Progress in Manipulation Planning with Synergistic Framework

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Joint work with Morteza Lahijanian, Lydia E. Kavraki, Moshe Y. Vardi
Robot Manipulation

Packing/unpacking
Preparing food
Serving at a Cafe
Task Formulation

Objects $O$

Locations of interest with labels $L$

Manipulation Task: Co-safe LTL formula over these atomic propositions

Object X is at a location with label Y

$\pi = O \times L$
Problem

Given:
1. Geometric model of manipulator, objects, and environment
2. Correspondence between labels and geometry
3. A co-safe LTL formula (task) over the atomic propositions $\pi$

Find:
Execution that satisfies the task.
Challenges

- ≥6 DoF Manipulator
- Complex Workspace
- Many Objects
- Temporal Task

HUGE continuous search space

? Abstraction

Smaller Continuous Problem
Smaller Continuous Problem
Smaller Continuous Problem

? Solving Strategy
Planning Strategy

Diagram:
- Task (LTL) flows into DFA
- DFA flows into Abstraction
- Abstraction flows into Task Planner (Graph Search)
  - Sequence of Actions
  - Graph Edge Weights
- Task Planner (Graph Search) flows into Coordinating Layer
  - Continuous Trajectory
- Coordinating Layer flows into Motion Planner (Sampling-based)
  - Plan Query for a Single Action
  - Exploration Data
- Motion Planner (Sampling-based) flows into Continuous Trajectory

Additional nodes:
- Objects
- Actions
- Workspace
Example - Baxter Cafe

First trash the empty can, then offer snacks to all guests and ask for tip from the guests already served.

$$\Diamond \left( \text{can} \in \text{trash} \land \bigwedge_{i=1}^{k} \Diamond \left( \text{snack} \in \text{guest}_i \land \Diamond \text{tip} \in \text{guest}_i \right) \right)$$

Planner picks one of many executions 😐
## Task Planning Time

<table>
<thead>
<tr>
<th># Objects</th>
<th># Locations</th>
<th># DFA States</th>
<th>Avg Total Task Planning Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>6</td>
<td>10</td>
<td>0.94</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>2</td>
<td>2.76</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>8</td>
<td>4.48</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>27</td>
<td>33.12</td>
</tr>
</tbody>
</table>

All results averaged over 50 runs
Task Planning

**States** $z$: Progress in performing the task

**Nodes** $v$: State of the world (object locations, etc.)

**Product Graph**
Nodes: $(z,v)$

Constructed while running Dijkstra's algorithm
Planning Time

<table>
<thead>
<tr>
<th># Objects</th>
<th># Locations</th>
<th># DFA States</th>
<th># Nodes Reached in Product</th>
<th>Avg Total Task Planning Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>6</td>
<td>10</td>
<td>19,370</td>
<td>0.94</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>2</td>
<td>44,100</td>
<td>2.76</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>8</td>
<td>75,511</td>
<td>4.48</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>27</td>
<td>498,000</td>
<td>33.12</td>
</tr>
</tbody>
</table>

All results averaged over 50 runs

Number of nodes grow exponentially to the depth of the search
Speeding Up Task Planning

• Use DFA state to estimate progress in product graph search
  – Relatively small (pre-processing possible)

• Apply heuristic search algorithms
  – Algorithms
    • A*
    • LPA*
  – Heuristics
    • Transitions-based heuristic
    • Literals-based heuristic
Heuristics

- Do a, then b
  \( \Diamond (a \land \neg b \land \Diamond b) \)

- Do a and b in any order
  \( \Diamond a \land \Diamond b \)

Minimum Number Of Transitions To Acceptance

- Minimum Number of Literals To Acceptance

- Do a, then b
  \[
  
  \begin{array}{c}
  0 \quad \text{a \& \neg b} \\
  1 \quad \neg b \\
  2 \quad 1
  \end{array}
  \]

- Do a and b in any order
  \[
  
  \begin{array}{c}
  0 \quad \neg a \land \neg b \\
  1 \quad a \land b \\
  2 \quad a \land \neg b \\
  3 \quad \neg b
  \end{array}
  \]
Task Planning Improvement

Task Planning Time for Benchmark Problems

Planning Time (s)

- Reach (2)
- Baxter (27)
- Swap5 (16)
- Swap6 (32)
- Swap7 (64)
- Swap8 (128)

Benchmark (DFA size)

Timeout 5 min

Dijkstra
Transition Heuristic
Literal Heuristic
Take-aways

• Formulate manipulation tasks in co-safe LTL
  – Challenge: high dimensional continuous space

• Address this problem through
  – Abstraction
  – Synergistic combination of task + motion planning

• Significantly speed up planning
  – Using heuristics computed based on task specification

• Current/future Direction
  – Faster motion planning
  – Improving synergy between task and motion planning