Planning of Graspless Manipulation by Multiple Robot Fingers

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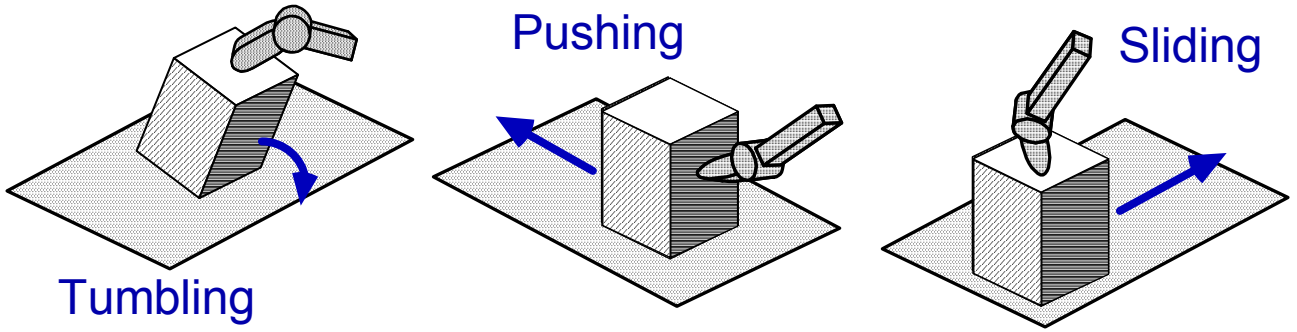
1. Introduction

Graspless Manipulation

to Manipulate Objects without Grasping



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

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

⇨ Planning of Graspless Manipulation is Difficult!

Objective

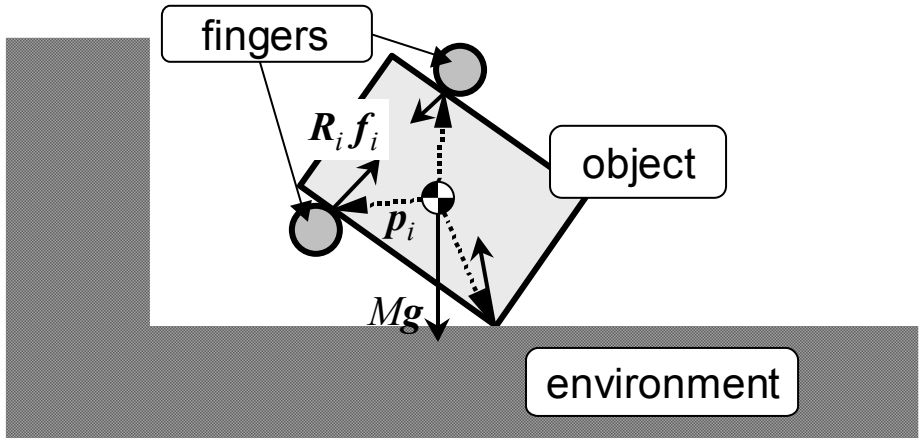
Planning of General Graspless Manipulation

- not only for a specific operation (e.g., pushing)
- in practical computation time

2. Problem Settlement

Assumptions

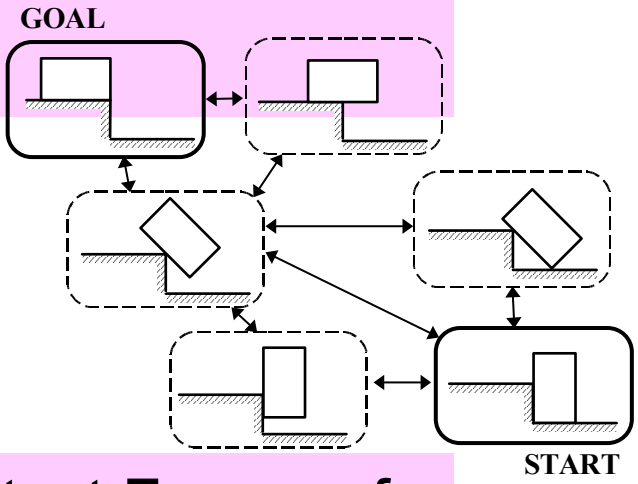
- Quasi-Static Planar Manipulation of a Polygonal Object
- Gravity and Coulomb Friction
- Circle-Shaped Robot Fingers
- No Slipping and Rolling of Fingers
- Contact-State Graph is Given



Planning Problem

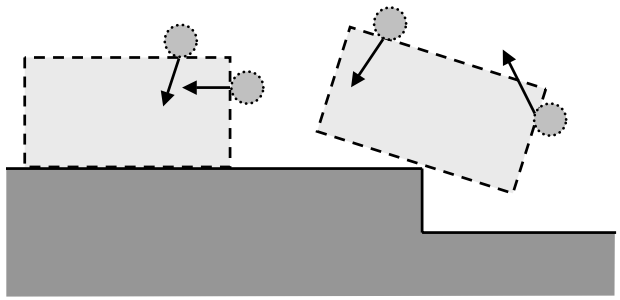
Input:

- Initial and Goal Configurations of the Object
- Contact-State Graph



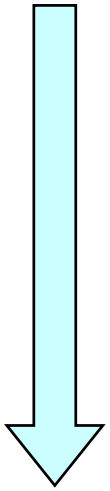
Output:

- Sequence of Positions and Contact Forces of Robot Fingers



Outline of Planning

Construction of Manipulation-Feasibility Graph



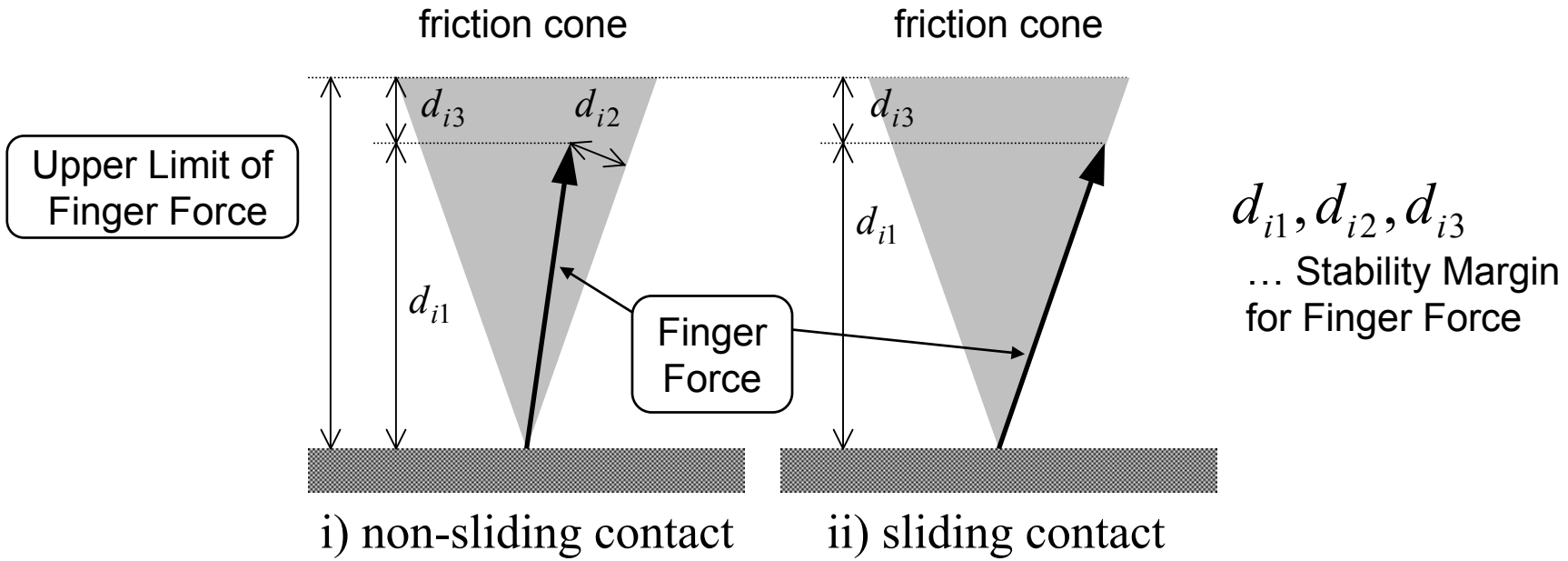
- Generation of Nodes
  - Select configurations with enough manipulation stability
- Generation of Arcs
  - arcs for object displacement, regrasping, and contact-state transition

Searching of Manipulation-Feasibility Graph

- cost assignment

3. Manipulation Stability Measure

Manipulation Stability



d_{i1}, d_{i2}, d_{i3}
… Stability Margin for Finger Force

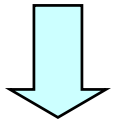
Manipulation Stability Measure: $d = \min d_{ij}$

(minimum margin in all the friction cones)

Determination of Optimal Finger Forces

Optimal Finger Forces:

Maximize the Manipulation Stability Measure d



Linear Programming Problem

$$\text{maximize } d = \boldsymbol{\lambda}^T \boldsymbol{d}$$

$$\text{subject to} \begin{cases} \boldsymbol{WRf} = \boldsymbol{Mg} & \ldots\text{Equilibrium Equation} \\ \boldsymbol{Af} - \boldsymbol{c} \geq \boldsymbol{d} & \ldots\text{Stability Margin for Each Contact} \\ \boldsymbol{Bf} = \boldsymbol{0} & \ldots\text{Constraints for Sliding Contacts} \\ \boldsymbol{d} \geq \boldsymbol{0} \end{cases}$$

$$\boldsymbol{\lambda} = [1, 0, \ldots, 0]^T$$

$$\boldsymbol{d} = [d, \ldots, d]^T$$

4. Manipulation-Feasibility Graph

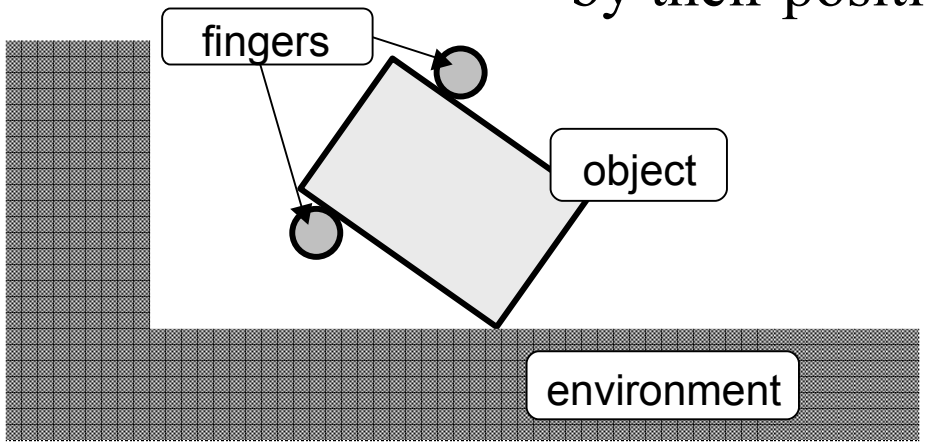
C-Space in a Contact State

D.O.F. of C-Space: $M + N$

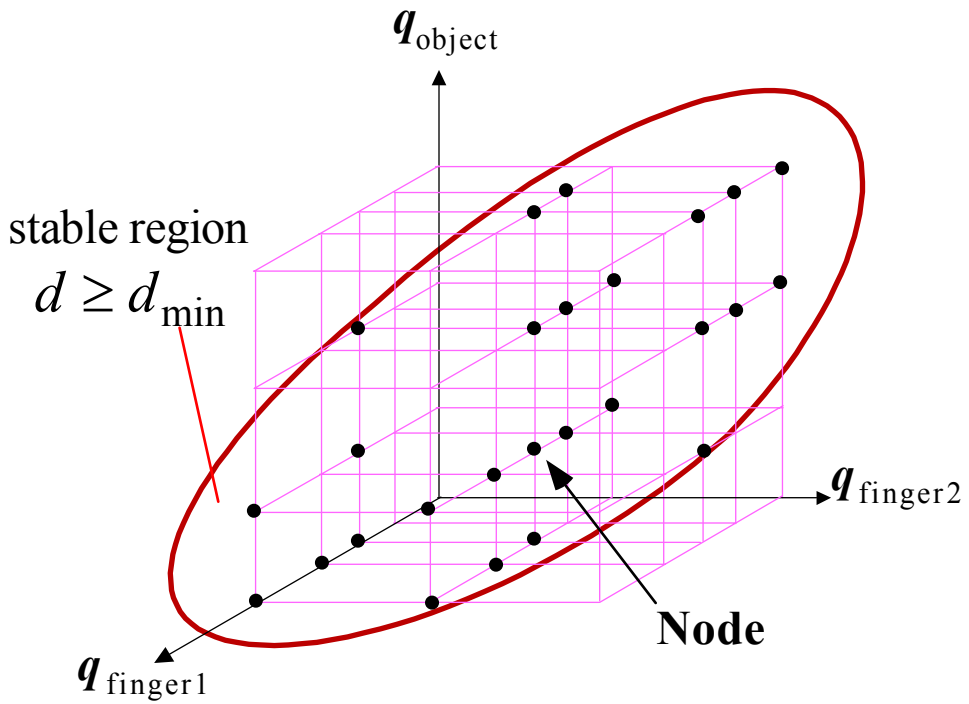
M…D.O.F. of Manipulated Object in the Contact State $(M \leq 2)$

N…Number of Robot Fingers

Configurations of robot fingers are represented by their positions on the object surface



Generation of Nodes



- Discretize C-Space
- Adopt nodes with enough stability measure

Generation of Arcs

Arcs in Manipulation-Feasibility Graph:

- Arcs for Object Displacement

  Moving object without changing finger positions

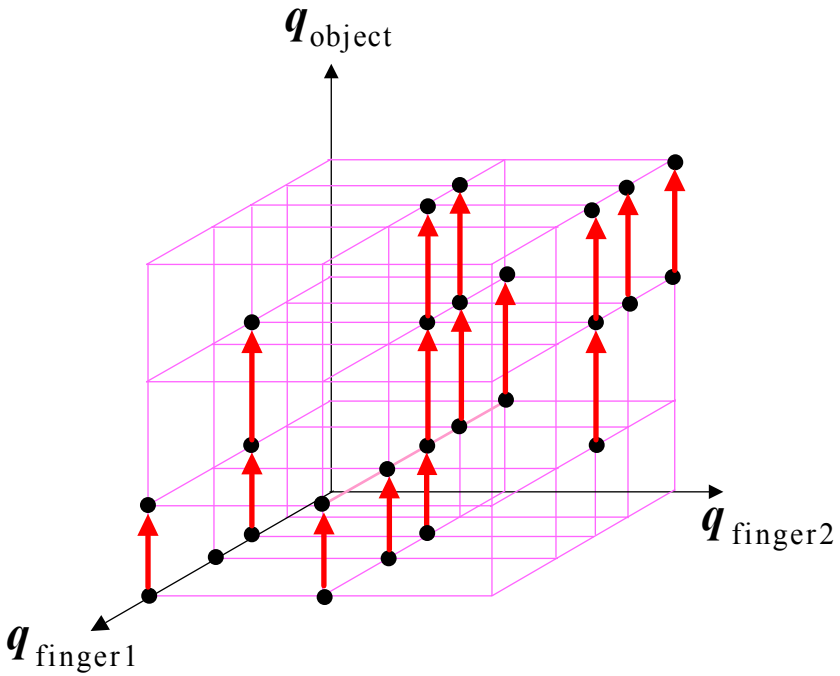
- Arcs for Regrasping

  Changing a finger position without object displacement

- Arcs for Contact-State Transition

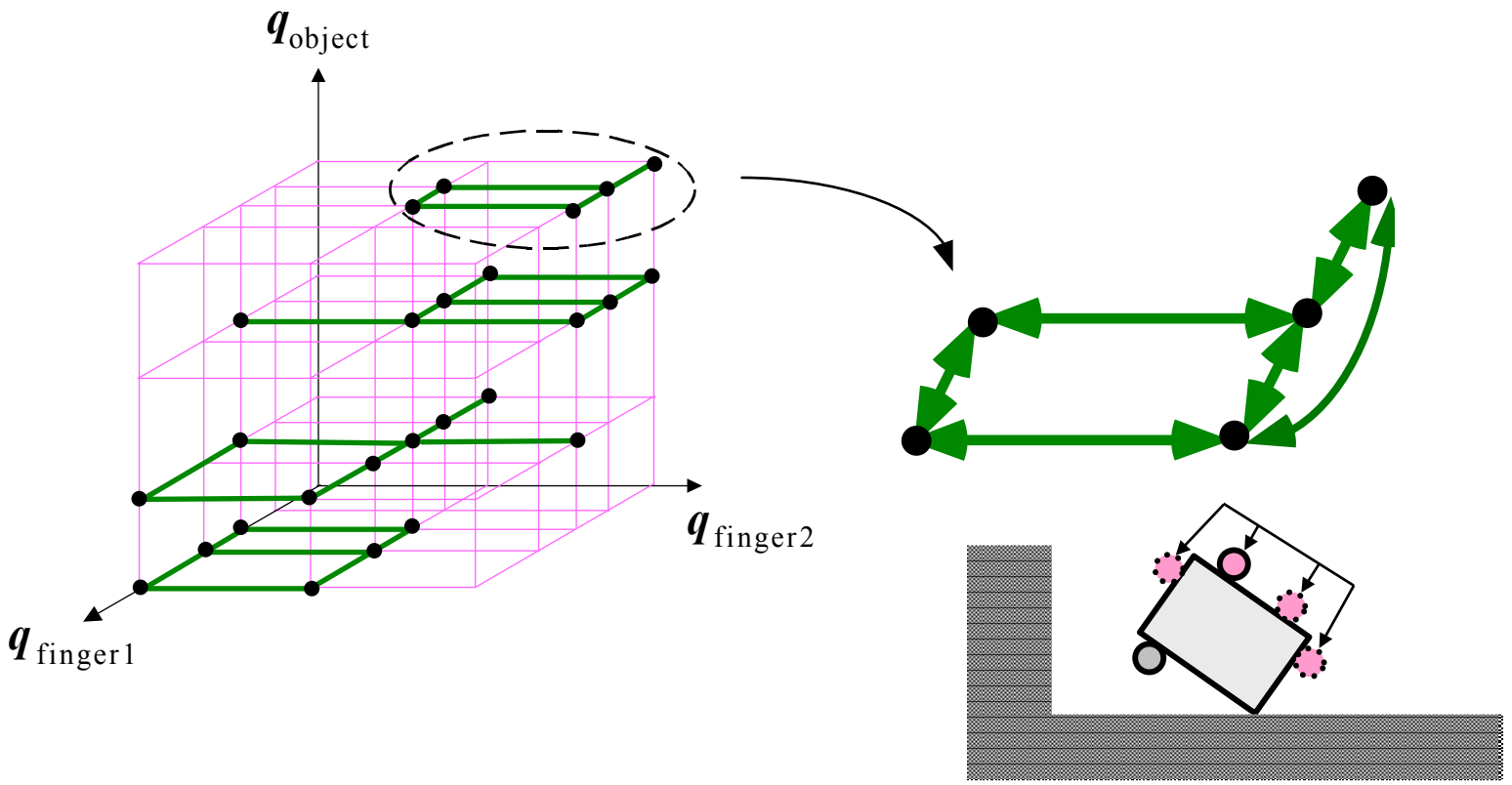
  For instants of contact-state transition

Arcs for Object Displacement



• Connect neighboring nodes with directed arcs if each manipulation is enough stable

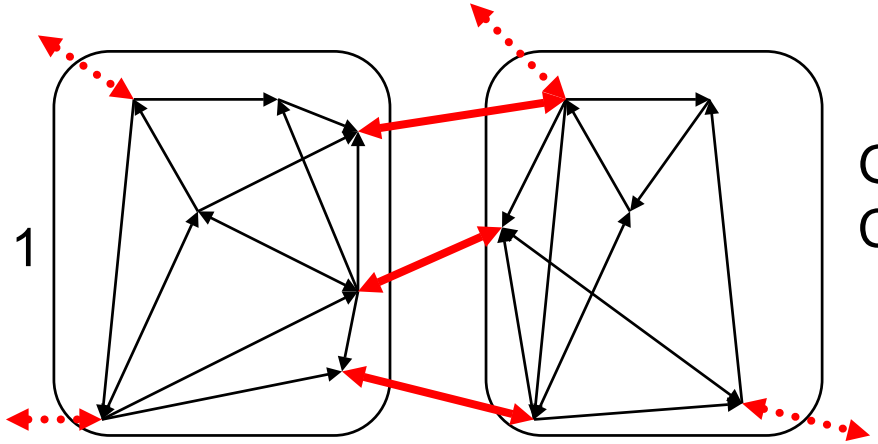
Arcs for Regrasping



• Connect nodes with bidirectional arcs if the object is stable without the regrasping finger

Arcs for Contact-State Transition

Graph for
Contact State 1



Graph for
Contact State 2

Connect Identical Configurations in Different Graphs

A Manipulation-Feasibility Graph
over Multiple Contact States

5. Planning of Graspless Manipulation

Obtain manipulation plan by graph searching

Planning Policies

- Avoid manipulation with low stability.

  ⇨ Discard arcs with low stability measure

- Primarily, minimize the number of times of regrasping.

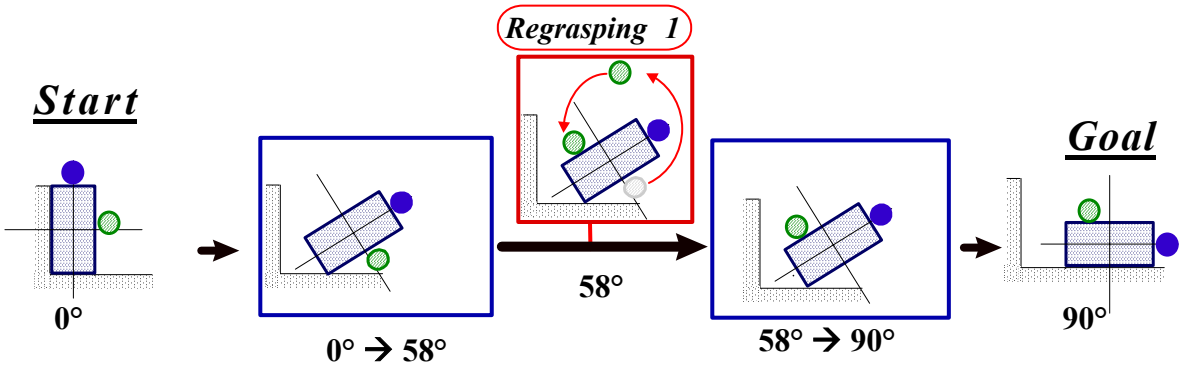
  ⇨ Assign very large cost to arcs for regrasping

- Secondarily, Minimize the load of the robot fingers.

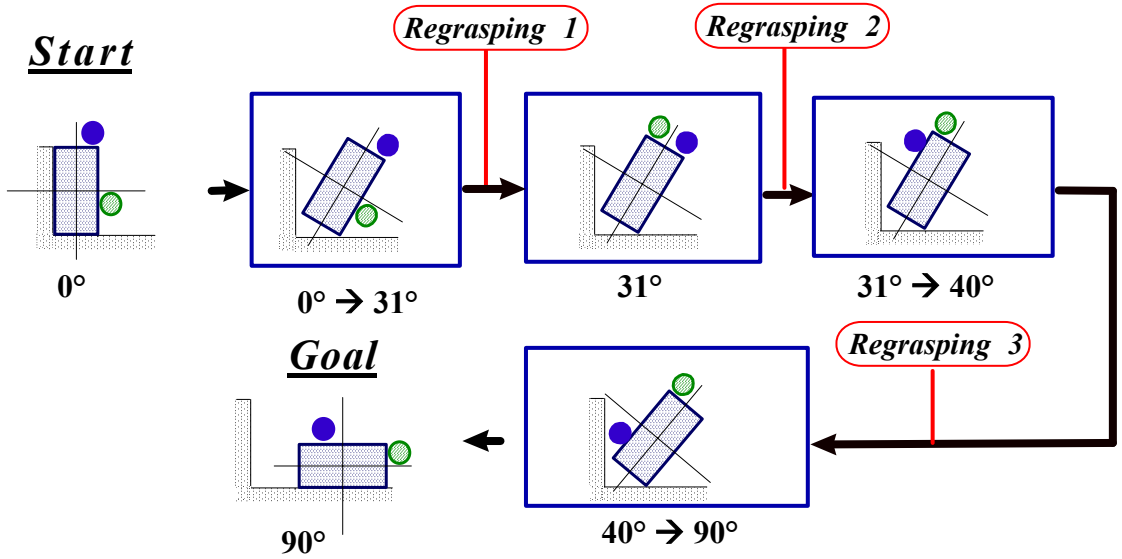
  ⇨ Assign cost c_{disp} to arcs for object displacement

$$c_{\text{disp}} = \sum \{(\text{finger force}) \times (\text{finger displacement})\}$$

Planned Result 1: Tumbling



Large Friction ($\mu = 0.5$)



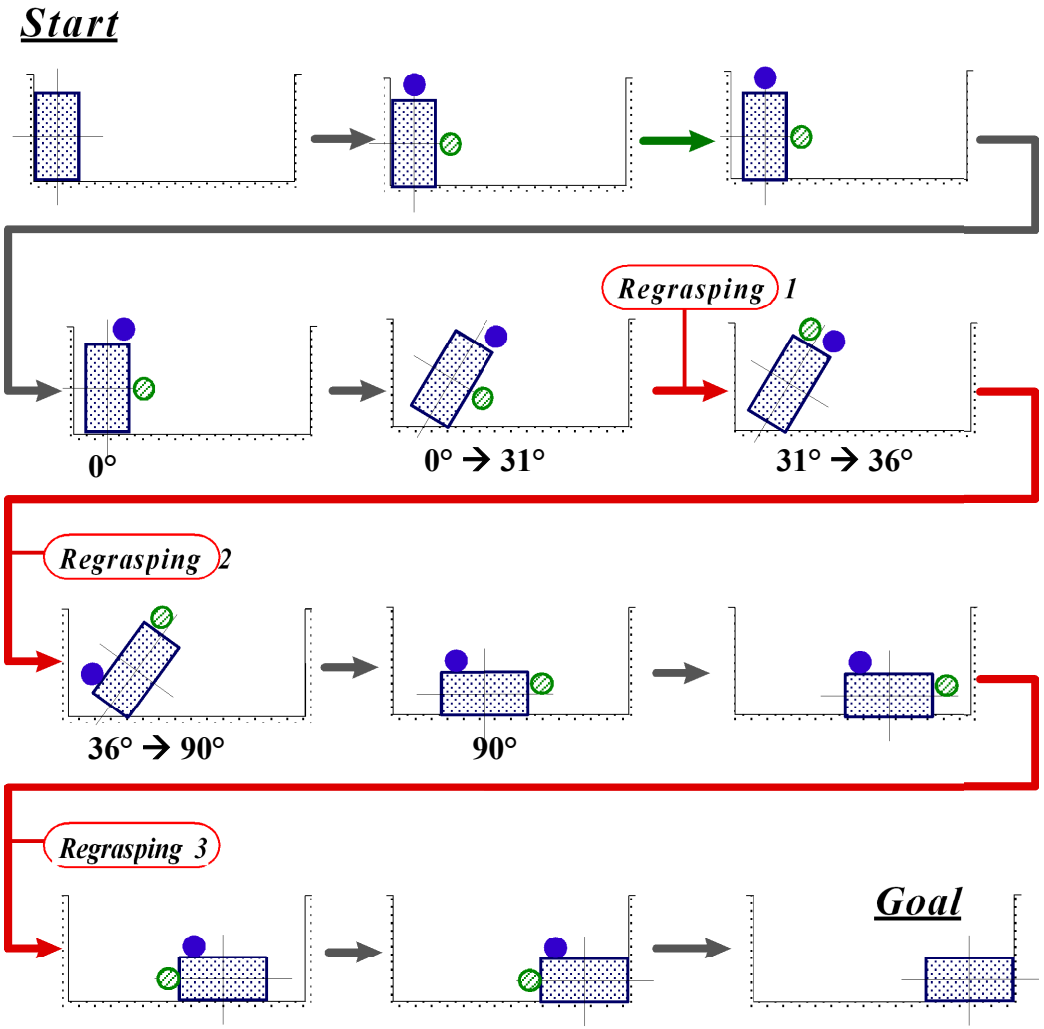
Small Friction ($\mu = 0.2$)

Planning Time:

20 CPU Seconds

(UltraSPARC-IIi 334MHz)

Planned Result 2: Composite Manipulation



Planning Time:

330 CPU Seconds

(UltraSPARC-IIi 334MHz)

6. Conclusion

Conclusion

A planning method for planar graspless manipulation based on mechanical analysis is proposed.

◆ Pushing and tumbling operations with regrasping are successfully generated.

Future Works

- Manipulation in 3D
- Incorporate Rolling of Robot Fingers on Object