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
## Planning of General Graspless Manipulation

### Objective

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

### Geometrical and Mechanical Analysis

<table>
<thead>
<tr>
<th>Manipulation Type</th>
<th>Analysis Type</th>
<th>Irreversibility</th>
</tr>
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<tr>
<td>Pick-and-Place</td>
<td>Geometrical Analysis (Collision-Avoidance)</td>
<td>Reversible</td>
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<tr>
<td>Graspless Manipulation</td>
<td>Geometrical and Mechanical Analysis (Contact Force, Friction)</td>
<td>Irreversible (e.g., pushable but unpullable)</td>
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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 Measure:

\[ d_{\text{ij}} = \min d_{ij} \]

(minimum margin in all the friction cones)

- **Upper Limit of Finger Force**
- **i) non-sliding contact**
- **ii) sliding contact**

\[ d_1, d_2, d_3 \]

... Stability Margin for Finger Force
Determination of Optimal Finger Forces

Optimal Finger Forces:
Maximize the Manipulation Stability Measure \( d \)

\[
\text{Linear Programming Problem}
\]

maximize \( d = \lambda^T d \)

subject to

\[
\begin{align*}
WRf &= Mg \quad \text{...Equilibrium Equation} \\
Af - c &\geq d \quad \text{...Stability Margin for Each Contact} \\
Bf &= 0 \quad \text{...Constraints for Sliding Contacts} \\
d &\geq 0 \\
\lambda &= [1, 0, \ldots, 0]^T \\
d &= [d, \ldots, d]^T
\end{align*}
\]
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

\( N \)...Number of Robot Fingers

(\( M \leq 2 \))

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
• 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 $c_{\text{disp}}$ 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)
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