A Quantitative Stability Measure for Graspless Manipulation

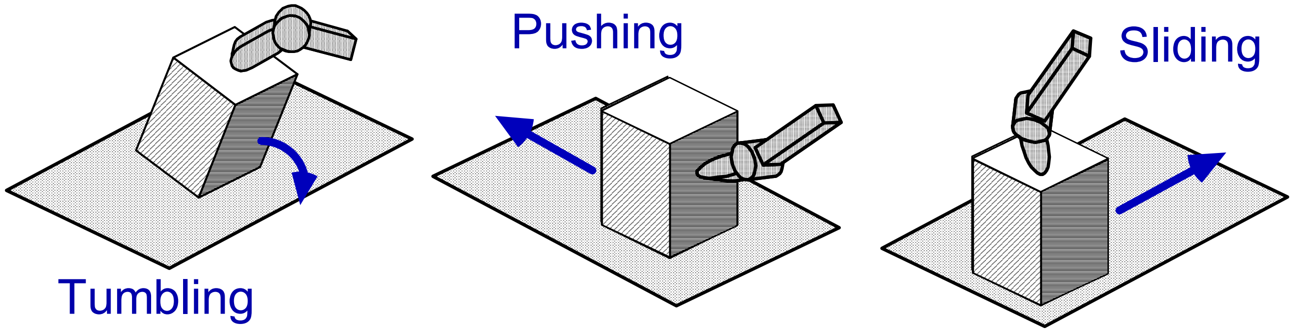
○ Yusuke MAEDA and Tamio ARAI

(The University of Tokyo)

1. Introduction

Graspless (Nonprehensile) Manipulation

to Manipulate Objects without Grasping [Aiyama 93]

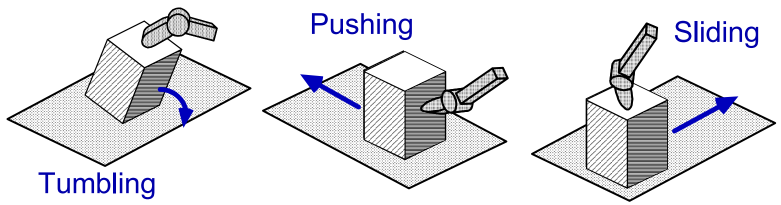


- No need to support all the weight of objects
- Complement to conventional pick-and-place

Disadvantage of Graspless Manipulation

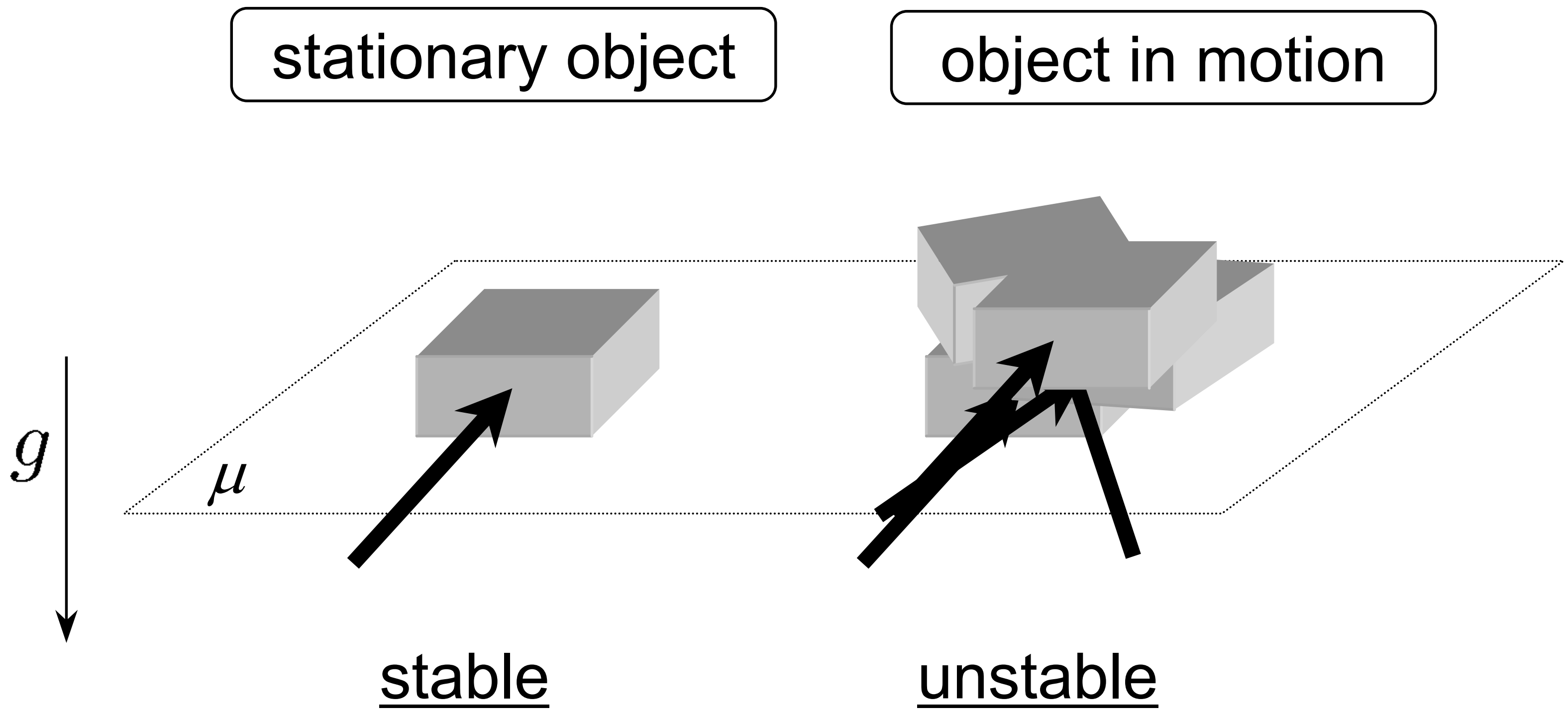
<u>Less Stability than Pick-and-Place</u>

- Not Form- nor Force-Closure



Evaluation of manipulation stability is important

Stability of Graspless Manipulation



Related Works

[Mason and Lynch 93]
…"Quasi-Static Closure" "Dynamic Closure"

[Trinkle 95]… "First-Order Stability"

[Maeda et al. 96]…Quantitative Stability Measure for
Manipulation without Sliding Contacts

[Yu and Yoshikawa 97]…"Contact Maintainability"

[Kijimoto et al. 99]… Quantitative Stability Measure for
Graspless Manipulation with Little Physical Basis

Objective

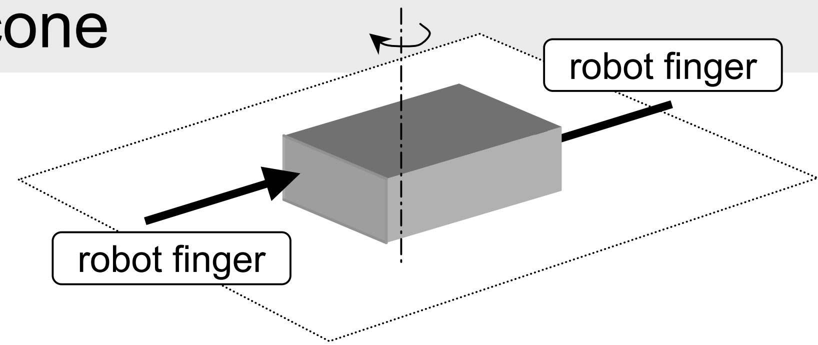
Quantitative Stability Measure for Graspless Manipulation

- Consideration to gravity and friction
- Applicable to not only pushing but also other graspless operations

2. Model of Contact Forces

Assumptions

- Quasi-Static manipulation of a polyhedral 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



Set of Applicable Contact Forces

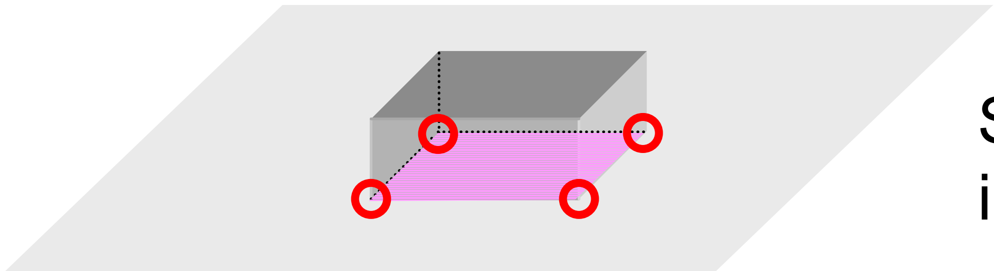
Set of Generalized Forces Applicable to Object through Point Contacts

Represented as Union of Polyhedral Convex Cones
[Yu and Yoshikawa 97, 01]

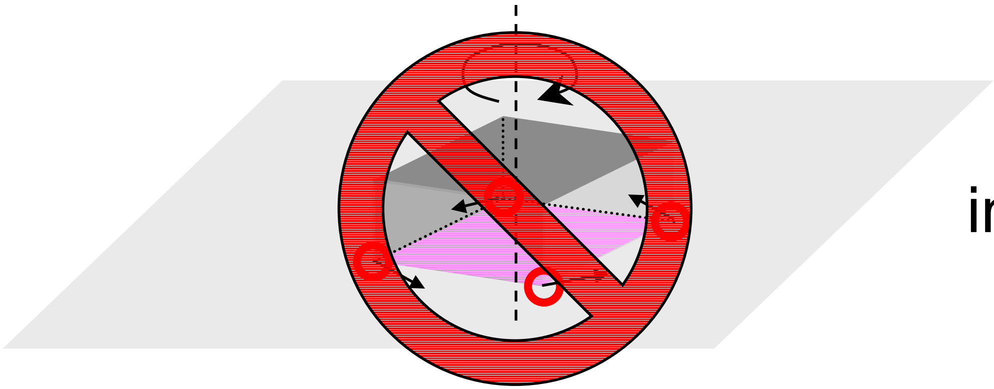
⇨ Approximate all the contacts with point contacts

Friction on Surface Contact

Representative Points



Stationary or
in Translation

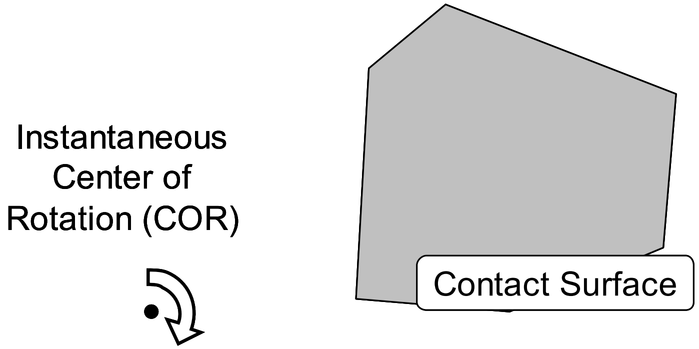


in Rotation

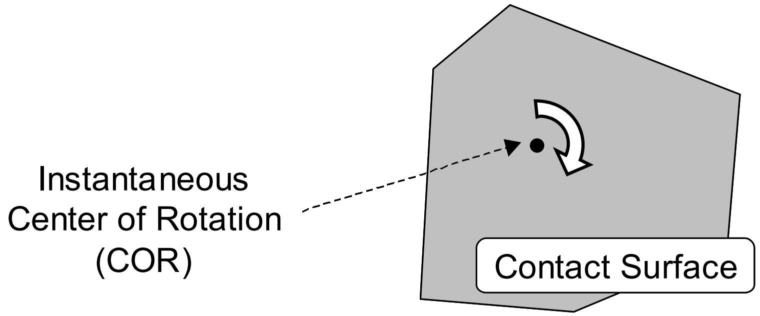
Surface Contact in Rotation

COR = Center Of Rotation

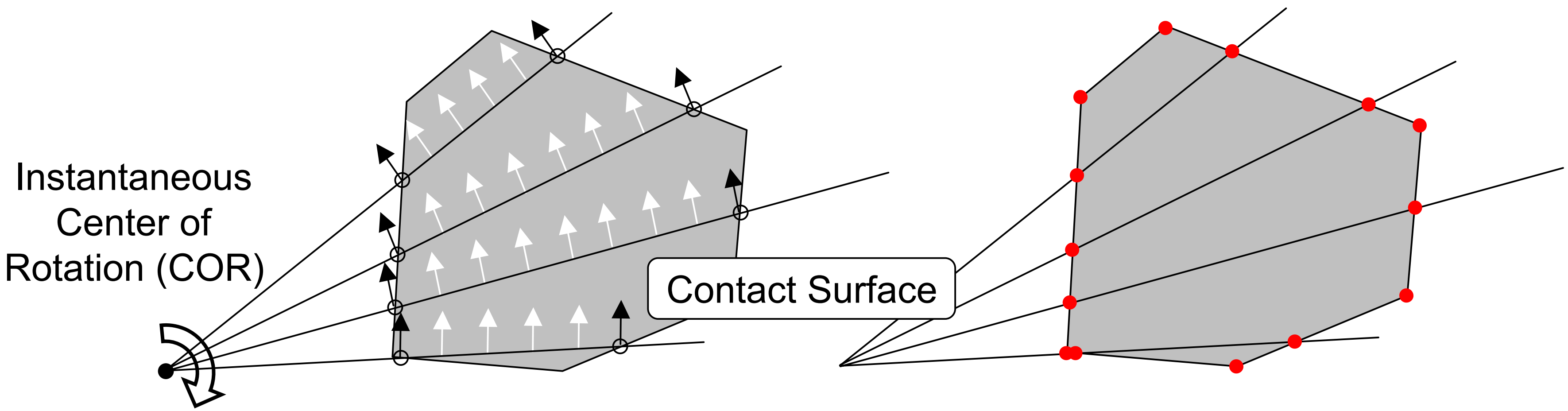
- Case 1: Instantaneous COR is *outside* the contact surface



- Case 2: Instantaneous COR is *on* the contact surface



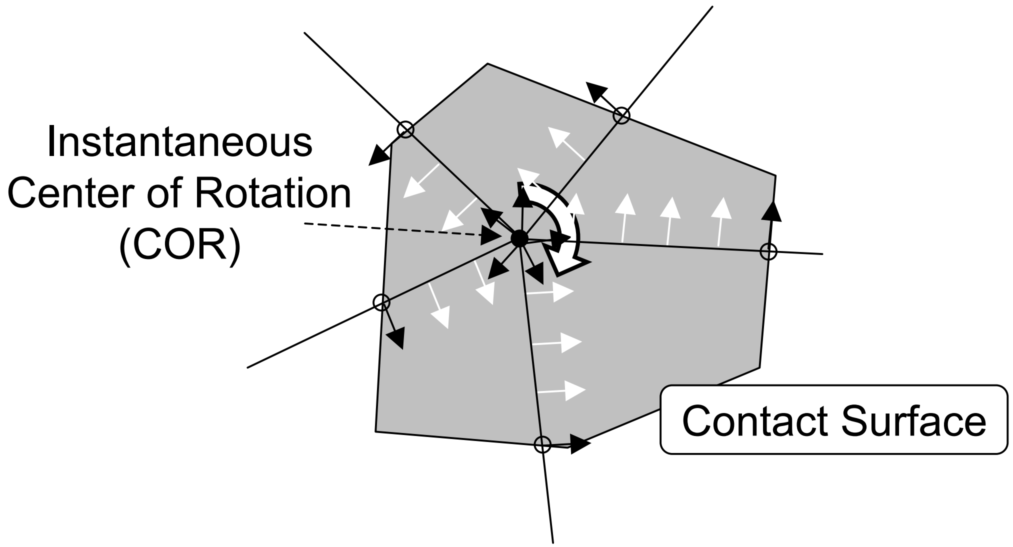
Case 1: COR is outside the contact surface



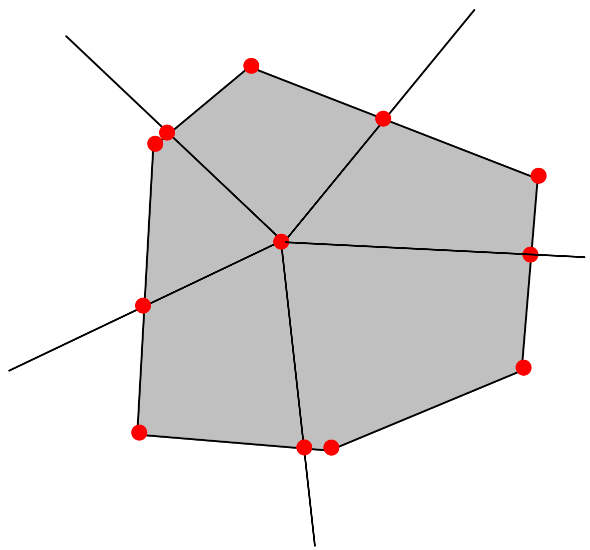
Contact forces on each half-line have the same direction vector

Approximation by Finite Representative Points

Case 2: COR is on the contact surface



Contact forces on each half-line have the same direction vector



Approximation by Finite Representative Points

3. New Stability Measure

Two Types of Stability of Graspless Manipulation

1. Ability of manipulated objects to resist disturbing force without changing their motion

2. Ability of manipulated objects to resume their original motion after a perturbation by disturbing force

Our Stability Measure

Magnitude of disturbing (generalized) force

that the object can resist without changing its motion

$$z = \min_{\|\hat{Q}_{\text{dist}}\|_M = 1} \max_{\substack{Q_{\text{known}} + Q = -t\hat{Q}_{\text{dist}}, \\ t > 0, Q \in \mathcal{A}}} \|Q_{\text{known}} + Q\|_M$$

Q : Resultant Contact Force

Q_{known} : Known External Force (gravity, etc.)

$\hat{Q}_{\text{dist}}$: Direction Vector of (Unknown) Disturbing Force

$$\|Q\|_M = \sqrt{Q^T M^{-1} Q}$$

M : Inertia Matrix of Object

Discussion about Stability Measure

Stability Value z:

Magnitude of Resistible Disturbance in the "Weakest" Direction

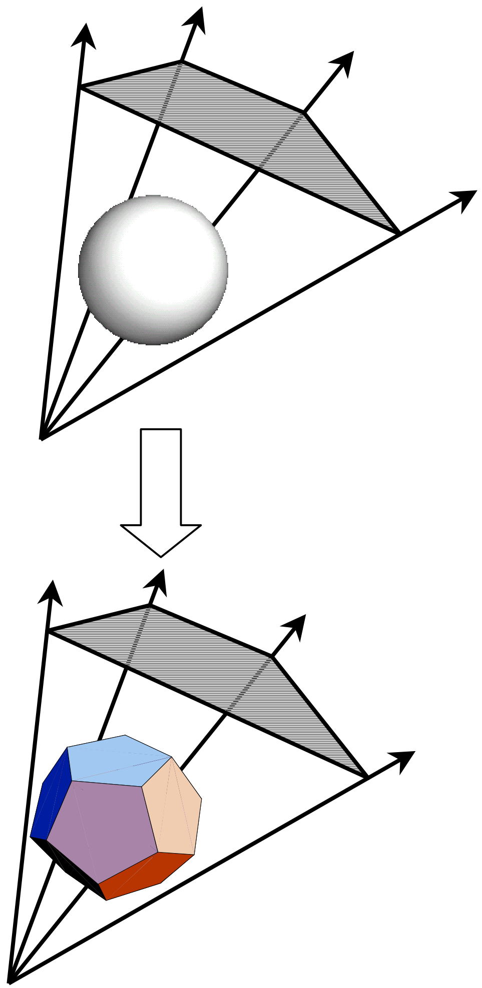
$z > 0$ … Disturbance smaller than z cannot perturb object motion

⇨ Stable Manipulation

$z = 0$ … Infinitesimal disturbance can perturb object motion

⇨ Unstable Manipulation

Calculation of the Stability Value by Linear Programming



$$z = \min_{\|\hat{Q}_{\text{dist}}\|_M = 1} \max_{\substack{Q_{\text{known}} + Q = -t\hat{Q}_{\text{dist}}, \\ t > 0, Q \in \mathcal{A}}} \|Q_{\text{known}} + Q\|_M$$

⇩ Approximation of Hypersphere as Hyperpolyhedron

$$z = \min_{i=1,\ldots,N} z_i$$

$$z_i = \max_j z_{ij}$$

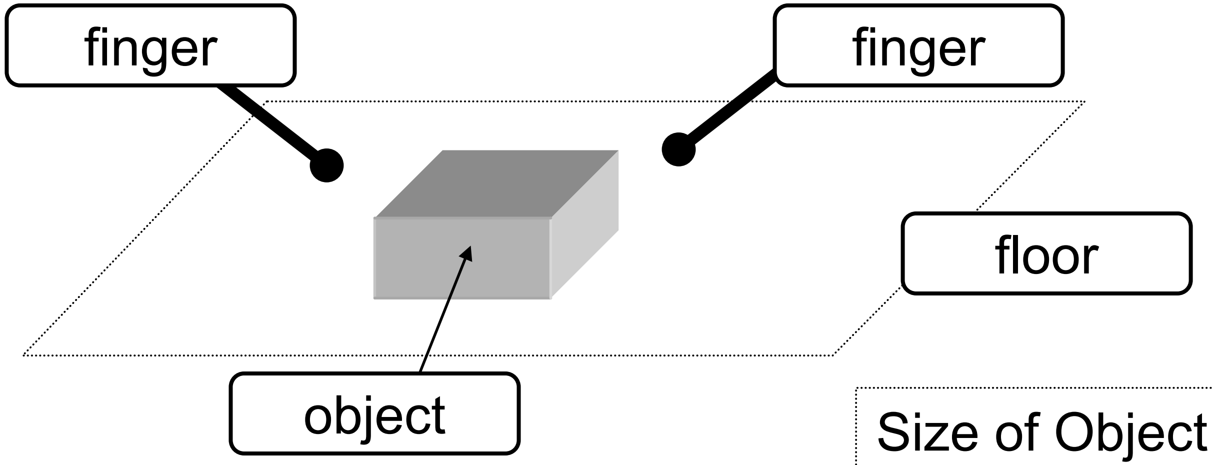
$$\text{subject to} \begin{cases} z_{ij}\boldsymbol{l}_i = \boldsymbol{Q}_{\text{known}} + \boldsymbol{W}_j \boldsymbol{C}_j \boldsymbol{k}_{ij} \\ \boldsymbol{\tau}_j = \boldsymbol{J}_j^T \boldsymbol{C}_j \boldsymbol{k}_{ij} \\ \boldsymbol{k}_{ij} \geq \boldsymbol{0} \end{cases}$$

(Numerical Examples: 76 vertices)

4. Numerical Examples

Graspless Manipulation of a Cuboid

Manipulation by Two Position-Controlled Robot Fingers

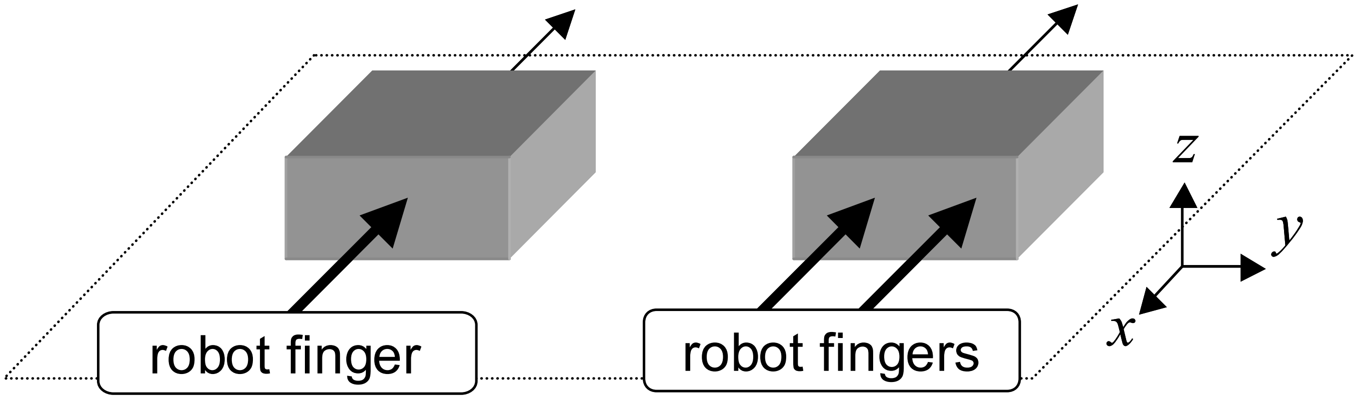


Size of Object: 2x2x1

Mass of Object: 1

Friction coefficient: 0.2

Translation by Pushing



stability = 0

unstable

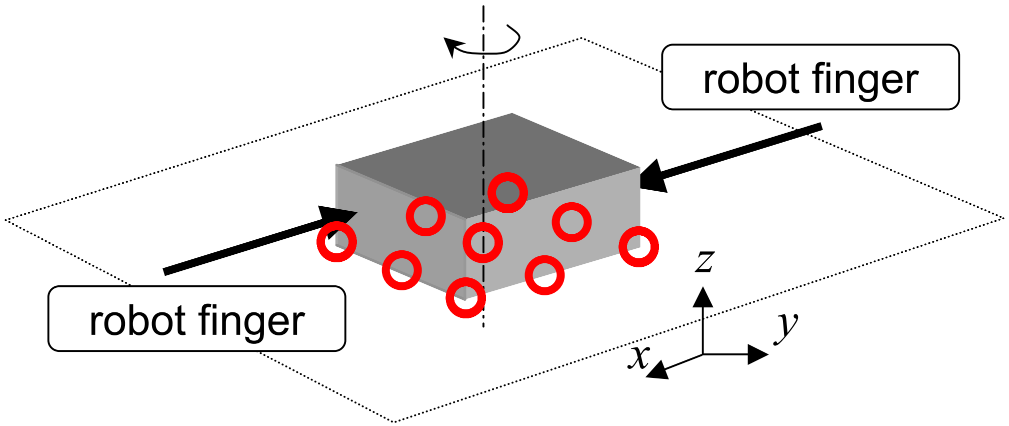
stability = 0.23

stable push
[Lynch 96]

Calculation Time:
0.1 CPU Seconds

(Pentium4-1.5GHz)

Rotation by Pushing



Stability = ~~1.2~~
~~1.1~~
0.7

Stable

Calculation Time:
1.3 CPU Seconds

(Pentium4-1.5GHz)

6. Conclusion

Summary

• A quantitative stability measure for graspless manipulation

• Calculation method of the measure by linear programming

Future Work

• Application to Planning of Graspless Manipulation