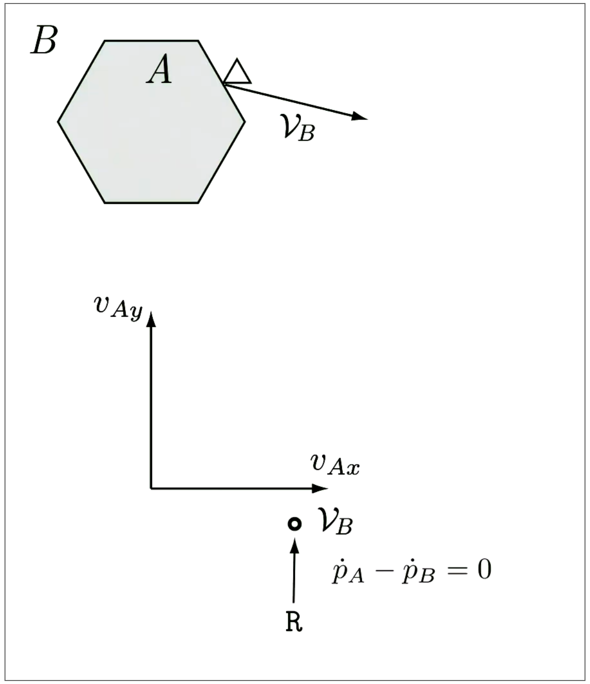

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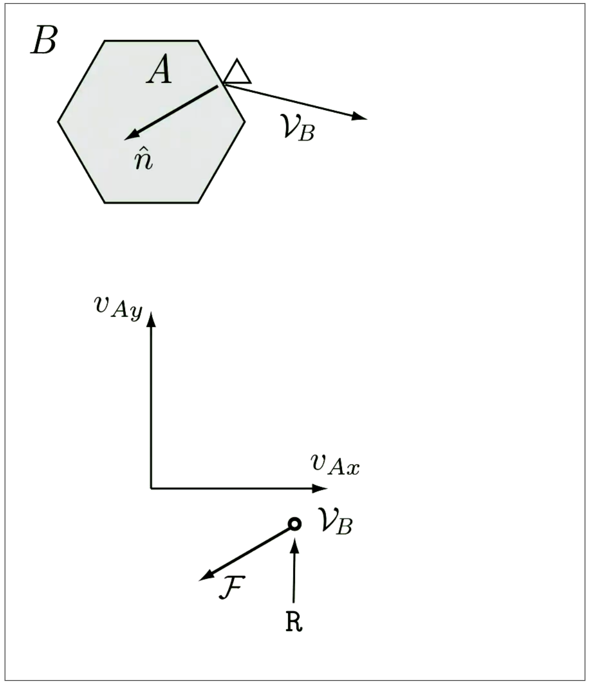

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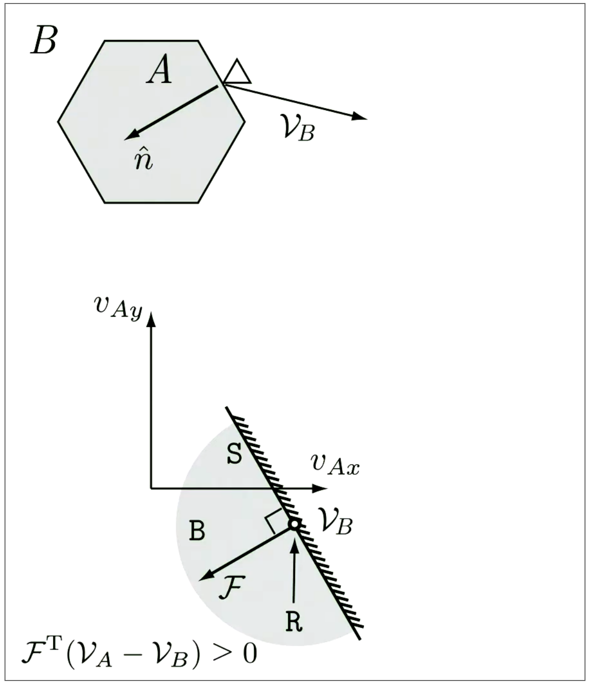


Source: Modern Robotics (Video supplements) **12.1.2. Contact Types: Rolling, Sliding, and Breaking**

Contact types

ROLLING, SLIDING, AND BREAKING FREE

Two bodies maintaining a single-point contact during motion undergo a **roll-slide motion**.

(B) breaking	$\hat{n}^T(\dot{p}_A - \dot{p}_B) > 0$
(S) sliding	$\hat{n}^T(\dot{p}_A - \dot{p}_B) = 0$
(R) rolling	$\dot{p}_A - \dot{p}_B = 0$

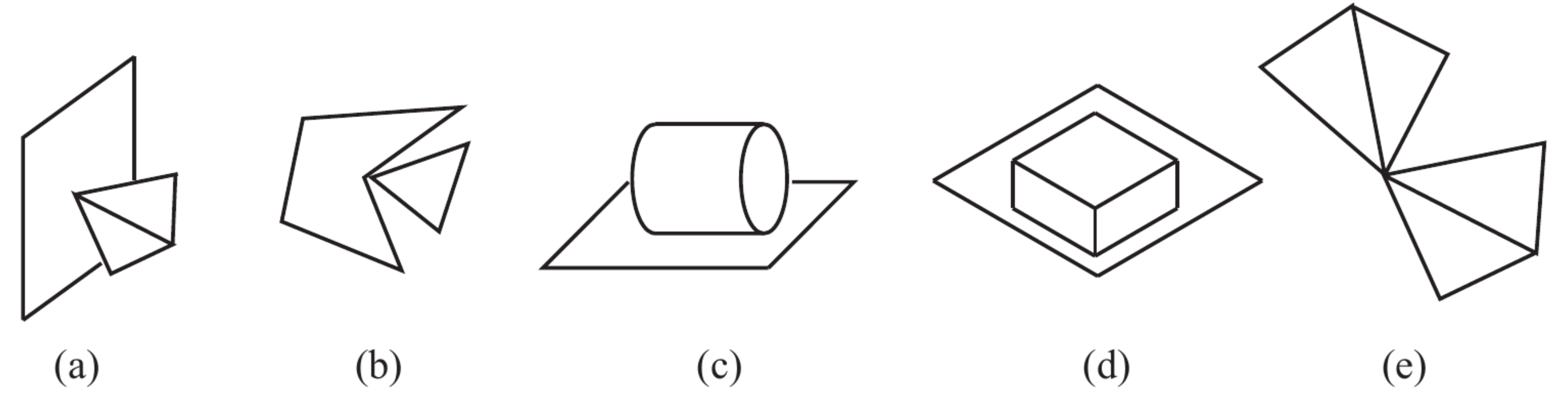
Source: Modern Robotics (Video supplements) **12.1.2. Contact Types: Rolling, Sliding, and Breaking**

Contact types

MULTIPLE CONTACTS

Contact types

OTHER TYPES OF CONTACTS



Source: Modern Robotics **12.1.5. Other types of contacts**

Graphical planar methods

Graphical representation of the feasible twist cone of a planar rigid body

Form closure

Form closure of a body is achieved if a set of stationary constraints prevents all motion of the body.
If these constraints are provided by robot fingers, we call this a **form-closure grasp**.

Source: Modern Robotics **12.1.7. Form closure**

Form closure

FORMAL DEFINITION

Contact forces and friction

COULOMB FRICTION

Contact forces and friction

COULOMB FRICTION

- μ friction coefficient
- If sliding velocity $v = 0$, then the tangential friction force $||f_t||$ is less or equal to the friction coeff μ times the normal force f_n:
  $||f_t|| \leq \mu f_n$
- If sliding velocity $v \neq 0$: $f_t = -\mu f_n \frac{v}{||v||}$
- If sliding velocity $v = 0, a \neq 0$: $f_t = -\mu f_n \frac{a}{||a||}$

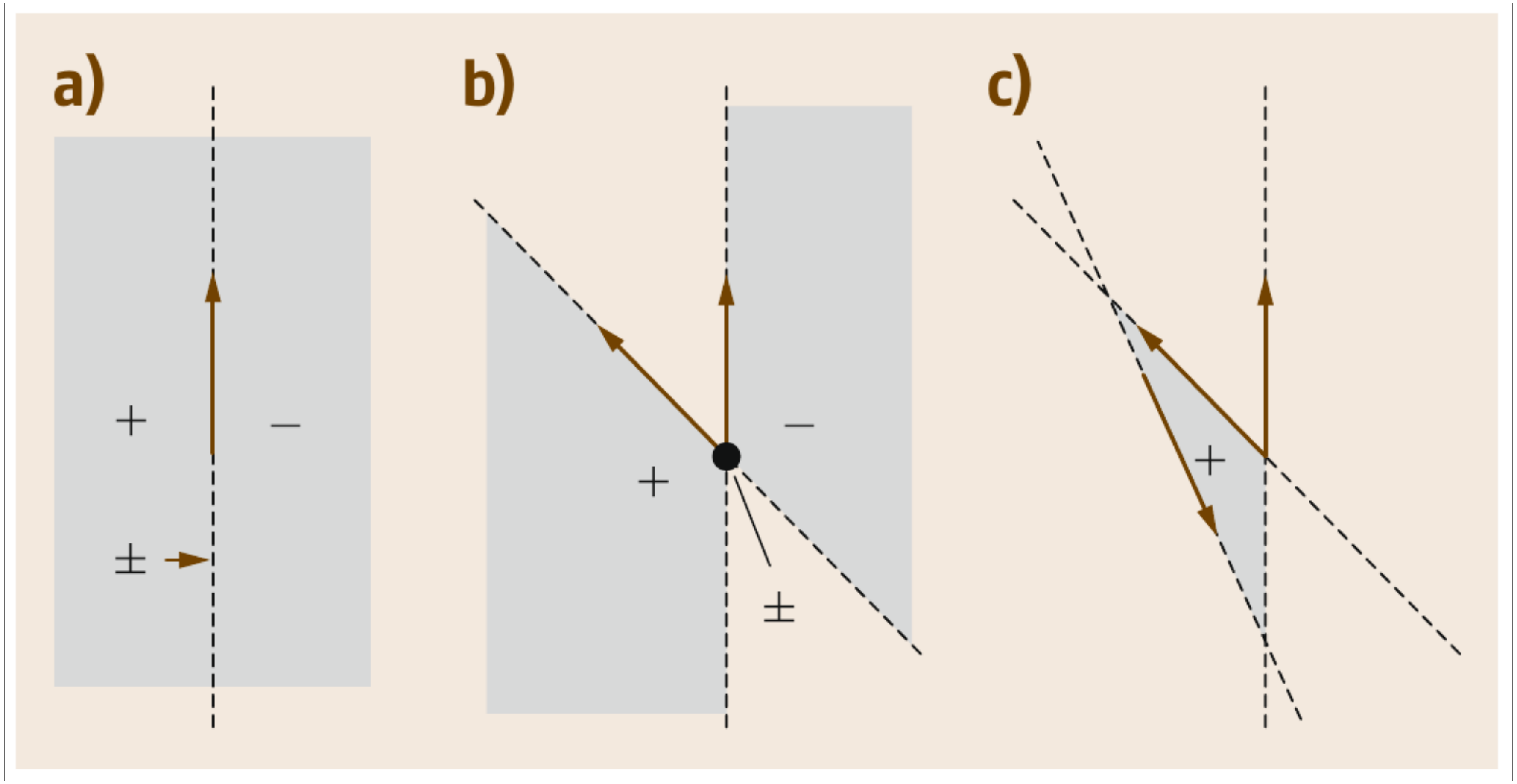
Coulomb friction

WARNING!

- Coulomb friction is only an approximation!
- **Multiple solutions** or **No solutions** (inconsistency)
- If we want to prove that a particular desired object motion occurs, we must also prove that no other motion can occur.

Graphical planar methods

Graphical representation of the positive span of a set of planar wrenches (a wrench cone)



Source: Handbook of robotics (2016) 37.3.1 Graphical Planar Methods

Force closure

Grasp quality

PRACTICE SUBJECT

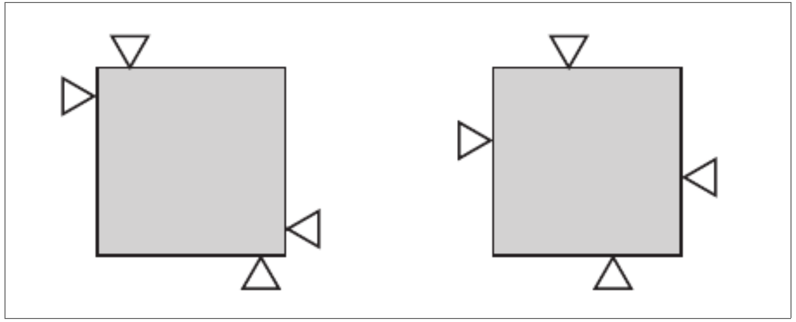
Grasp quality

WHY IS IT IMPORTANT?

- Not all grasps are equal
- Decide which grasp to apply
- Ensure rigid grasp
- Ensure robust control over object position

Grasp quality

HOW TO COMPUTE IT?



Both grasps yield form closure, but which is better?

Source: Modern Robotics: 12.1.7.3 Measuring the quality of a form-closure grasp

Grasp metric

HOW TO DEFINE/COMPUTE IT?

Input:

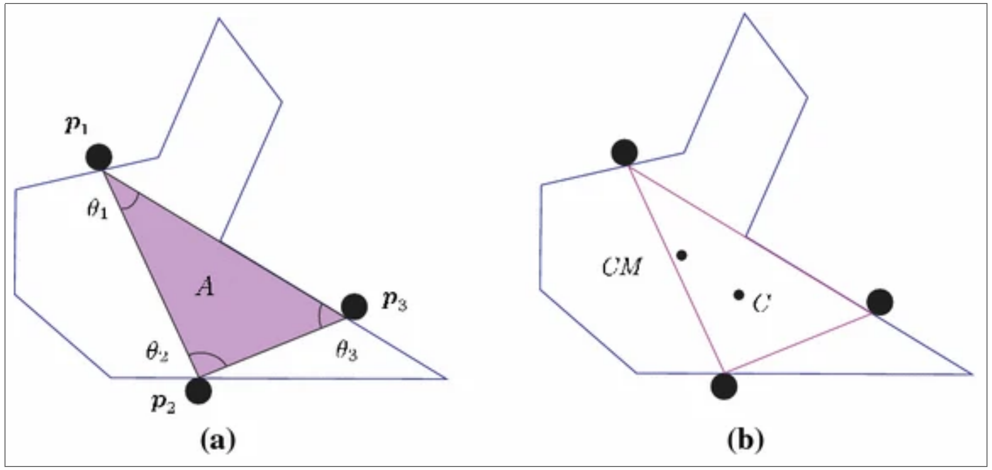
- a set of contacts $\{F_i\}$
- an object to grasp

Output:

- a single value Qual($\{F_i\}$)

Grasp metric

EXAMPLE

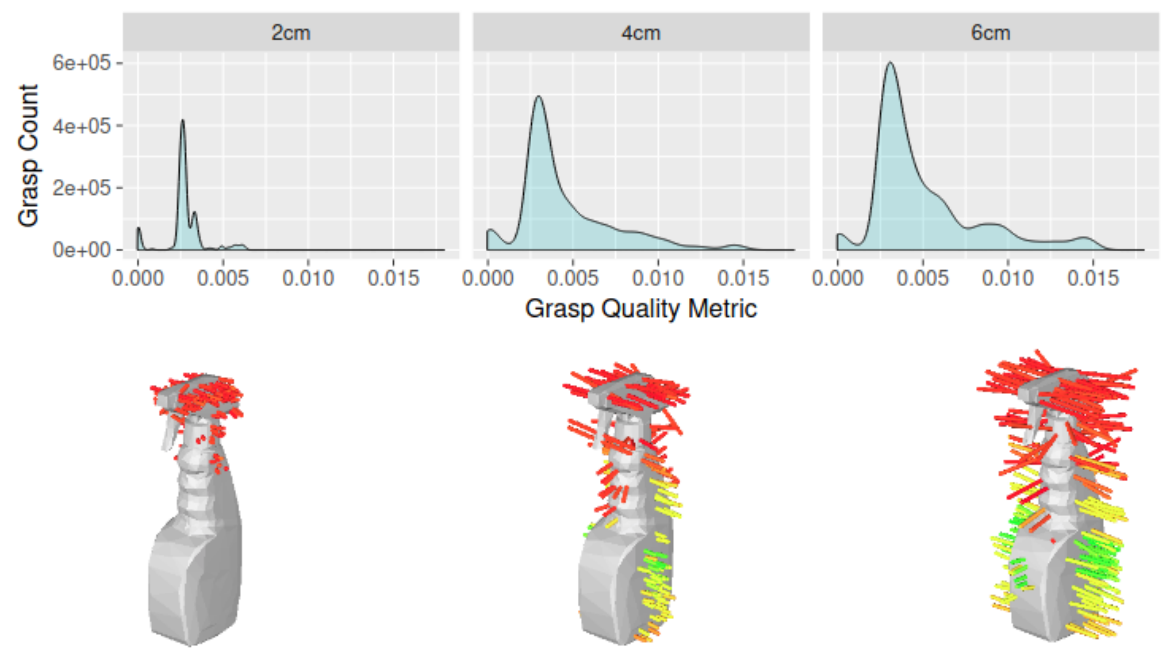


Examples of physical interpretation of quality measures based on geometric relations:
(a) Shape of the grasp polygon determined by the internal angles, and area of the grasp polygon;
(b) Distance between the centroid C of the grasp polygon and the object's center of mass CM.

Source: **Grasp quality measures: review and performanc; Roa et al. (2015)**

Grasp quality

Example



Grasp quality evaluation

Source: **Dex-Net as a Service (DNaaS): A Cloud-Based Robust Robot Grasp Planning System; Li et al (2018)**

Grasping algorithms

Grasping algorithms

	Analytic algorithms	Learning-based algorithms
Approach	Kinematic & Dynamics	Classification and learning methods
Intuition	*For this known object, the computed optimal grasp is **this***	*I see the object only partially, but on average for similar objects **this** grasp works the best.*
Input required	• object model • mass, center of mass • inertia matrix • friction coefficient	• depth/RGB+D images
Computational cost	Expensive	Slow training Fast inference
Examples	Review [*]	• 6DOF GraspNet • DexNet 4.0 • **GPD**

Learning-based algorithms

GRASP POSE DETECTION (GPD) IN DENSE CLUTTER

Learning-based algorithms

6-DOF GraspNet

Learning-based algorithms

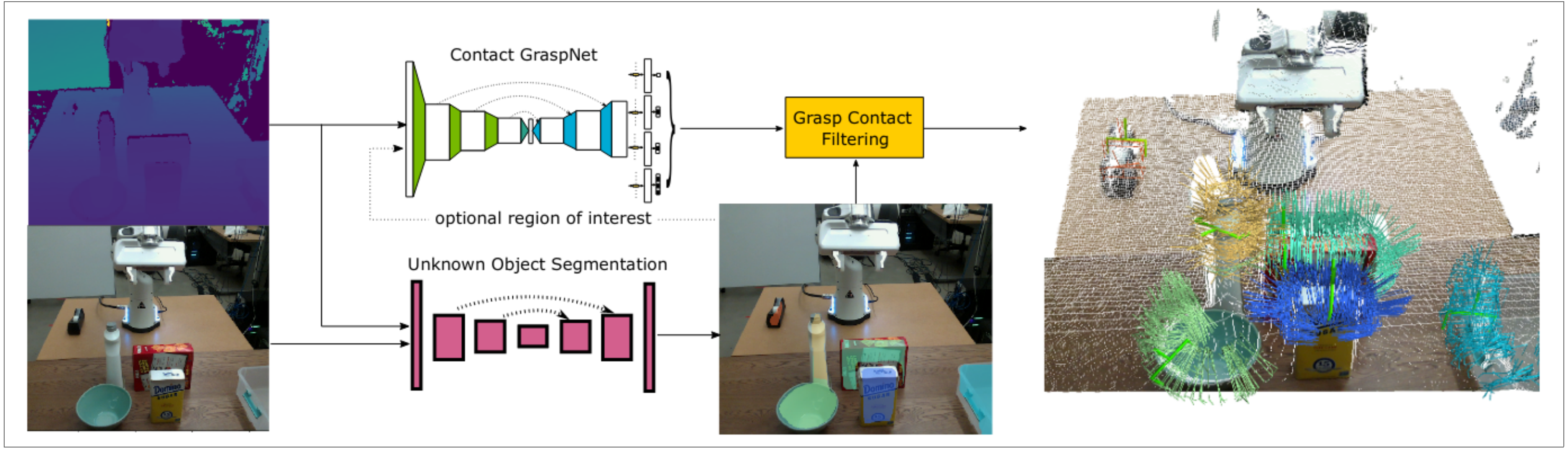
CONTACT GRASPNET

Grasping pipeline and related problems

Grasping pipeline and related problems

1. Segment objects
2. Sample grasp candidates
3. Evaluate and sort grasp candidates
4. Add surrounding scene as obstacles
5. Plan arm movement
6. Execute

Example: Contact GraspNet



Source: **Contact-GraspNet: Efficient 6-DoF Grasp Generation in Cluttered Scenes; Sundermeyer et al. (2021)**

Where could I work after studying grasping?

- **ABB**
- **Ambi Robotics**
- **FESTO**
- Honda research institute
- KUKA
- **Toyota Research Institute**
- **Vicarious**

Questions ?

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