A Quantitative Test for the Robustness of Graspless Manipulation

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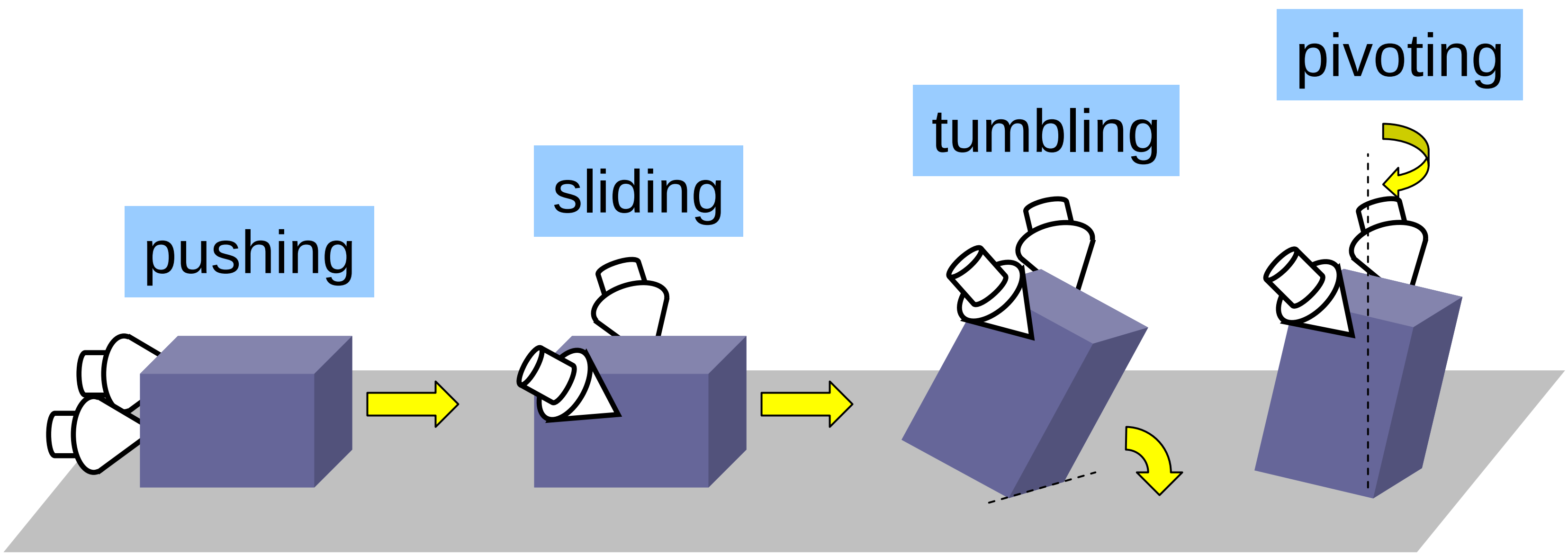
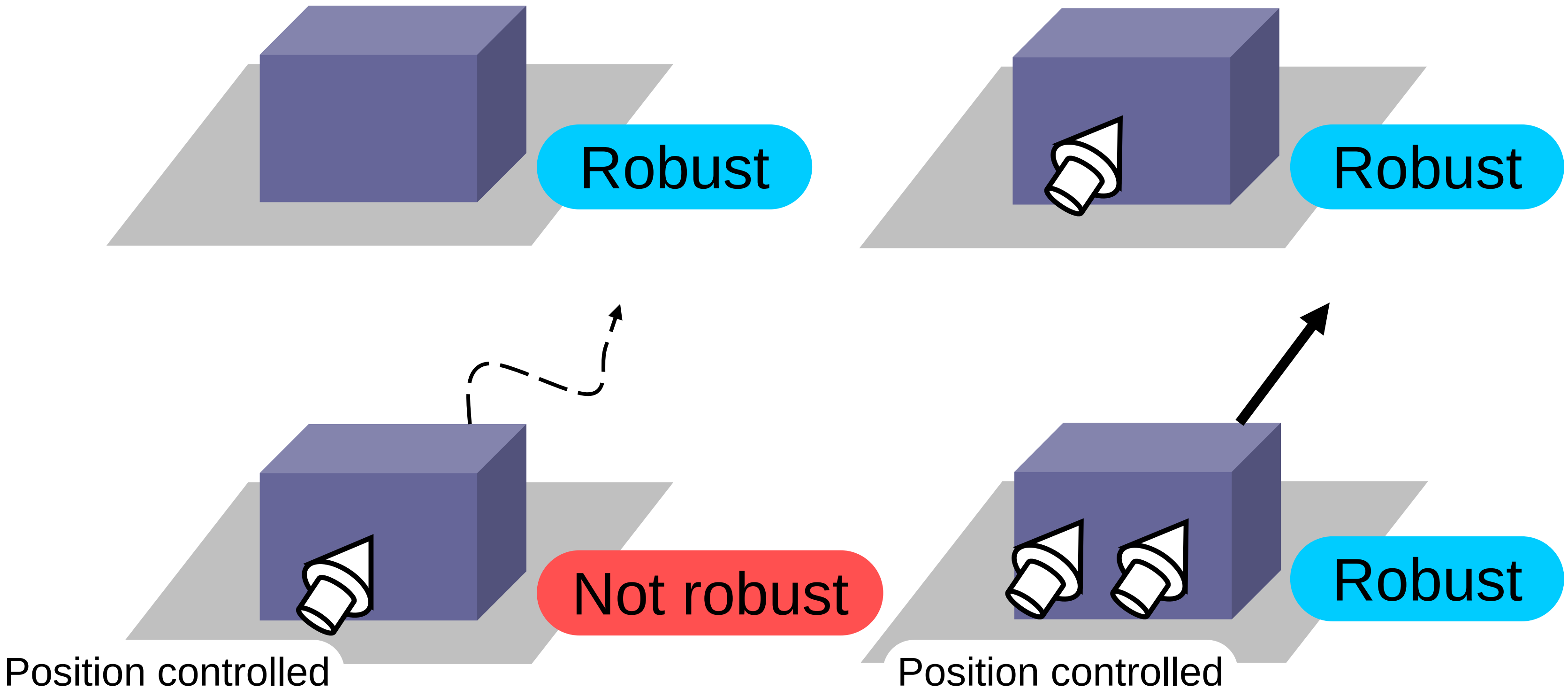
1. Introduction

Graspless manipulation

- Non-grasping
- Objects are in contact with the environment



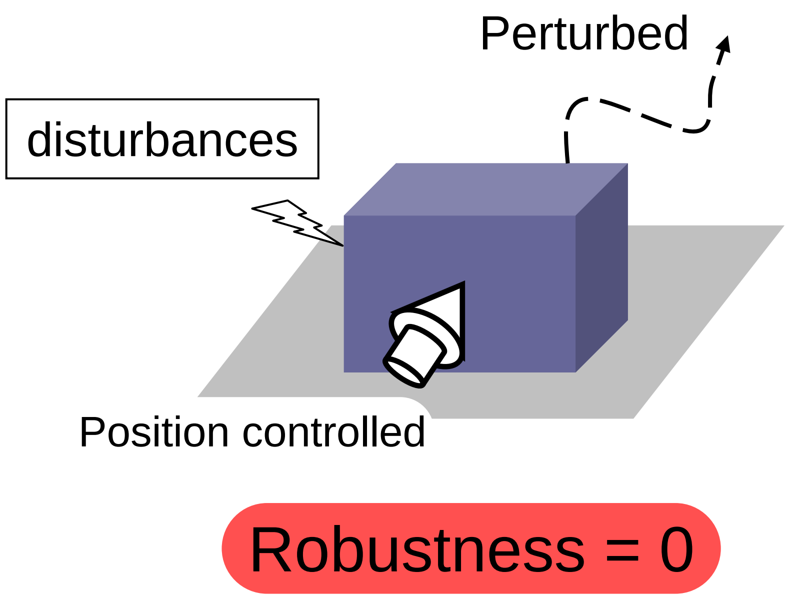
Robustness against External Disturbances

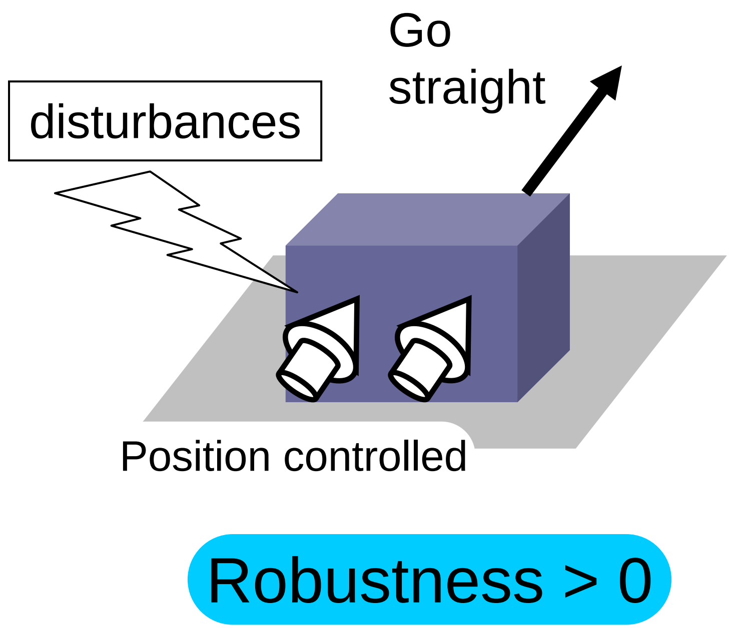


For graspless manipulation,
we need to evaluate the robustness

Definition of "Robustness measure of manipulation"

How much the manipulated object can resist external disturbances without changing its motion
[Maeda 02 ICRA]

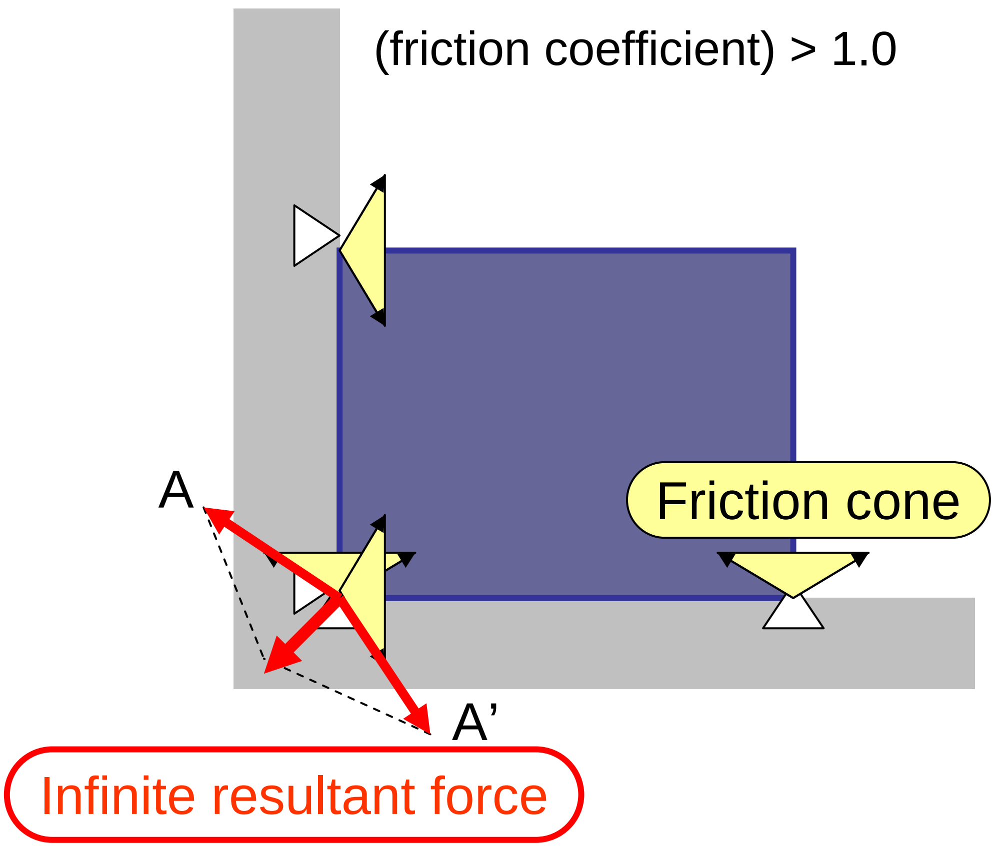




Overestimated robustness measures in some cases

[Maeda 02 ICRA]

<Case: A cuboid on a corner>



(2D schematic view)

assumption

Arbitrary contact forces are feasible in each friction cone

⇩

Infinite robustness value

We cannot move the object on a corner !!

Objective

A new quantitative test for the robustness of graspless manipulation

- More accurate than our previous method [Meada 02]

Our approach

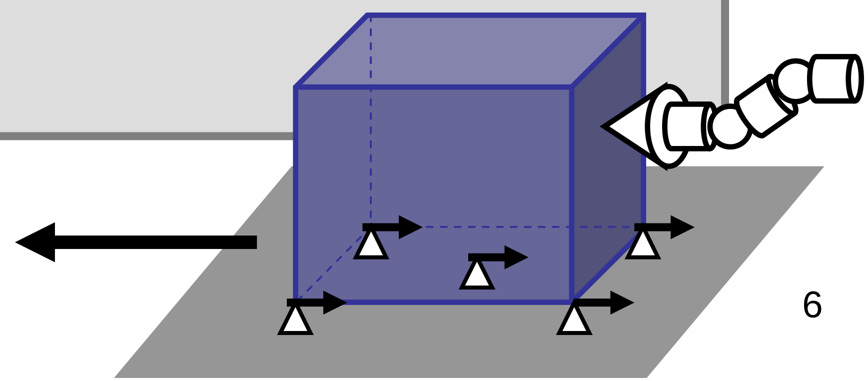
We consider the constraints on static friction originally derived by [Omata 00, 01] for power grasps

2. Mechanical Model

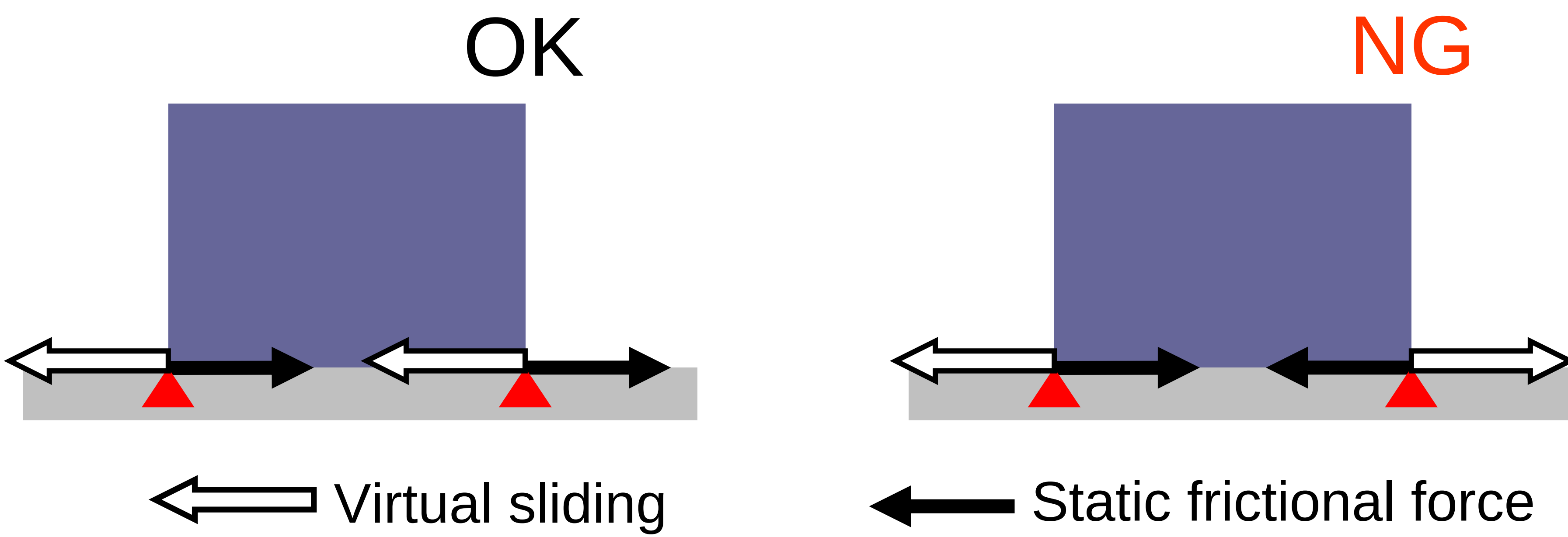
Assumptions

- Rigid bodies
- Stationary or in quasi-static manipulation
- Coulomb friction
- Approximation of all the contact by finite-point contacts
- Approximation of friction cone by polyhedral convex cone
- Position- or force-controlled robots
- Infinite servo-stiffness

  for position-controlled robots



Relationship between *virtual* sliding and static frictional force [Omata 00, 01]



Consider a combination of virtual slidings

⇨ Exclude impossible frictional forces

Constraint on static friction [Omata 01]

$$\boldsymbol{B} \begin{bmatrix} \boldsymbol{W}^T & \boldsymbol{J} \end{bmatrix} \begin{bmatrix} \boldsymbol{V} \\ -\dot{\boldsymbol{\theta}} \end{bmatrix} = \boldsymbol{T}\dot{\boldsymbol{Y}}$$

Selection matrix

Wrench matrix

Jacobian matrix

Virtual object velocity

Virtual joint velocity

Tangent Vectors

Virtual sliding velocity

Virtual sliding velocity ($\dot{\boldsymbol{Y}}$) is constrained

⇒ Static frictional forces are also constrained.

3. Robustness measure

How much the manipulated object can resist external disturbances without changing its motion

The value of the robustness, z

$$
z = \min_{Q_{\text{dist}}} \max_{\boldsymbol{k}} \| \boldsymbol{Q}_{\text{known}} + \boldsymbol{W}\boldsymbol{C}\boldsymbol{k} \|_{\boldsymbol{R}}
$$

$$
\text{subject to} \begin{cases}
\boldsymbol{T}^T \boldsymbol{C}\boldsymbol{k} \in \mathcal{F} \\
\boldsymbol{A}(\boldsymbol{N}^T \boldsymbol{C}\boldsymbol{k} - \boldsymbol{f}_n) = \boldsymbol{0} \\
\boldsymbol{Q}_{\text{dist}} + \boldsymbol{Q}_{\text{known}} + \boldsymbol{W}\boldsymbol{C}\boldsymbol{k} = \boldsymbol{0} \\
\| \boldsymbol{Q}_{\text{dist}} \|_{\boldsymbol{R}} = 1 \\
\boldsymbol{k} \geq \boldsymbol{0}.
\end{cases}
$$

- Constraints on static friction
- Constraints on contacts with force-controlled robot fingers
- Equilibrium equation
- Normalization in 6-dimensions

We solve the minimax optimization problem

Difficulties

- Constraints on static friction is nonlinear

⇨ We divide the problem into subproblems based on the sign of the elements of virtual sliding.

- Arbitrary directions in 6-dimensional force/moment space

⇨ Approximation by considering only some typical directions

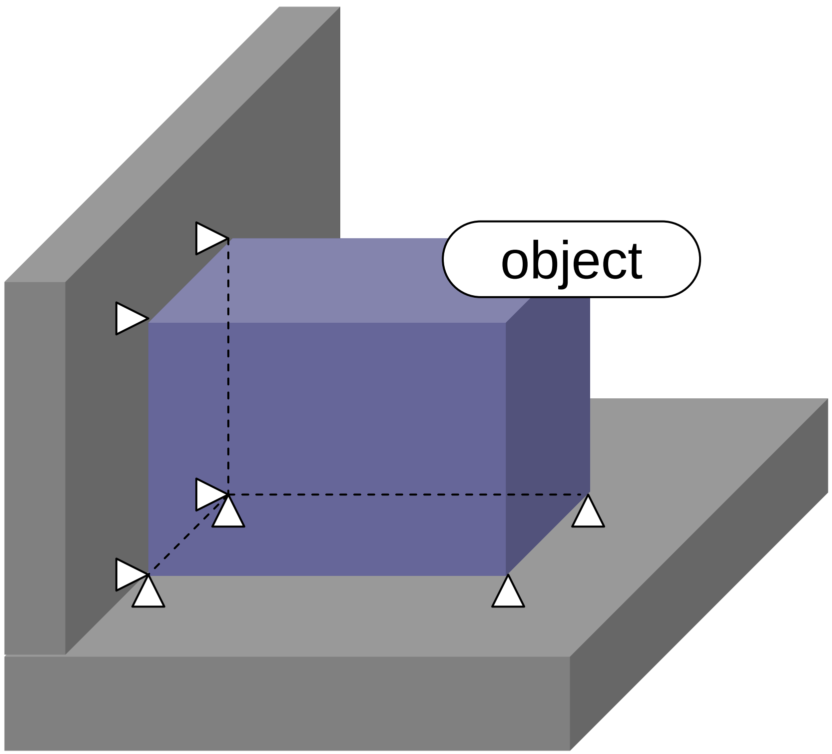
⇩

We solve a series of the linear programming problems to obtain the approximate value of the robustness.

4. Numerical examples

(on Celeron 2.4GHz PC)

<Example: An object on a corner>

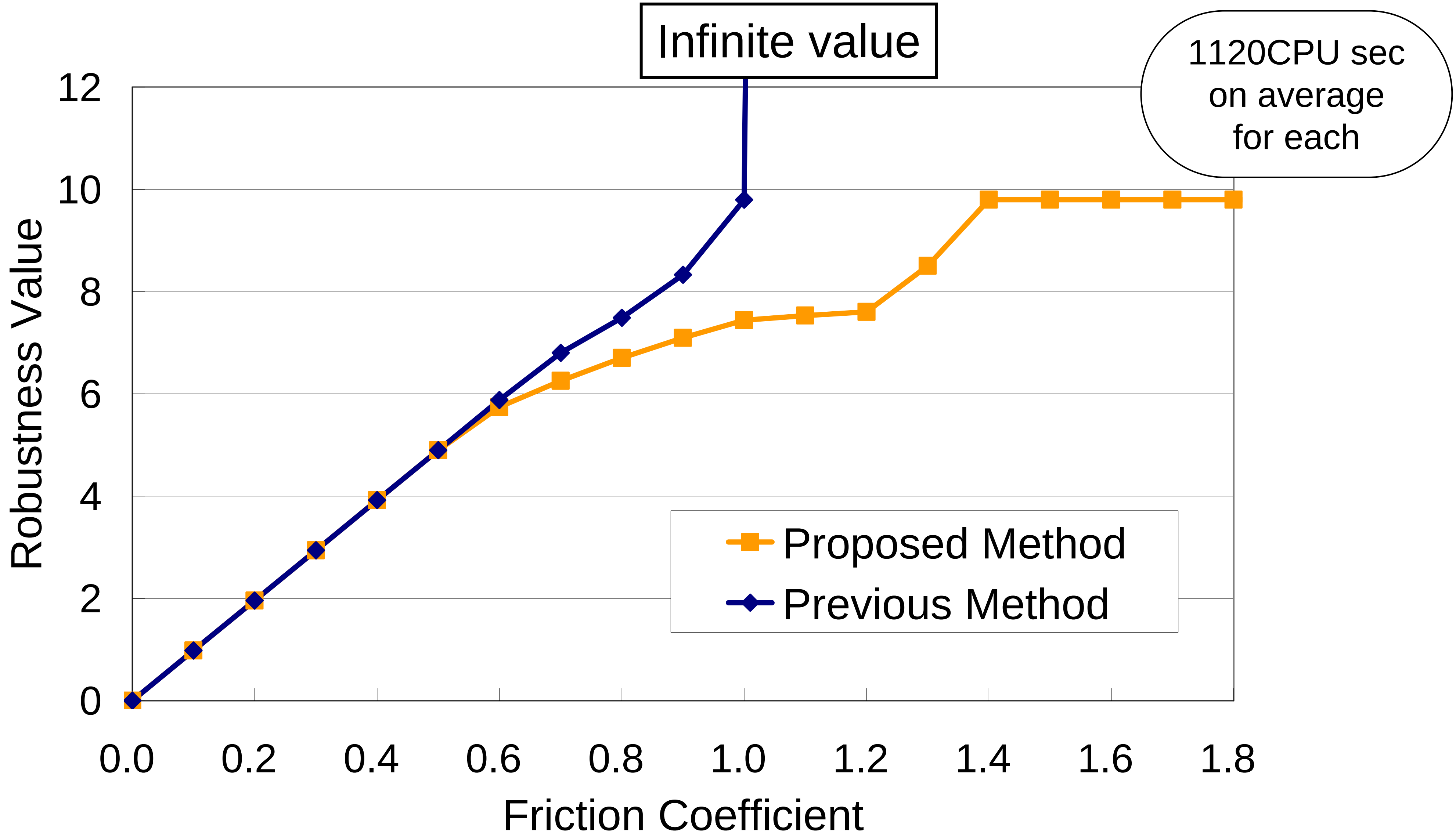


- Object
  - Size : 2×2×2
  - Mass : 1
- Gravitational acceleration : 9.8

Previous method [Maeda 02]

⇒ Unreasonable result

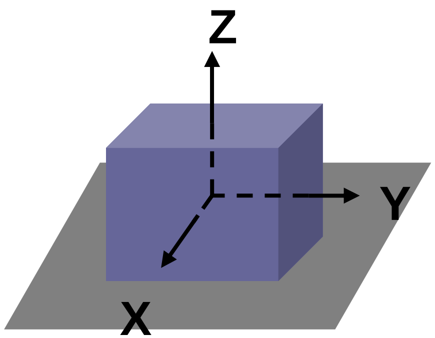
because of not excluding some impossible contact forces



Our proposed method can evaluate the robustness more accurately than previous method.

<Example: Pushing a cuboid>

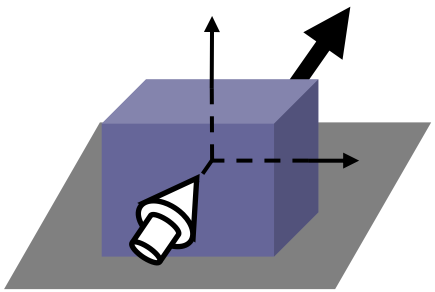
Friction coefficient : 0.3
Object size : 2×2×1



[Stationary with no robot fingers]

(Robustness value) = 2.94 — 68CPU sec

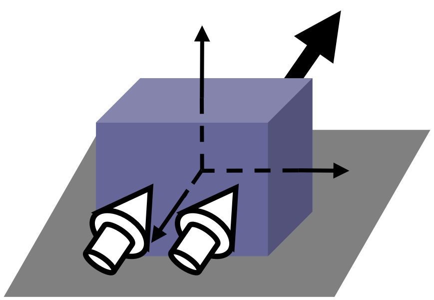
Equal to the maximum static frictional forces
(1×9.8×0.3 = 2.94)



[One-point pushing
with position-controlled robot finger]

(Robustness value) = 0 — 36CPU sec

Infinitesimal external disturbances can perturb the motion



[Two-point pushing
with position-controlled robot fingers]

(Robustness value) = 0.88 — 113CPU sec

These calculation results match the real-world phenomena

5. Conclusion

Summary

A new quantitative test for the robustness of quasi-static graspless manipulation for rigid bodies with Coulomb friction

- Consideration of constraints on static frictional force originally derived by Omata and Nagata [Omata 00, 01]
- More accurate evaluation than our previous work [Maeda 02]

Future work

- Reduction of the computation time
- Application to manipulation planning