Planning of Quasi-Static Graspless Manipulation

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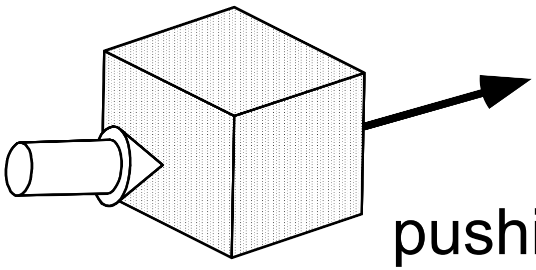
1. Introduction
2. Model of Graspless Manipulation
3. Calculation of Movable Directions
4. Planning of Planar Graspless Manipulation
5. Conclusion

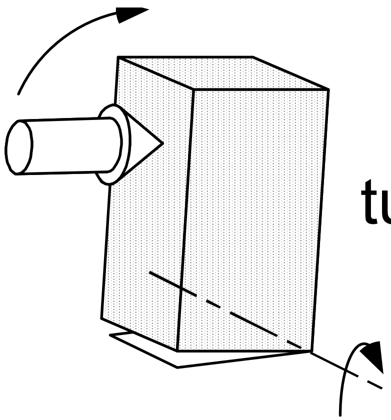
1. Introduction

Graspless Manipulation

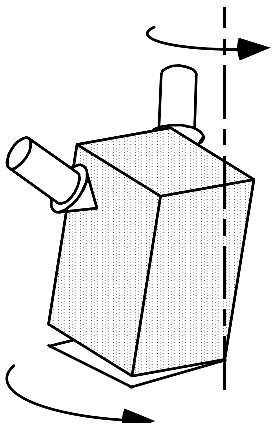


pushing

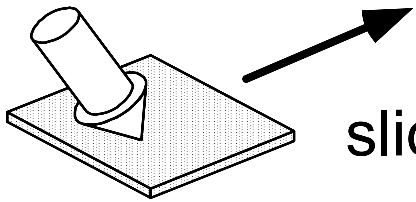
- lower load
- simpler mechanism
- complement to pick-and-place



tumbling

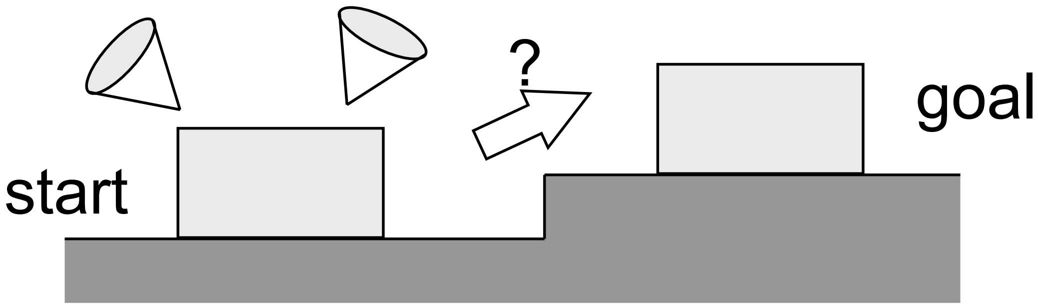


pivoting



sliding

Planning of Graspless Manipulation



How to manipulate an object
from initial configuration to goal configuration

Problem

- Planning of graspless manipulation is more difficult than that of pick-and-place because of contacts with the environment

Difficulty in Planning of Graspless Manipulation

	Required Analysis for Planning	Manipulation
Pick-and-Place	Geometrical Analysis (Collision Avoidance)	Reversible
Graspless Manipulation	Geometrical and Mechanical Analysis (Contact Force, Friction, Gravity)	Irreversible (e.g., pushable but unpullable)

Pushing: [Terasaki 93] [Kurisu 94] [Lynch 96]

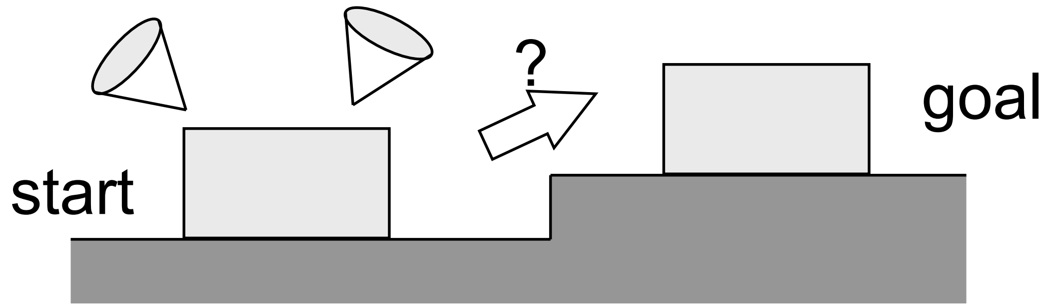
Manipulation by only Type-A Contacts: [Erdmann 98]

Manipulation with only Sliding Contacts: [Trinkle 93]

Objective

Planning of General Graspless Manipulation

Planning method that can deal with various operations



cf. [MAEDA et al. @ICRA2001]

- Planning of General Graspless Manipulation
- Contact-State Graph Required

Approach

Challenging Point

How to reduce computation time for mechanical analysis

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Approximate Calculation Algorithm of Movable Directions of a Manipulated Object

Replace many-time calculations
for movable directions of the object
with one-time approximate calculation

Outline of Presentation

Model of Graspless Manipulation

⇩

Calculation of Movable Directions

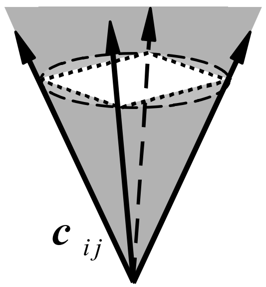
⇩

Planning of Graspless Manipulation

2. Model of Graspless Manipulation

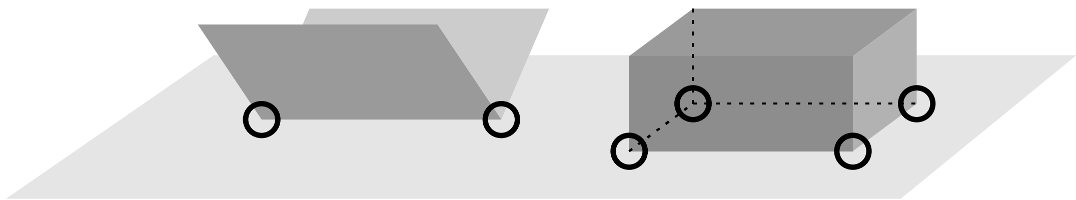
Assumptions

- Manipulation is quasi-static
- Under gravity
- Coulomb friction
(static and kinetic friction coefficients are equal)



◆approximation of friction cones
with polyhedral convex cones

◆replace line contacts and surface contacts
with their equivalent point contacts



Representation of Contact Forces

- Wrench through Contacts with Environment

$$\boldsymbol{W}_{\text{env}}\boldsymbol{k}_{\text{env}} \quad (\boldsymbol{k}_{\text{env}} \geq \boldsymbol{0})$$

…Polyhedral Convex Cone
(Composite Friction Cone)

$\boldsymbol{W}_{\text{env}}$: Matrix that converts contact forces to wrench with regard to C.O.M.

$\boldsymbol{k}_{\text{env}} = [\boldsymbol{k}_1^T \ \cdots \ \boldsymbol{k}_n^T]^T$: coefficient vector for contact forces

- Wrench through Contacts with Robots

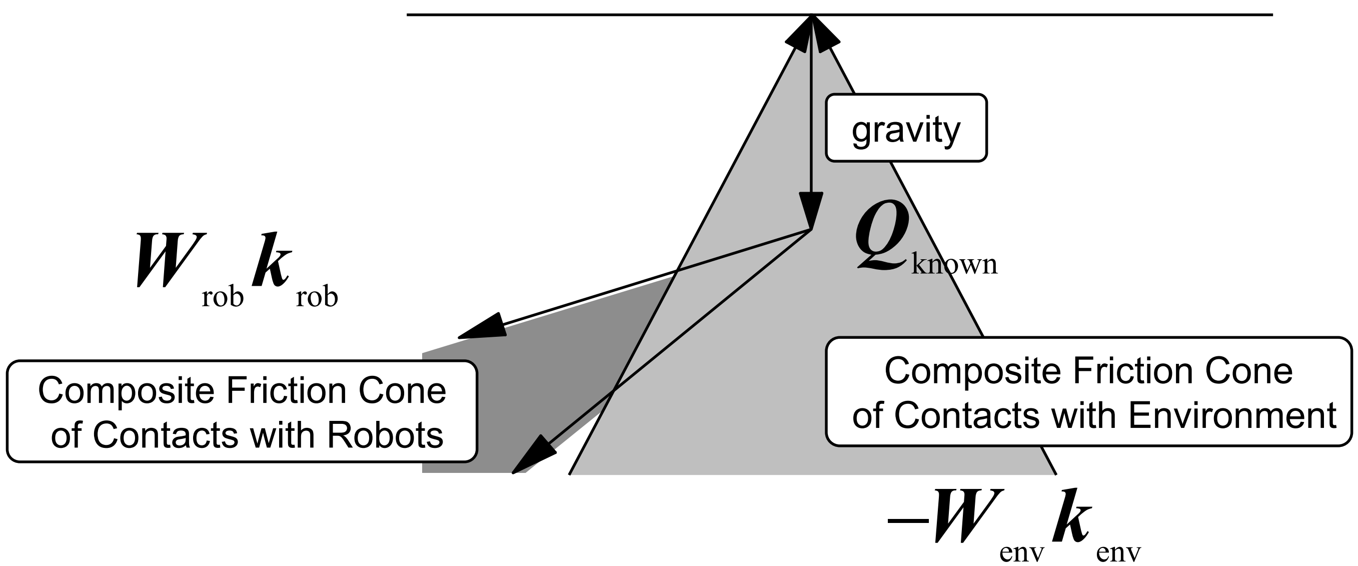
$$\boldsymbol{W}_{\text{rob}}\boldsymbol{k}_{\text{rob}} \quad (\boldsymbol{k}_{\text{rob}} \geq \boldsymbol{0})$$

…Polyhedral Convex Cone

Equilibrium Equation of Object

$$\boldsymbol{Q}_{\text{known}} + \boldsymbol{W}_{\text{rob}} \boldsymbol{k}_{\text{rob}} = -\boldsymbol{W}_{\text{env}} \boldsymbol{k}_{\text{env}}$$

$\boldsymbol{Q}_{\text{known}}$: Known (constant) external force (Gravity)



3. Calculation of Movable Directions

Movable Directions of Object

- Geometrically Movable Directions
  - Directions of object motion without geometrical interference with the environment
  - Represented by polyhedral convex cones
- Mechanically Movable Directions
  - Mechanically manipulable directions by robots

Required for Manipulation Planning

Required Calculation of Movable Directions for Planning

<u>Existing Researches</u>

• Calculation of a Mechanically Movable Direction for *an* External Force

• Time-Consuming for Planning

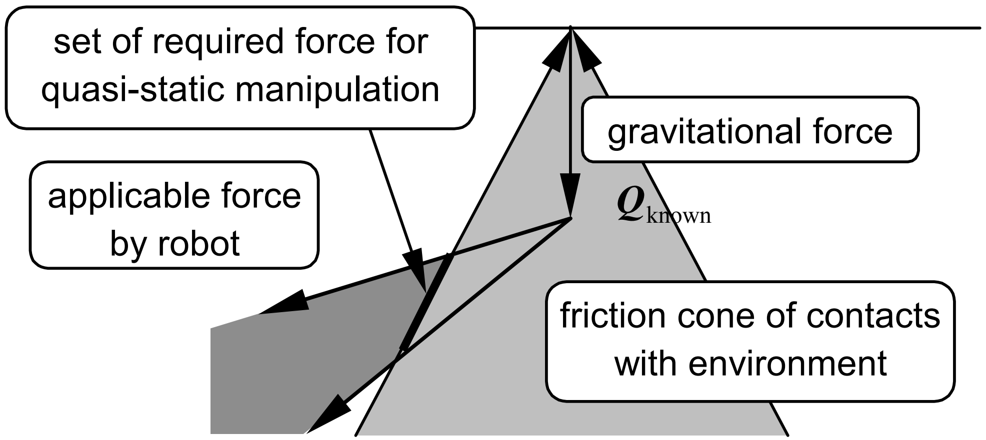
⇩

Approximate Calculation of a *Set* of Mechanically Movable Directions for a *Set* of External Forces

Calculation of a Set of External Forces for Quasi-Static Manipulation

Forces that can quasi-statically manipulate an object
= Forces that break the equilibrium of the object infinitesimally

Intersection of Friction Cone of Contacts with Robots and Surface of Friction Cone of Contacts with Environment



Approximate Calculation Algorithm of Movable Directions

I. Calculate a set of external forces that can quasi-statically manipulate the object (intersection of friction cones)

II. Calculate a set of virtual acceleration of the object in free space by the set of external forces

III. Project the set of acceleration onto the surface of the polyhedral convex cone for geometrically movable directions

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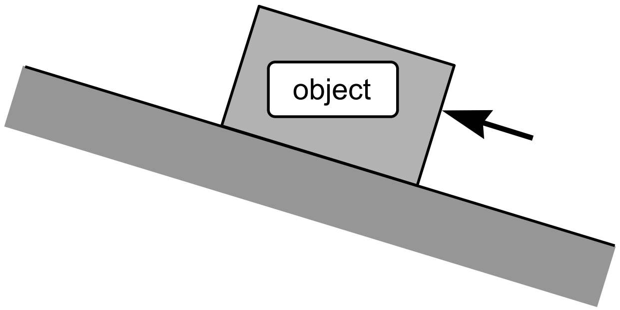
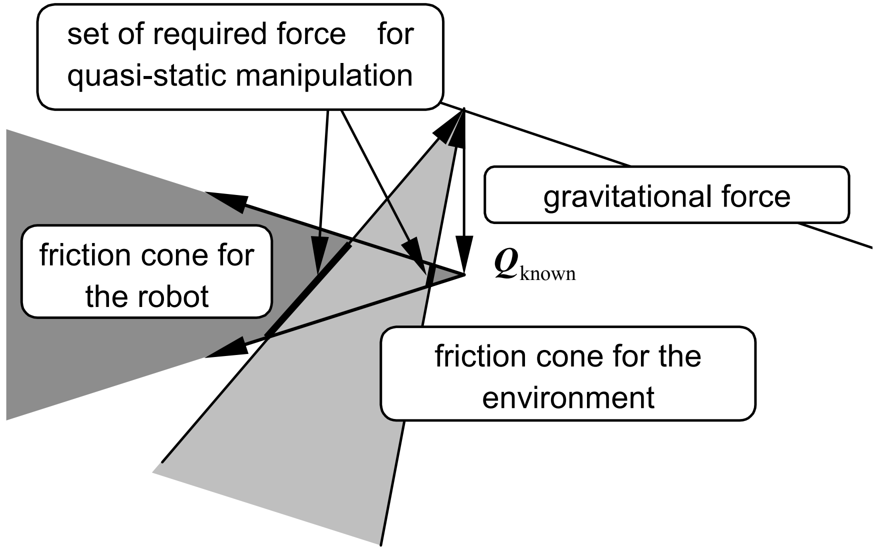
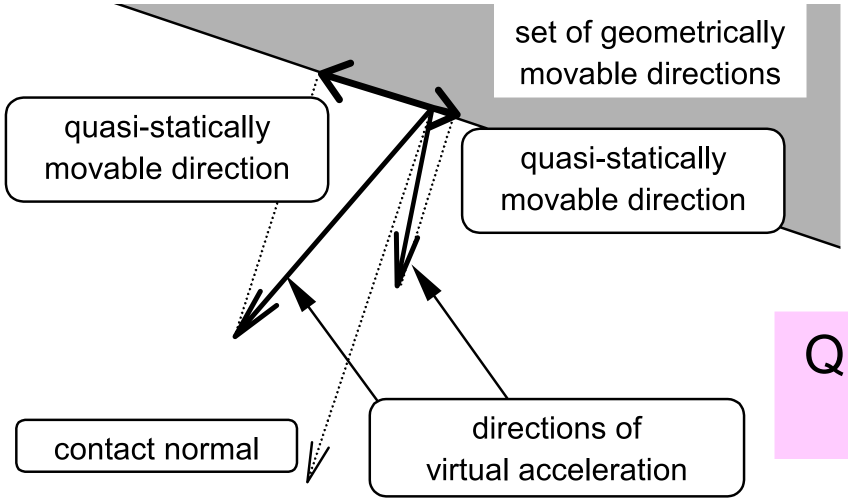
The projection corresponds to a set of movable directions

Example: Pushing on a Slope

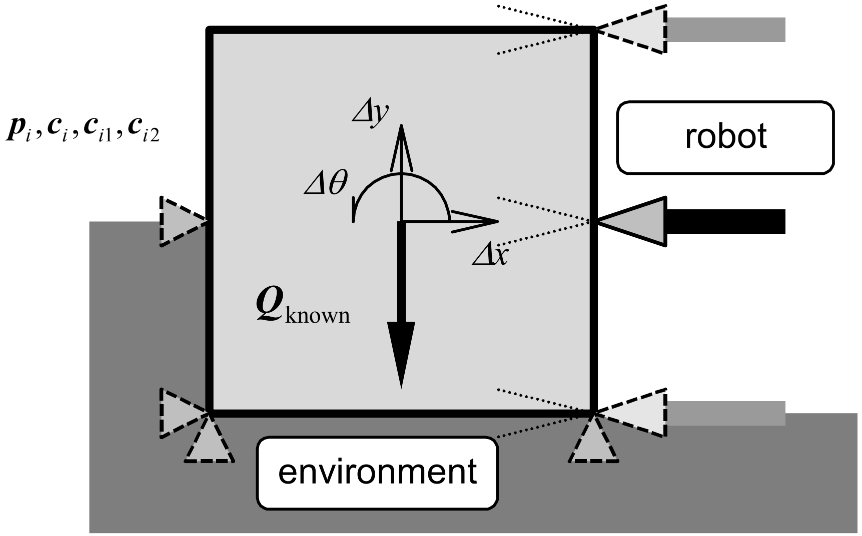






Quasi-Statically Movable Directions:
both Uphill & Downhill

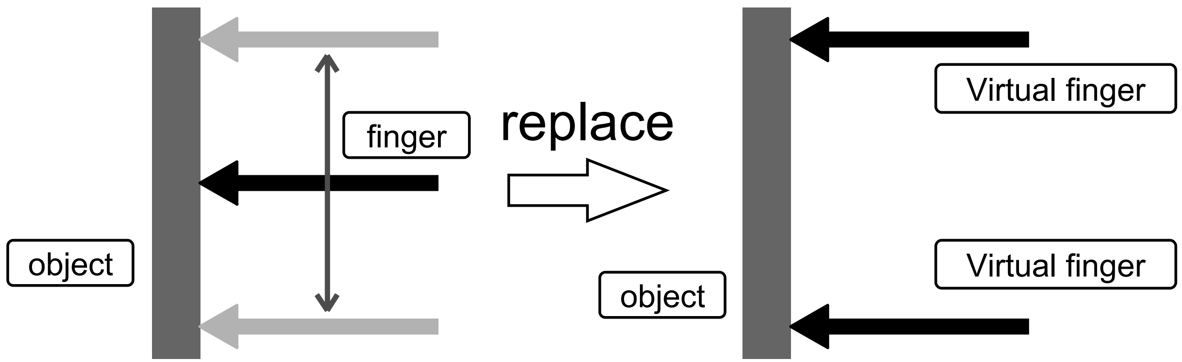
Numerical Example



Square-Shaped Object in Contact with Environment

- length of each side of object = 2
- friction coefficient between object and environment = 0.3
- friction coefficient between object and robot = 0.2
- weight of object = 9.8

Set of External Forces that Can Be Applied to the Object

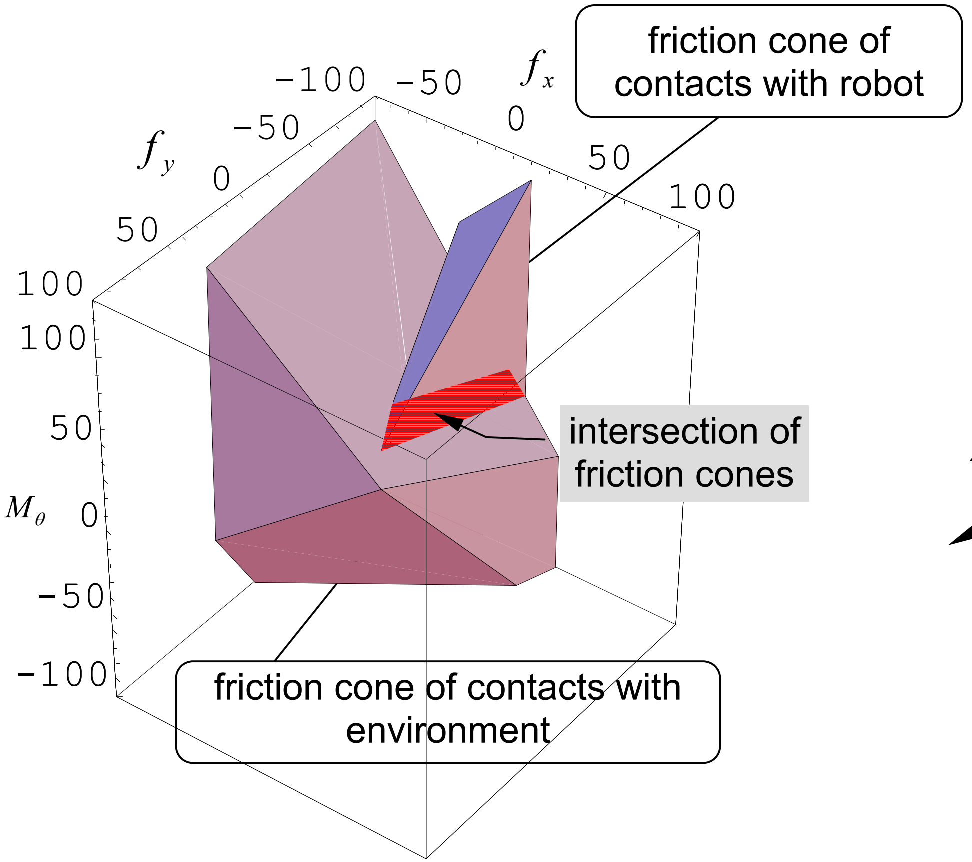


[Omata 1991]

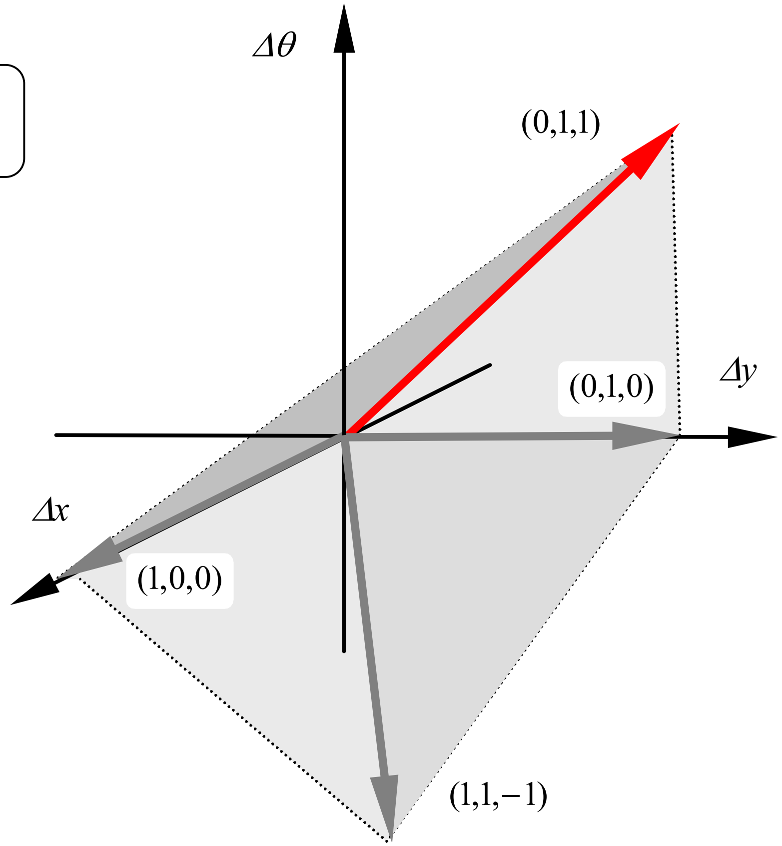
The effect of change of a robot finger
can be represented by two virtual fixed fingers

Calculation Result

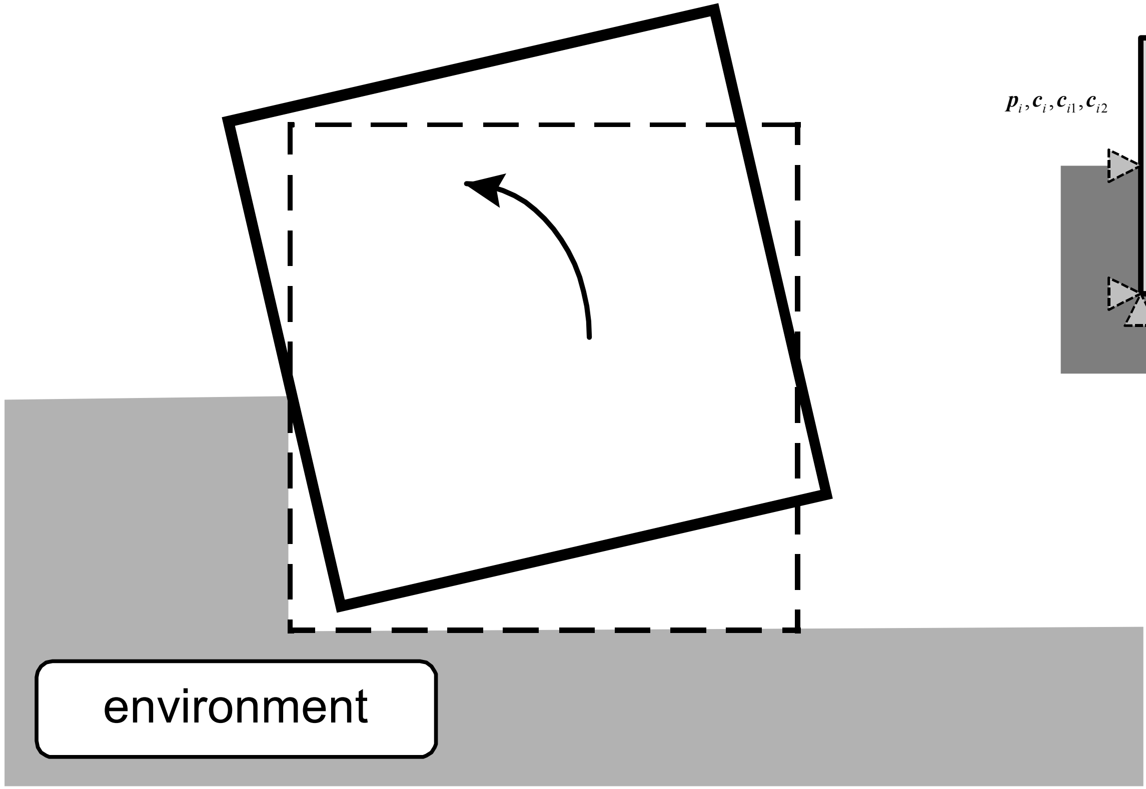
Intersection of Friction Cones

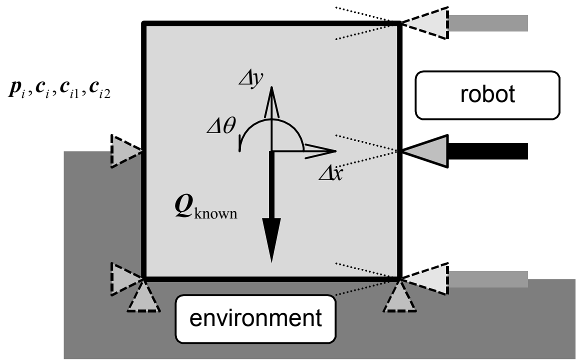


Geometrically Movable Directions



Quasi-Statically Movable Direction



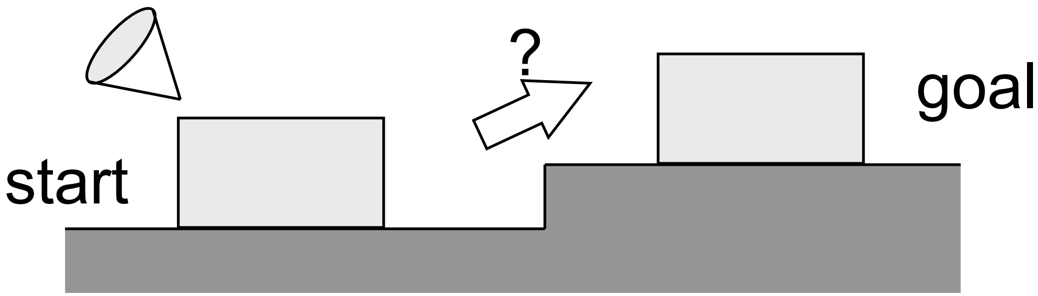


$$(\Delta x, \Delta y, \Delta q) = (0, 1, 1)$$

(rolling motion over the step)

4. Planning of Graspless Manipulation

Planning of Planar Graspless Manipulation Using Calculation Method of Movable Directions



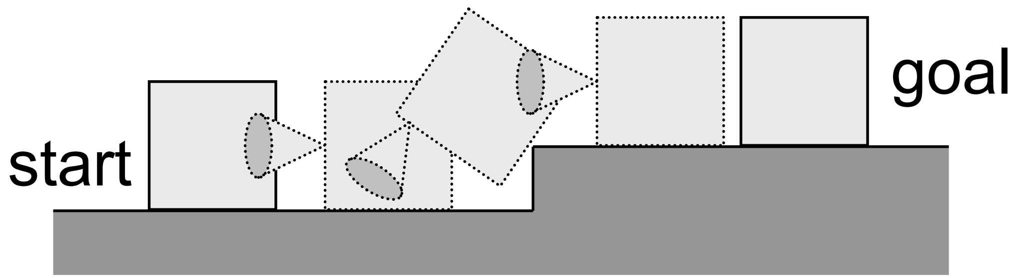
Assumptions:

- One-finger Robot, Point Contact
- Finger can apply any force within friction cone

Specification of Planning

Input:

Initial and Goal Configurations of the Object



Output:

Path of Object, Path of Robot Fingertip,
Time Series of Fingertip Force

Procedure of Planning

- Generation of Graph

I. Discretize C-Space to Generate Nodes

II. Calculate Feasible Area of Robot Fingertip

III. Calculate Quasi-Statically Movable Directions and Connect Nodes by Arcs

IV. Assign Manipulation Cost to Each Arc

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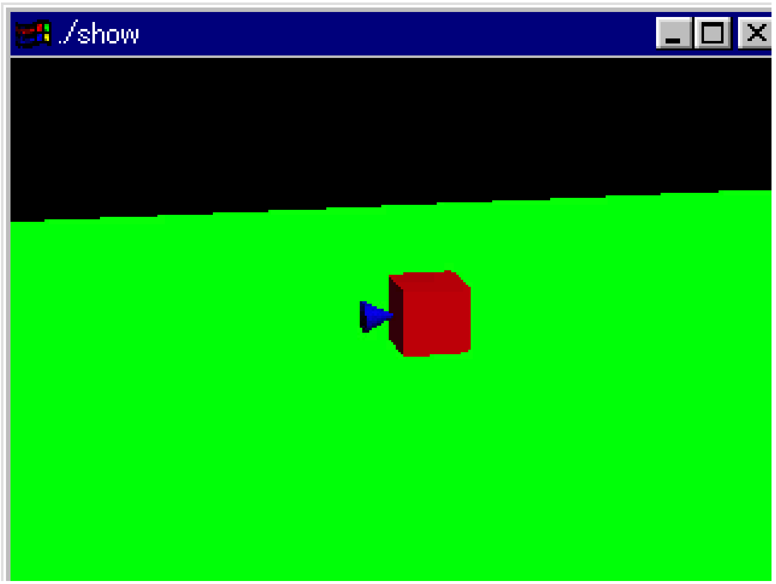
- Graph Searching

Search Minimum-Cost Path from Initial to Goal Configurations
(Dijkstra's Algorithm)

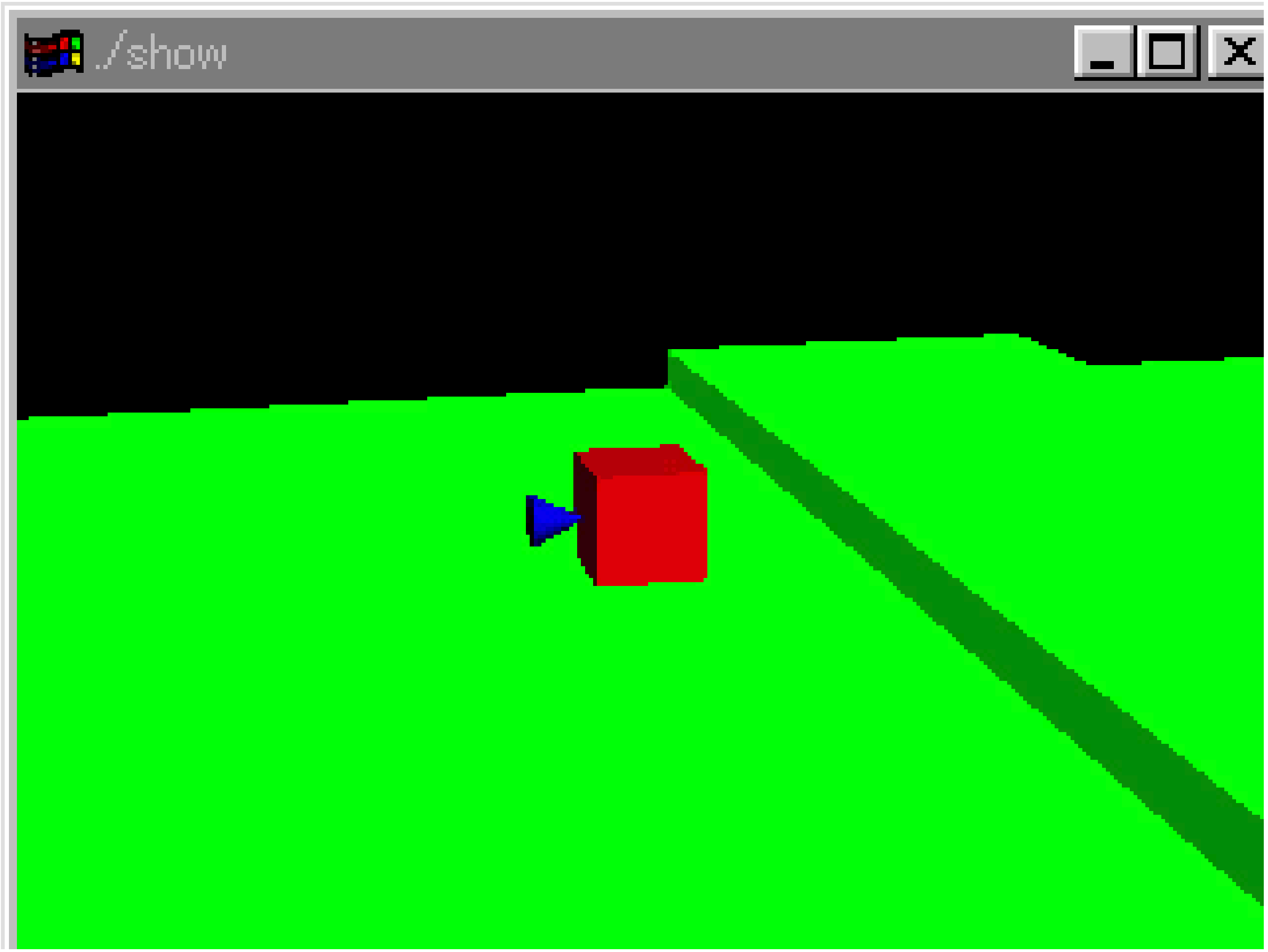
Planned Results: Pushing and Pulling



Pushing on a Plane

“Pulling” on a Slope

Planned Result: Pushing and Tumbling



Pushing and Tumbling

Study on Planned Manipulation

- Basic graspless manipulations (Pushing, Pulling, Tumbling) are generated
- Jump of Finger Position

  ⇨ Two-Finger Manipulation with Regrasping
- Computation Time (C-Space of 36,000 Nodes)

  about 4.5 CPU minutes (UltraSPARC-IIi 334MHz)

5. Conclusion

Conclusion

We proposed

Approximate Calculation Method
of Quasi-Statically Movable Directions of Object

based on mechanical analysis

Using this method,we showed

Planning of Planar Graspless Manipulation

Future Work

Validation of Approximate Calculation Method
for Movable Directions