Automatic Determination of Finger Control Modes for Graspless Manipulation

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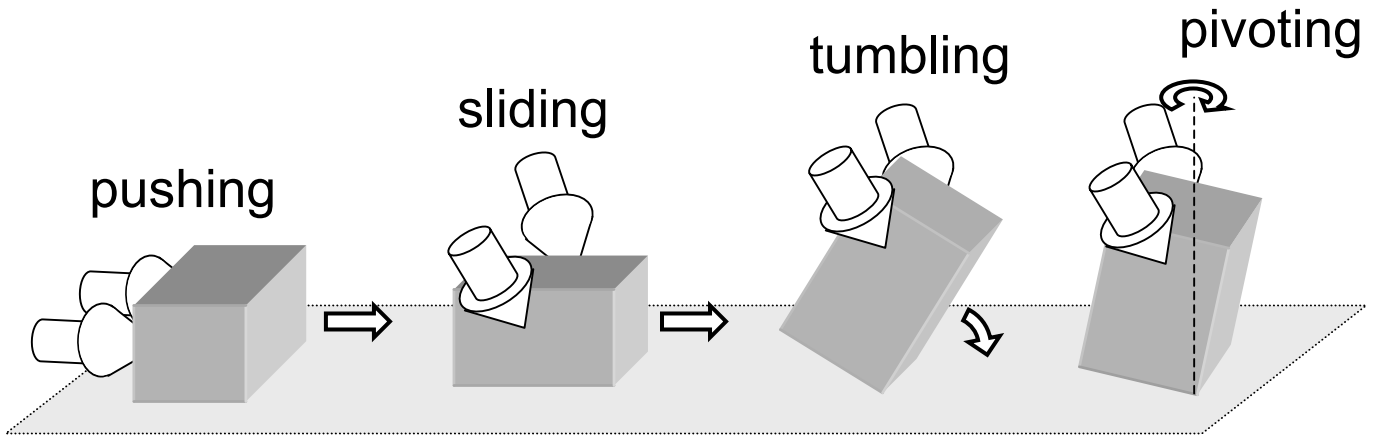
1. Introduction

Graspless (Nonprehensile) Manipulation

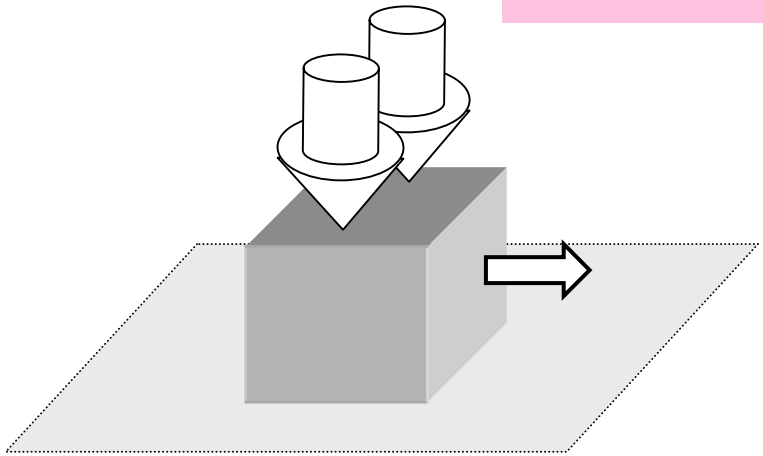
to Manipulate Objects without Grasping [Aiyama 93]



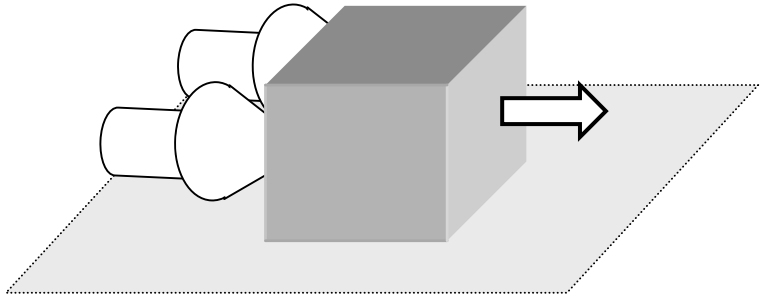
- Manipulation without supporting object weight
- Manipulation when grasping is impossible

Finger Control Modes in Graspless Manipulation

Force Control or Position Control?



force control is preferable
(for avoiding excessive internal force)



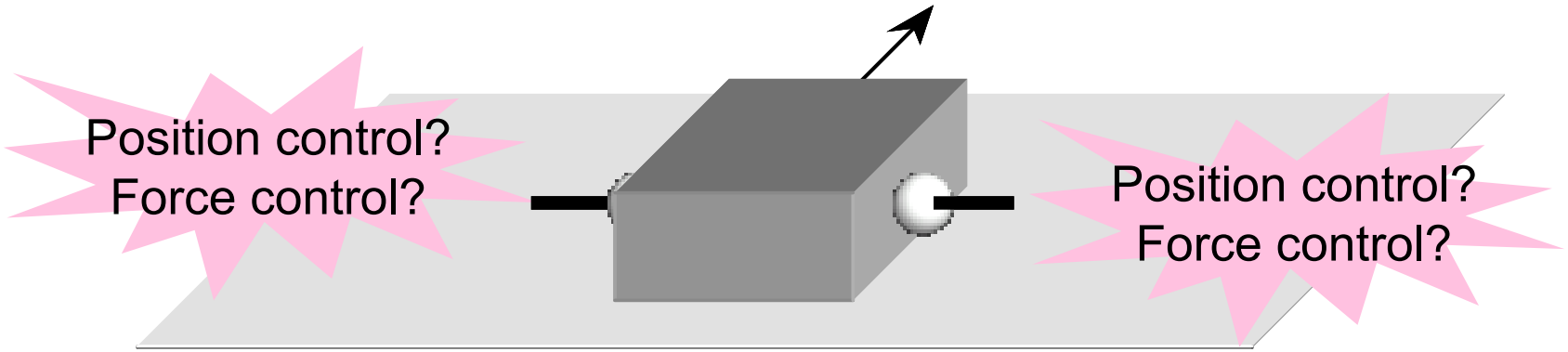
position control is preferable
(for higher manipulation stability)

⇨ Both position control and force control should be used appropriately in graspless manipulation

Objective

To develop a method to determine appropriate finger control modes (position control/force control) for graspless manipulation

(moreover, to determine desired forces of force-controlled fingers)



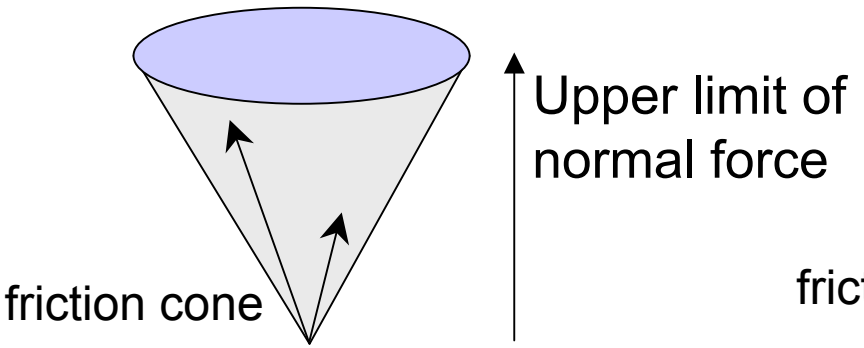
2. Model of Graspless Manipulation

Assumptions

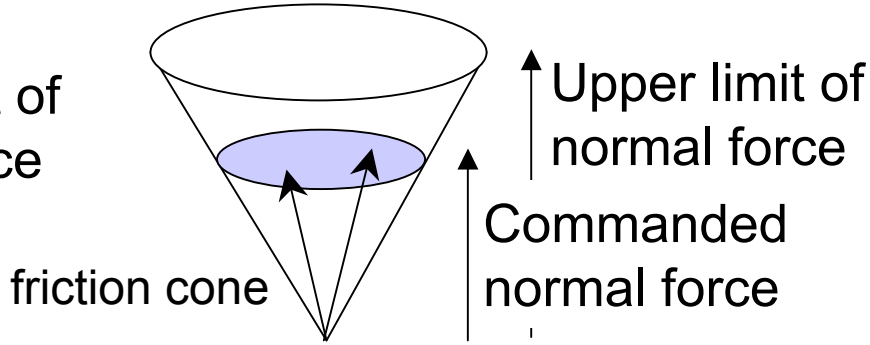
- Quasi-static manipulation of a rigid object
- Under gravity and Coulomb friction
- Friction coefficient is uniform on each contact surface
- Static and kinetic friction coefficients are equal
- Each friction cone can be approximated as a polyhedral convex cone
- Each robot finger is in one-point contact with the object
- Each finger is in position control mode or force control mode (hybrid position/force control)

Model of Finger Forces

Position-controlled finger



Force-controlled finger



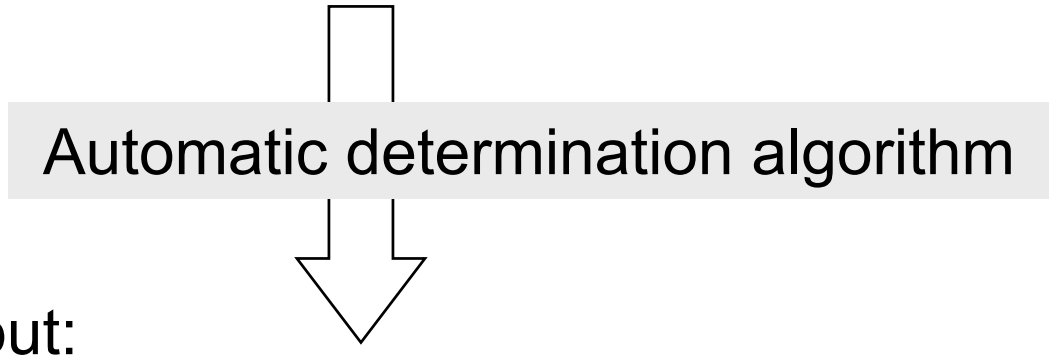
- Finger can apply arbitrary forces within its friction cone *passively*

- Finger can apply commanded normal force *actively* and arbitrary tangential force within its friction cone *passively*

Problem to be Solved

Input:

- Desired (instantaneous) object motion
- Fingertip locations on the object



Output:

- Finger control modes (position control/force control)
- Desired normal finger forces (for force-controlled fingers)

3. Determination of Finger Control Modes

Basic Idea

Maximize manipulation stability as far as excessive internal forces could not be generated

✧ The possibility of excessive internal force can be judged by linear programming [Maeda et al., IROS96]

✧ A stability index for graspless manipulation can be calculated by linear programming
[Maeda and ARAI, ICRA02]

⇨ Finger control modes can be determined through a series of linear programming

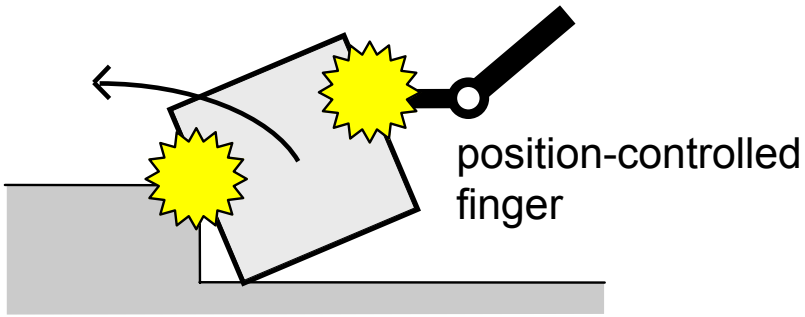
Judgment of the Possibility of Excessive Internal Force

By the following linear programming [Maeda 96]

$$\text{maximize } p = \boldsymbol{b}_{\text{env}}^T \boldsymbol{k}_{\text{env}} + \boldsymbol{b}_{\text{rob}}^T \boldsymbol{k}_{\text{rob}}$$

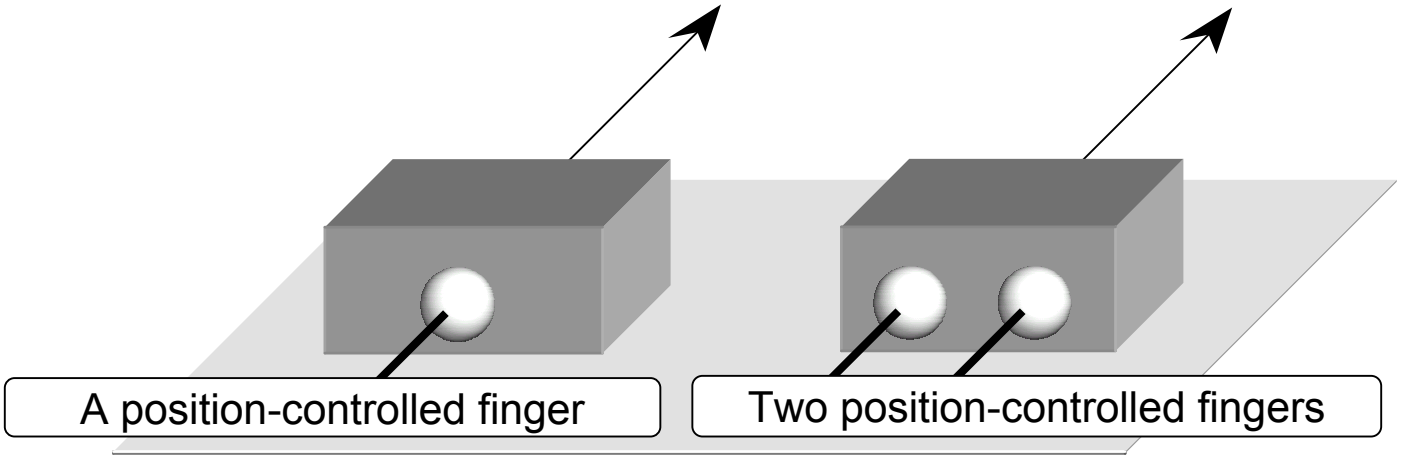
$$\text{subject to } \begin{cases} \boldsymbol{W}_{\text{env}} \boldsymbol{C}_{\text{env}} \boldsymbol{k}_{\text{env}} + \boldsymbol{W}_{\text{rob}} \boldsymbol{A}_{\text{pos}} \boldsymbol{C}_{\text{rob}} \boldsymbol{k}_{\text{rob}} = \boldsymbol{0} \\ \boldsymbol{k}_{\text{env}} \geq \boldsymbol{0}, \boldsymbol{k}_{\text{rob}} \geq \boldsymbol{0} \end{cases}$$

- $p \to \infty$ Excessive internal force may be generated
- $p \to 0$ Excessive internal force could not be generated



Stability Index for Graspless Manipulation

the magnitude of disturbing (generalized) force that the object can resist without changing its motion. [Maeda 02]



Calculation of Manipulation Stability

- The manipulation stability index, z, can be calculated approximately by linear programming when all the finger control modes are specified.

$$\text{maximize } z$$

$$\text{subject to } \begin{cases} z\boldsymbol{M}^{-1/2}\boldsymbol{l}_1 = \boldsymbol{Q}_{\text{known}} + \boldsymbol{W}_{\text{env}}\boldsymbol{C}_{\text{env}}\boldsymbol{k}_{\text{env}\,1}\boldsymbol{W}_{\text{rob}}\boldsymbol{C}_{\text{rob}}\boldsymbol{k}_{\text{rob}\,1} \\ \quad\vdots \\ z\boldsymbol{M}^{-1/2}\boldsymbol{l}_N = \boldsymbol{Q}_{\text{known}} + \boldsymbol{W}_{\text{env}}\boldsymbol{C}_{\text{env}}\boldsymbol{k}_{\text{env}\,N} + \boldsymbol{W}_{\text{rob}}\boldsymbol{C}_{\text{rob}}\boldsymbol{k}_{\text{rob}\,N} \\ \boldsymbol{N}_{\text{rob}}^T\boldsymbol{C}_{\text{rob}}\boldsymbol{k}_{\text{rob}\,1} \le \boldsymbol{f}_{\max},\ \ldots,\ \boldsymbol{N}_{\text{rob}}^T\boldsymbol{C}_{\text{rob}}\boldsymbol{k}_{\text{rob}\,N} \le \boldsymbol{f}_{\max} \\ \boldsymbol{N}_{\text{rob}}^T\boldsymbol{A}_{\text{force}}\boldsymbol{C}_{\text{rob}}\boldsymbol{k}_{\text{rob}\,1} = \boldsymbol{f}_{\text{com}},\ \ldots,\ \boldsymbol{N}_{\text{rob}}^T\boldsymbol{A}_{\text{force}}\boldsymbol{C}_{\text{rob}}\boldsymbol{k}_{\text{rob}\,N} = \boldsymbol{f}_{\text{com}} \\ \boldsymbol{k}_{\text{env}\,1}, \ldots, \boldsymbol{k}_{\text{env}\,N} \ge \boldsymbol{0},\ \boldsymbol{k}_{\text{rob}\,1}, \ldots, \boldsymbol{k}_{\text{rob}\,N} \ge \boldsymbol{0} \end{cases}$$

(desired finger forces can be determined simultaneously)

Procedure for Control Mode Determination

1. Assume a combination of control modes (position control / force control) for each robot finger.
2. Check the possibility of excessive internal force.
   ($\rightarrow$ If excessive internal force may be generated, give up this combination and go to step 4)
3. Calculate desired normal finger forces so that the index of manipulation stability will be maximized
   ($\rightarrow$ If the index is larger than the current maximum value, replace it.)
4. If all the combinations of control modes have been already checked, stop. Otherwise, go back to step 1.

4. Numerical Examples

Sliding a cuboid on a plane by two fingers

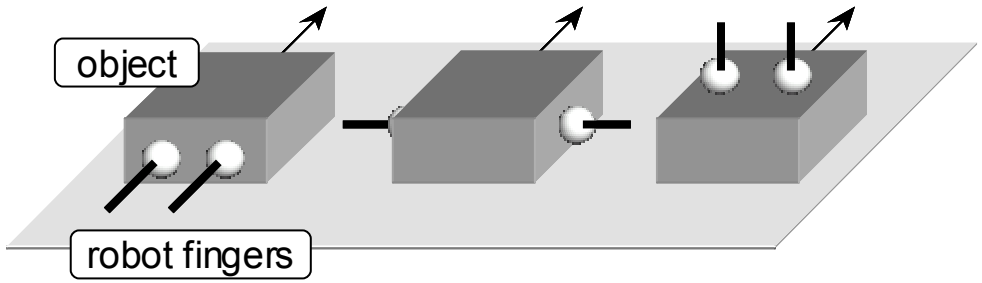
Mass of object = 1

Friction coef. between environment and object = 0.2

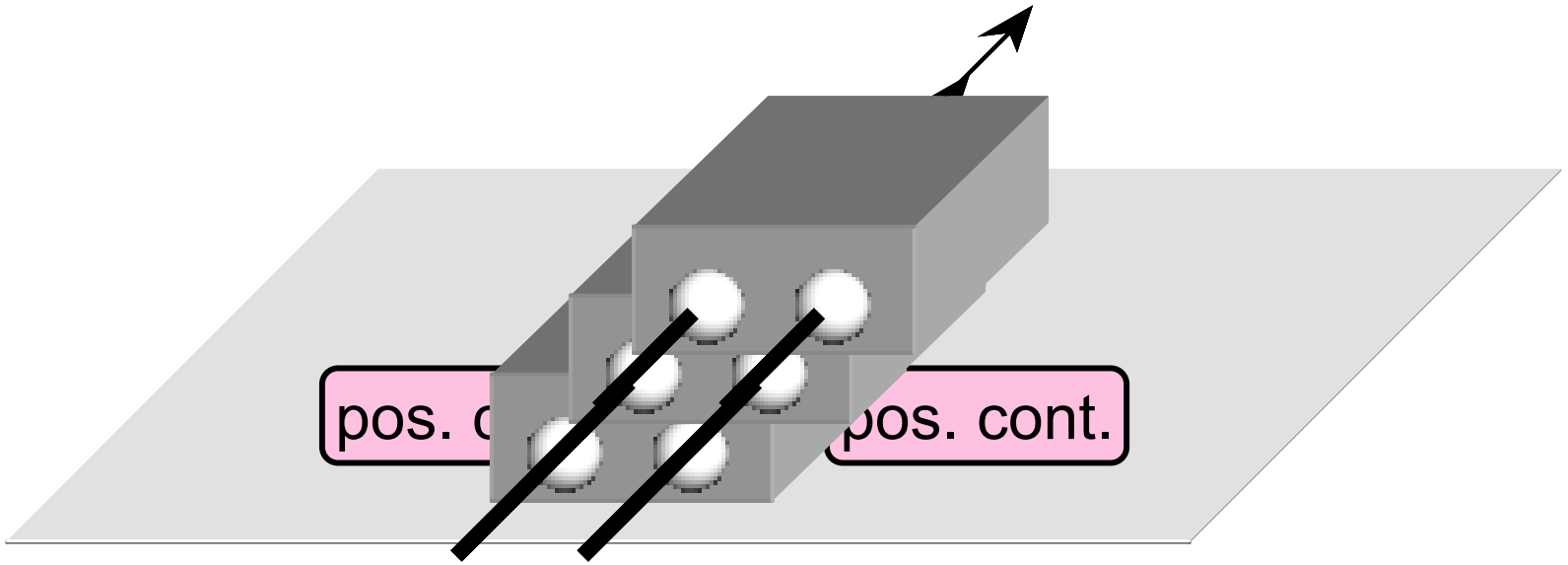
Friction coef. between fingers and object = 0.5

Maximum finger force = 10

Acceleration of gravity = 9.8



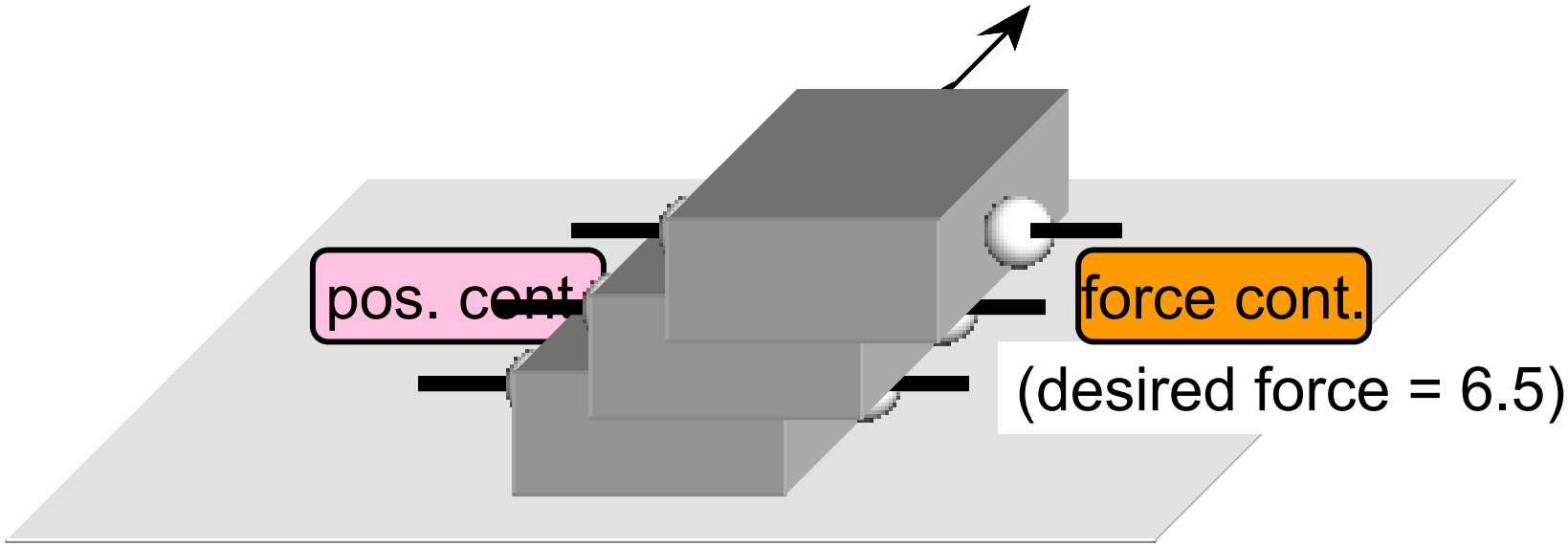
Pushing Cuboid from Behind to Slide



stability = 0.6

Computation time: 0.02 CPU seconds (Pentium4-1.6GHz)

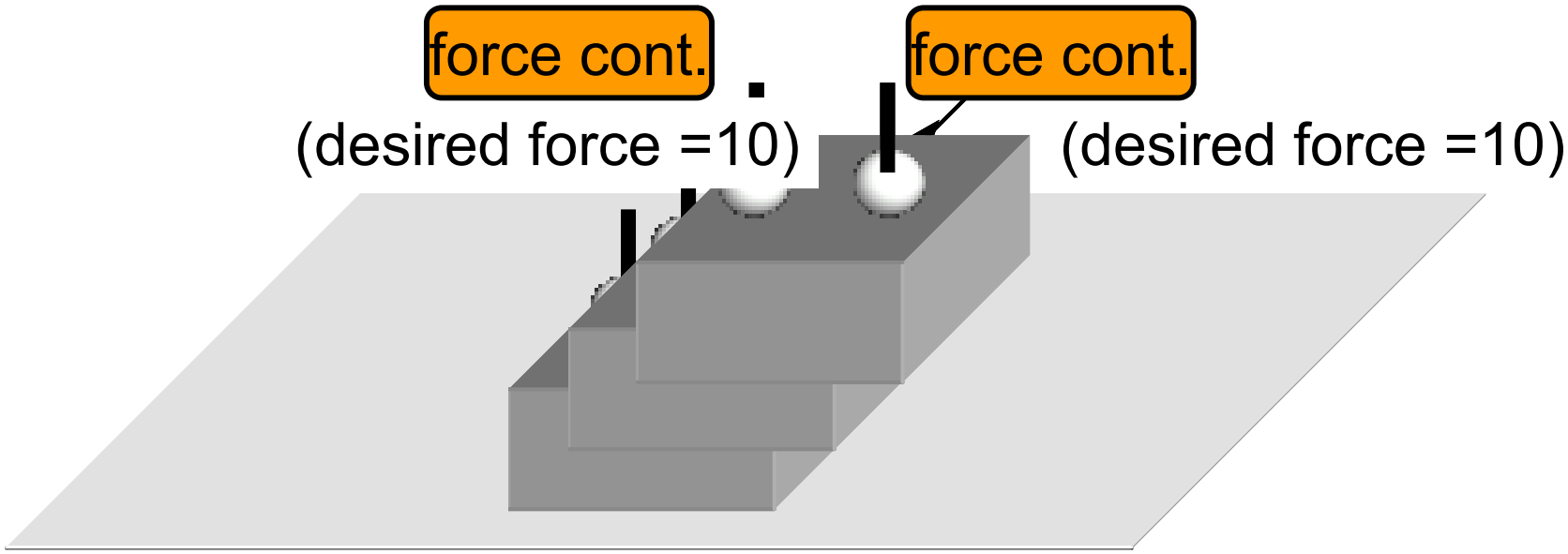
Pinching Cuboid to Slide



stability = 2.4

Computation time: 0.7 CPU seconds (Pentium4-1.6GHz)

Dragging Cuboid to Slide



stability = 1.7

Computation time: 0.3 CPU seconds (Pentium4-1.6GHz)

Tumbling a Cuboid on a Plane by Two Fingers

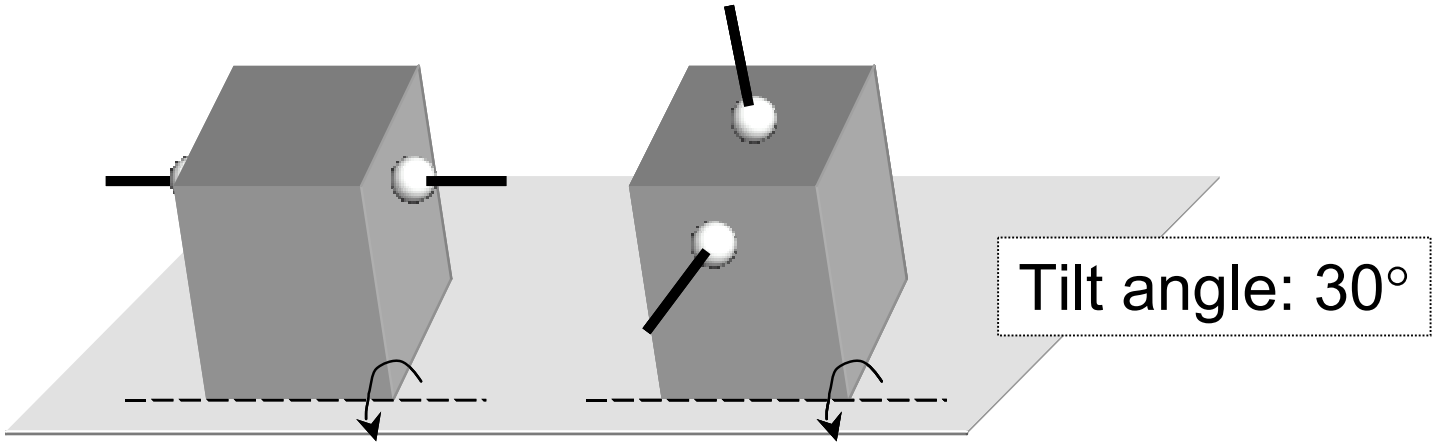
Mass of object = 1

Friction coef. between environment and object = 0.2

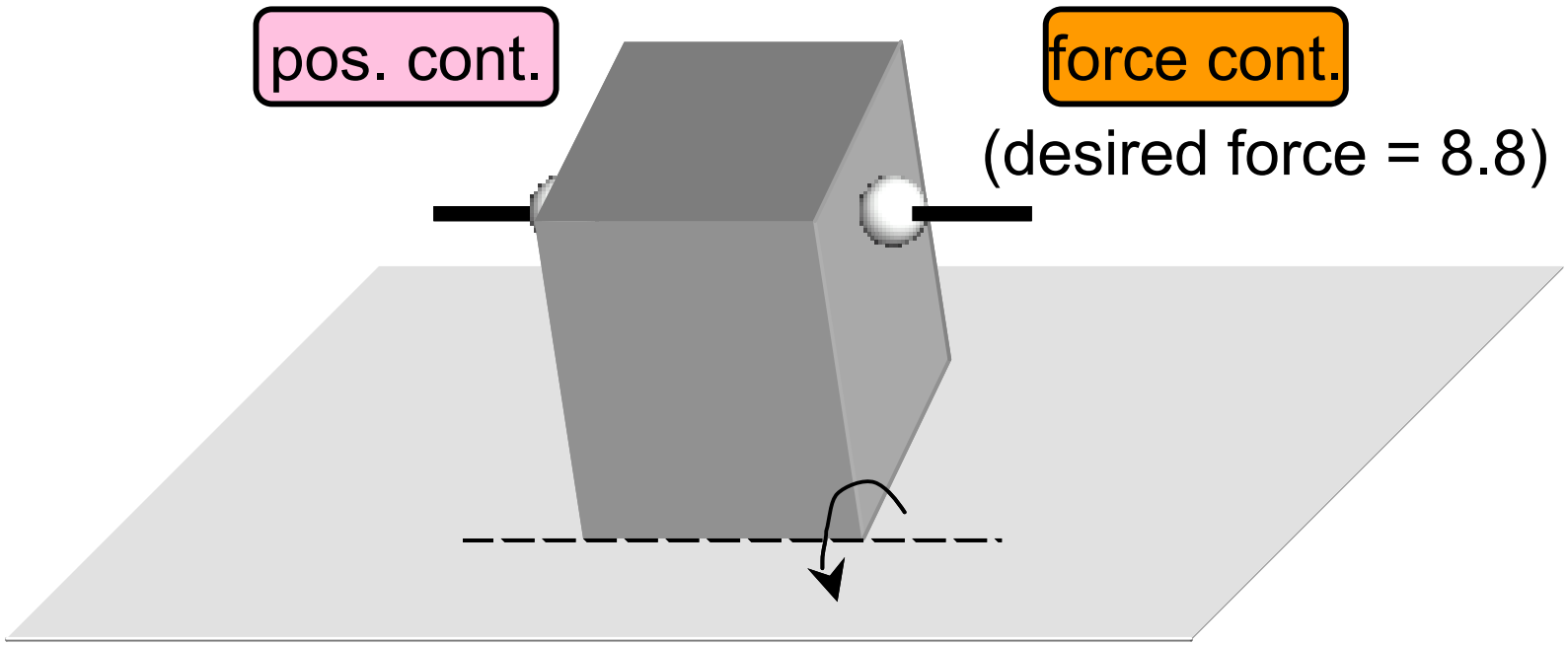
Friction coef. between fingers and object = 0.5

Maximum finger force = 10

Acceleration of gravity = 9.8



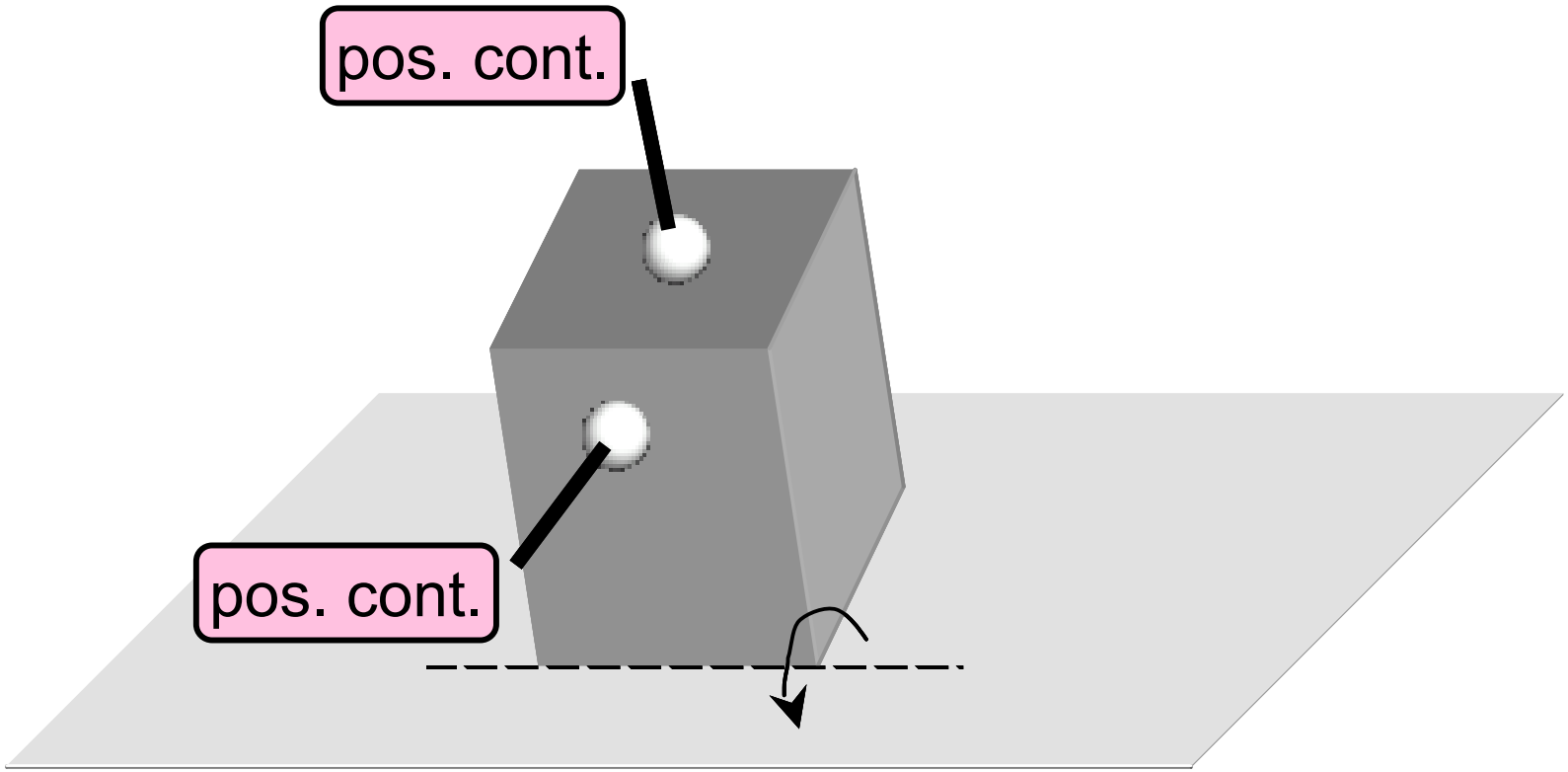
Tumbling of Cuboid (1)



stability = 2.5

Computation time: 1.1 CPU seconds (Pentium4-1.6GHz)

Tumbling of Cuboid (2)

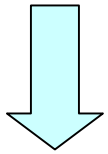


stability = 1.1

Computation time: 0.4 CPU seconds (Pentium4-1.6GHz)

Discussion

Finger control modes are determined to maximize manipulation stability as far as excessive internal forces could not be generated



- Position control is used as much as possible
- Force control is used only when needed

5. Conclusion

Summary

- A linear-programming-based method to determine finger control modes for graspless manipulation is developed.
- The following things are considered in the determination:
  - Avoidance of excessive internal forces
  - Maximization of manipulation stability
- Numerical examples are shown.

Application

- Planning of graspless manipulation
  - Motion planner for graspless manipulation by robot fingers considering finger control modes