Applying Search Based Probabilistic Inference Algorithms to Probabilistic Conformant Planning: Preliminary Results

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Overview

- Probabilistic Conformant Planning
  - Agent, Example, Problem, and Task

- Graphical Model and Probabilistic Inference
  - Probabilistic Conformant Planning as Marginal MAP Inference
  - AND/OR Search Algorithms for Marginal MAP Inference

- Compiling Graphical Models from Planning Problems
  - Example Domain: Blocks World
  - Compiling Probabilistic PDDL into 2 stage DBN
  - Compiling Finite Domain Representation (SAS+) into 2 stage DBN

- Experiment Results (Blocks World Domain)
Probabilistic Conformant Planning

- Agent

- No observation
- Uncertain environment
  - Uncertain initial states: Probability distribution over possible states
  - Uncertain action effects: Probability distribution over possible effects
- Find a sequence of actions that reach goal with desired criteria
  - given plan length, maximize the probability of reaching goal, etc

Stuart Russell and Peter Norvig. Artificial Intelligence: A Modern Approach (3rd Ed.)
Probabilistic Conformant Planning - Example

- Spacecraft Recovery*
  - Complex systems could fail
  - Observation is sometimes limited
  - Diagnosis yields plausible states with scores (probability)
  - Generate a fail-safe recovery plan that can be applied to all plausible states.

*Fragment-based Conformant Planning, J. Kurien, P. Nayak, and D. Smith AIPS 2002
Probabilistic Conformant Planning
- Problem and Task

Probabilistic Conformant Planning Problem
\[ P = \langle S, A, I, G, T \rangle \]
- \( S \) : a set of possible states
- \( A \) : a set of actions
- \( I \) : initial belief state (probability distribution over initial states)
- \( G \) : a set of goal states
- \( T \) : Markovian state transition function (\( T: S \times A \times S \rightarrow [0, 1] \))

Probabilistic Conformant Planning Task
\[ \langle P, L \rangle: \text{Maximize probability of reaching goal given fixed plan length } L \]
\[ \langle P, \theta \rangle: \text{A plan of arbitrary length reaching goal with a probability higher than } \theta \]
Graphical Models

A graphical model \((X, D, F)\)
- \(X = \{X_1, \ldots, X_n\}\) variables
- \(D = \{D_1, \ldots, D_n\}\) domains
- \(F = \{f_1, \ldots, f_m\}\) functions
  - Constraints, CPTs, CNFs, ...

Operators
- Combination (product)
- Elimination (max/sum)

Tasks
- Probability of Evidence (PR)
  \[ Pr(e) = \sum_{X_s} \prod_j f_j(X_s, e) \]
- Most Probable Explanation (MPE)
  \[ x_{MPE} = \arg\max_x \prod_j f_j(x) \]
- Marginal MAP (Maximum A Posteriori)
  \[ x_{MAP} = \arg\max_{x_m \in X_M} \sum_{x_s \in X_s} \prod_j f_j(x_m, x_s) \]

All these tasks are NP-hard
Exploit problem structure
(primal graph)
Conformant Planning as Marginal MAP

- **Finite Horizon Probabilistic Conformant Planning** \(<S, A, I, G, T, L>\)
  - Random variables
    \[
    S = \{s^0, s^1, \ldots, s^L\} \quad s^t = \{s^t_0, s^t_1, \ldots, s^t_N\} \\
    A = \{a^0, a^1, \ldots, a^L\} \quad a^t = \{a^t_0, a^t_1, \ldots a^t_M\}
    \]
  - State transition function
    \[
    Pr(s^{t+1}|s^t, a^t) = T(s^t, a^t, s^{t+1})
    \]
  - Joint probability distribution given a plan that satisfying the goal
    \[
    P(s^0, s^1, \ldots, s^L|s^L \in G, a^0, a^1, \ldots, a^{L-1}) = P(s^0)[\prod_{t=0..L-1} P(s^{t+1}|s^t, a^t)]P(s^L|s^L \in G, s^{L-1}, a^{L-1})
    \]
  - Optimal Plan as MMAP
    \[
    \text{argmax}_{\{a^0, a^1, \ldots, a^{L-1}\}} \sum_{\{s^0, s^1, \ldots, s^L\}} P(s^0, s^1, \ldots, s^L|s^L \in G, a^0, a^1, \ldots, a^{L-1})
    \]
AND/OR Search Algorithm for MMAP

**Graphical Model**

**AND/OR Search Graph**
[Dechter and Mateescue 2006]

**AND/OR Branch and Bound Search**
[Kask, Dechter 2001]
[Marinescu, Dechter 2005-2009]

**Mini-bucket Elimination with Moment Matching**
[Dechter and Rish 1997, 2003]
[Flerova, Ihler 2011]

**Breadth Rotate Search**
[Otten, Dechter 2011]

\[
\min_{\mathbf{x}} \sum_{i=0}^{n}\max_{x_i}(f_i(x_i, x_j) + \lambda_i(x_i), \lambda_j(x_j))
\]
Example Domain: Blocks World

State: OnTable (b1) and On(b2, b1) and Clear(b2) and EmptyHand

action: pick-up-from-block(b2, b1)

State: OnTable (b1) and Clear(b1) and Holding(b2)

action: put-down-to-table(b2)

State: OnTable (b1) and OnTable(b2) and Clear(b1) and Clear (b2) and EmptyHand
Example Domain: Blocks World

State: OnTable (b2) and Clear(b2) and Holding(b1)

action: pick-up-from-table(b1)

State: OnTable (b2) and Clear(b2) and Holding(b1)

action: put-on-block(b1, b2)

State: OnTable (b2) and On(b1, b2) and Clear(b1) and EmptyHand
Blocks World in PDDL (deterministic)

- Predicates for describing states
  - Clear(?b block), OnTable(?b block),
  - On(?b1, ?b2 block), Holding(?b block), EmptyHand

- Initial State
  - On(b2, b1) and OnTable(b1) and Clear(b2) and EmptyHand

- Goal State
  - On(b1, b2) and OnTable(b2) and Clear(b1) and EmptyHand

- Action Schema for describing actions
  - Pick-up-from-block (?b1 ?b2 - block)
  - Pick-up-from-Table (?b – block)
  - Put-on-block(?b1 ?b2 – block)
  - Put-down-to-table(?b – block)
Blocks World in PDDL (deterministic)

- Action schema for describing deterministic state transitions
  - Pick-up-from-block(?b1, ?b2 - block)
    - Precondition: EmptyHand and Clear(?b1) and On(?b1, ?b2)
    - Effect: Holding(?b1) and Clear(?b2) and
      (Not EmptyHand) and (Not Clear(?b1)) and (Not On(?b1, ?b2))
  - Pick-up-from-table(?b - block)
    - Precondition: EmptyHand and Clear(?b) and OnTable(?b)
    - Effect: Holding(?b) and
      (Not EmptyHand) and (Not OnTable(?b)) and (Not Clear(?b))
Compiling Graphical Models from Planning Domains

IPCI-1998, 2000
McDermott et al 1998

Planning Domain Definition Language
- standard language for “classical planning problems”
- influenced by STRIPS and ADL formalism

[Helmer 2006, 2009]

Finite Domain Representation (SAS+)
- Multi-valued state variables
- Simplified Action Structure+ (SAS+) (Backstrom 1995)

IPC- 2004
Younes and Littman 2004

Probabilistic Planning Domain Definition Language
Extension of PDDL 2.1 to support “Probabilistic Actions”

Two Encoding Schemes

2 Stage DBN
& Replicate it over L finite horizon

Finite Domain Representation (SAS+)
with Probabilistic Effects
Blocks World in PPDDL (Probabilistic)

- Action schema for describing **probabilistic state transitions**

  - Pick-up-from-block(?b1, ?b2 - block)
    - Precondition: EmptyHand and Clear(?b1) and On(?b1, ?b2)
    - Effect1: \textbf{0.75} Holding(?b1) and Clear(?b2) and (Not EmptyHand) and (Not Clear(?b1)) and (Not On(?b1, ?b2))
    - Effect2: \textbf{0.25} Clear(?b2) and OnTable(?b1) and (Not On(?b1, ?b2))

  - Pick-up-from-table(?b - block)
    - Precondition: EmptyHand and Clear(?b) and OnTable(?b)
    - Effect1: \textbf{0.75} Holding(?b) and (Not EmptyHand) and (Not OnTable(?b)) and (Not Clear(?b))
Compiling PPDDL into 2 stage DBN

Convert each ground action schema into 2TDBN

- Pre-state variable
  - Clear b1
  - OnTable b1
  - On b1 b2
  - Holding b1
  - EmptyHand
- Effect variable (probabilistic)
  - pickupfromtable b1
- Post state variable
  - Clear b1
  - OnTable b1
  - On b1 b2
  - Holding b1
  - EmptyHand
  - Clear b2
  - OnTable b2
  - On b2 b1
  - Holding b2

as shown in PPDDL 1.0 Specification
Compiling PPDDL into 2 stage DBN

- Introduce additional variables to bound scope
  - Precondition, Add effect, Del effect, Action

as serial encoding of SATPLAN
Compiling PPDDL into 2 stage DBN

- Combine all 2TDBNs into Single 2TDBN
  - If scope size needs to be bounded, introduce hidden variables

Diagram:

- s1
- s2
- s3
- s4
- hidden
- precondition
Compiling PPDDL into 2TDBN

- Slippery Gripper Domain Example
Complexity of Translation from PPDDL

- **Input PPDDL parameters**
  - Number of ground objects = $|Obj|$
  - Number of action schemata = $|AS|$
    - Maximum number of object parameters = $|P|$
    - Maximum number of probabilistic effects = $|Eff|$
  - Number of predicates = $|Pred|$

- **Number of Variables at each time**
  - Number of action variables $\leq 2 \cdot |AS| \cdot |Obj|^P$
  - Number of state variables = $|Pred| \cdot |Obj|^P$
  - Number of effect variables = $|AS| \cdot |Obj|^P$
  - Number of Add/Del state variables $\leq 2 \cdot |Pred| \cdot |Obj|^P \cdot |Eff|$
  - $O(3 \cdot |AS| \cdot |Obj|^P + (3 + |Eff|) \cdot |Pred| \cdot |Obj|^P)$
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Extension of PDDL 2.1 to support “Probabilistic Actions”

Two Encoding Schemes

2 Stage DBN & Replicate it over L finite horizon

Finite Domain Representation (SAS+)
with Probabilistic Effects
Blocks World in FDR (SAS+)

- Simplified Action Structure+ (Backstrom 1995)
  - Multi-valued state variables
    - State variable is an aggregate of mutually exclusive ground predicates
  - Operators (collection of changes of values in state variables)
    - Prevail condition: Value of a variable remains same
    - Pre-condition: Value of a variable before state transition
    - Post-condition: Value of a variable after state transition

- Translate PDDL → FDR (Helmert 2009)
  - Generalize SAS+ with conditional effects and derived predicates
  - Automated translator from PDDL 2.2 to SAS+
Multi-Valued State Variables

- 9 binary state variables
  - clear b1, OnTable b1, On b1, b2, Holding b1, Emptyhand,
    clear b2, OnTable b2, Onb2 b1, Holding b2

translated as

- 5 multi-valued state variables
  - $\text{Var0} = \{\text{Clear}(b1), \text{Not Clear}(b1)\}$
  - $\text{Var1} = \{\text{Clear}(b2), \text{Not Clear}(b2)\}$
  - $\text{Var2} = \{\text{EmptyHand}, \text{Not EmptyHand}\}$
  - $\text{Var3} = \{\text{Holding}(b1), \text{On}(b1, b2), \text{OnTable}(b1)\}$
  - $\text{Var4} = \{\text{Holding}(b2), \text{On}(b2, b1), \text{OnTable}(b2)\}$
Blocks World in FDR (SAS+)

Operators for describing **deterministic** state transitions

- Translate each ground action schema as a collection of transitions of state variables

- Pick-up-from-block(?b1, ?b2 - block)
  - Precondition: EmptyHand and Clear(?b1) and On(?b1, ?b2)
  - Effect: Holding(?b1) and Clear(?b2) and (Not EmptyHand) and (Not Clear(?b1)) and (Not On(?b1, ?b2))

translated as

- Pick-up-from-block(?b1, ?b2 - block)
  - Var0: 0 → 1 (Clear(b1) → Not Clear(b1))
  - Var1: * → 0 (any value → Not Clear(b2))
  - Var2: 0 → 1 (EmptyHand → Not EmptyHand)
  - Var3: 1 → 0 (On(b1, b2) → Holding(b1))
Blocks World in FDR (SAS+)

- Operators for describing **probabilistic** state transitions
  - Original FDR(SAS+) does not translate probabilistic actions
  - Determinization of PPDDL action schema
    - FF-Replan (Yoon, Fern, and Giva 2007)
    - make each of the probabilistic effects as a single action schema and drop the probability value
  - Translate determinized PPDDL as FDR(SAS+)
  - Combine probabilistic effects
Compiling FDR(SAS+) into 2 stage DBN

- Convert each ground action into 2TDBN

Precondition:
- Var 0 → 0
- Var 2 → 0
- Var 3 → 1

Post transitions:
- Var 0 → 1
- Var 2 → 1
- Var 3 → 0

Post states:
- Var 0
- Var 1
- Var 2
- Var 3

Pre transitions:
- Var 0 → 0
- Var 2 → 0
- Var 3 → 1

Post transitions:
- Var 0 → 1
- Var 2 → 1
- Var 3 → 0

Post states:
- Var 0
- Var 1
- Var 2
- Var 3

Effect:
- Pickupfromblock b1 b2

Precondition:
- Var 0: 0 → 1
- Var 1: * → 0
- Var 2: 0 → 1
- Var 3: 1 → 0

Effect:
- (Clear(b1) → Not Clear(b1))
- (EmptyHand → Not EmptyHand)
- (On(b1, b2) → Holding(b1))
Compiling FDR(SAS+) into 2 stage DBN

- Combine all 2TDBNs into Single 2TDBN
  - If scope size is too big, introduce hidden variables

- Optimize translation (in progress)
  - Minimize number of
    - Precondition, pre/post transition variables
    - Hidden variables
  - Minimization turns into finding maximal bi-cliques
    - action effects are expressed as conjunction of state value assignments (equality predicates)
Complexity of Translation from FDR(SAS+)

- Input PDDL/FDR parameters for action variables
  - Number of ground objects = $|Obj|$
  - Number of action schemata = $|AS|$
    - Maximum number of object parameters = $|P|$
    - Maximum number of probabilistic effects = $|Eff|$
  - Number of multi-valued state variables = $|S|$

- Maximum domain size = $k$

- Number of Variables at each time stage
  - action variables = $|AS| \cdot |Obj|^P$
  - state variables = $|S|$
  - Pre-transition variables = $|S| \cdot k$
  - Post-transition variables $\leq 2 \cdot |S| \cdot k$
  - Pre-condition variables $\leq 2 \cdot |AS| \cdot |Obj|^P \cdot |Eff|$
  - FDR $O((1 + 2 \cdot |Eff|)(|AS| \cdot |Obj|^P) + (1 + 3k) \cdot |S|)$
  - ppddl $O(3 \cdot |AS| \cdot |Obj|^P + (3 + |Eff|) \cdot |Pred| \cdot |Obj|^P)$
Experiment Results: Blocks World

Probabilistic Inference Algorithms

<table>
<thead>
<tr>
<th></th>
<th>BRAOBB-MMAP</th>
<th>BRAOBB-MAP + PR</th>
<th>GLS+ PR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimality</td>
<td>Optimal</td>
<td>Suboptimal</td>
<td>Suboptimal</td>
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<tr>
<td>Search Space</td>
<td>Marginal MAP/ Constrained</td>
<td>MAP / Unconstrained</td>
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<tr>
<td>Heuristic</td>
<td>WMB-MM(i)</td>
<td>MBE-MM(i)</td>
<td>-</td>
</tr>
</tbody>
</table>

- **Breath Rotate + AOBB** [Otten, Dechter 2011] [Marinescue, Dechter 2005-2009]
  - Branch and Bound Search on AND/OR Graph with Sub-problem rotations

- **WMB-MM(i)** [Dechter, Rish 1997, 2003] [Liu, Ihler 2011] [flero, Ihler 2011]
  - Weighted mini-bucket elimination with moment matching

- **GLS+** [Hutter et al, 2005]
  - Stochastic local search algorithm for MAP inference

- **PR**
  - Perform summation in AND/OR search graph
AND/OR Search Algorithm for MMAP

**Graphical Model**

AND/OR Search Graph

[Dechter and Mateescu 2006]

**Mini-bucket Elimination with Moment Matching**

[Dechter and Rish 1997, 2003]
[Flerova, Ihler 2011]

**AND/OR Branch and Bound Search**

[Kask, Dechter 2001]
[Marinescu, Dechter 2005-2009]

**Breadth Rotate Search**

[Otten, Dechter 2011]
Experiment Results: Blocks World

Blocks World Domains

- Taken from International Planning Competition ‘04
  - The original task was planning with full observation
    Easier problem (MAP inference)
  - Original domain has 7 action schemata (removed 3)

Problem Instances

- Reverse configuration
  - Initially all blocks are stacked as a tower. Planning task is reversing the stack
- Number of Blocks: 2, 3, 4 blocks
- Length of Time: up to 20 time horizon
## PPDDL vs. FDR(SAS+) translation

<table>
<thead>
<tr>
<th>instance blocks, horizon</th>
<th>Translation From PPDDL</th>
<th>Translation From FDR(SAS+)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ppddl to dbn n, a, w&lt;sub&gt;c&lt;/sub&gt;, h&lt;sub&gt;c&lt;/sub&gt;</td>
<td>braobb-mmap time (sec)</td>
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<td>299, 40, 48, 76</td>
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<tr>
<td>2, 8</td>
<td>473, 64, 72, 112</td>
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<td>2, 11</td>
<td>647, 88, 96, 149</td>
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<td>2, 14</td>
<td>821, 112, 120, 169</td>
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<td>2, 17</td>
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<td>2, 20</td>
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<td>4075, 480, 672, 841</td>
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</table>

- Translation from FDR(SAS+)
  - 1.3 ~ 2.6 times speed up
  - constrained induced width of problem is much less
### MMAP vs. MAP + PR Inference

<table>
<thead>
<tr>
<th>instance blocks, horizon</th>
<th>pddl to dbn n, a, w_c, h_c, w_u, h_u</th>
<th>BRAOBB-MMAP time (sec)</th>
<th>BRAOBB-MMAP pr(G)</th>
<th>BRAOBB-MAP time (sec)</th>
<th>BRAOBB-MAP pr(G)</th>
<th>GLS+ time (sec)</th>
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- MMAP finds optimal solution if it could
- MAP finds suboptimal plan faster than MMAP
- GLS+ can reach longer horizon than MMAP and MAP
- Finding any plan that exceeds threshold
  - Probabilistic-FF [Domshlak and Hoffmann. 2007] produces plan quickly when threshold is small
  - Search based inference algorithms finds plan at higher threshold

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Conclusion

- Applied probabilistic inference to conformant planning
  - MMAP produces optimal plan
  - Specialized solver (PFF) performed well on low probability of success regime but it fails on high probability regime
  - MAP inference algorithm could produce suboptimal plans in a shorter time bounds
Conclusion

- Limitations of grounding & translation
  - Translation from FDR produced better results
  - Size of translation matters!
    - Exponential ( |objects| |params| )
    - Duplicate the structure over L time horizons
  - Typical size of problems
    - POMDP |A| ~ 10
    - Conformant Planning (uncertainty in initial states)

- State-of-the-art
  - (Taig and Brafman 2015)
  - (Domshlak and Hoffman 2007)