Effective Heuristics and Belief Tracking for Planning with Incomplete Information

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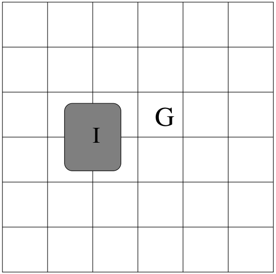
Incomplete Information: Conformant Planning

Task

Robot must move from **uncertain** *I* into *G* with **certainty**.



- Similar to classical planning except for **uncertain** ***I***
- **Plans**, however, quite **different**: best **conformant** plan **must move the robot to a corner first (localization)**

Motivation

Conformant planning is **special case** of contingent planning

Ideas provide the **basis** for

- Planning with Sensing (Brafman & Hoffmann, 2005)
- Derivation of Finite–State Controllers (Bonet, Palacios, Geffner, 2009)

Obtaining conformant planners that **scale up** well is critical.

Conformant Planning: Belief State Formulation

- **Belief state**: **set** of possible states
- Actions map belief state b into belief state b_a

$$b_a = \{s' | s' \in F(a, s) \,\&s \in b\}$$

- Conformant planning is path–finding in **belief space**

Challenges: # of belief states is **doubly exponential** in # of vars.

- **Effective representation** of belief states b
- **Effective heuristic** $h(b)$ for estimating cost to G in belief space

Recent alternative: translation into classical planning (Palacios & Geffner 2007).

Basic Translation: Move to the "knowledge level"

conformant problem $P = \langle F, O, I, G \rangle$

1. F fluents in P
2. O actions with effects $C \rightarrow L$
3. I initial situation, CNF **clauses** over F-literals
4. G goal situation, **conjuction** of F-literals

classical problem $K_0(P) = \langle F', O', I', G' \rangle$

1. $F' = \{KL, K\neg L \mid L \in F\}$
2. $O' = O$ **but** preconditions L replaced by KL, effects $C \rightarrow L$ replaced by rules
   - **Support** $KC \rightarrow KL$
   - **Cancellation** $\neg K\neg C \rightarrow \neg K\neg L$
3. $I' = \{KL \mid \text{clause } L \in I\}$
4. $G' = \{KL \mid L \in G\}$

Basic Translation: Properties

$K_0(P)$ is **sound** but **incomplete**:

- **Soundness**: every classical plan for $K_0(P)$ is a conformant plan for P
- **Completeness**: all plans for P are classical plans for $K_0(P)$.

Key Elements in General Translation $K_{T,M}(P)$

1. A set T of **tags** t
   - consistent sets of **assumptions** (literals) about initial situation I:

$$I \not\models \neg t$$

2. A set M of **merges** m
   - **valid subsets of tags** (DNF)

$$I \models \bigvee_{t \in m} t$$

3. Tagged literals KL/t meaning that L true **if** t **initially** true

General Translation: $K_{T,M}(P)$

conformant problem $P = \langle F, O, I, G \rangle$

...

classical problem $K_{T,M}(P) = \langle F', O', I', G' \rangle$

- $F' = \{KL/t\ , K\neg L/t \mid L \in F\ \&\ t \in T\}$
- $O' = O$ **but** preconditions L replaced by KL, effects $C \rightarrow L$ replaced by rules
  - **Support** $KC/t \rightarrow KL/t$
  - **Cancellation** $\neg K\neg C/t \rightarrow \neg K\neg L/t$
  - Plus **merge actions**

$$\bigwedge_{t \in m, m \in M} KL/t \ \rightarrow \ KL$$

- $I' = \{KL/t \mid \text{if } I \models t \supset L\}$
- $G' = \{KL \mid L \in G\}$

Compiling Uncertainty Away: Properties

- Translation $K_{T,M}(P)$ **always sound**, for suitable choice of sets of **tags** and **merges**, it is **complete**
- **Conformant width** is roughly the **max # of relevant uncertain** variables that interact in P
- $K_i(P)$ is **polynomial instance** of $K_{T,M}(P)$ that is **complete** for problems with conformant width **bounded** by i
- Most benchmarks have **bounded** width and **equal** to 1!
- $K_i(P)$ with $i = 1$, is basis for conformant planner $T0$ (Palacios & Geffner, 2009)

Shortcomings of the Translation–based Approach

1. For problems with high width, **complete translation** unfeasible
2. **Incomplete** yet **tractable** translations may
   - render a solvable problem **unsolvable**
   - result in **infinite** heuristic values for solvable beliefs
3. Relevant information like **cardinality of beliefs**, seems to get **lost in translation**

Contributions of this work

1. **New translation** $K^i_S(P)$
   - Exponential in i, always **complete**, not always **sound**
   - $K^i_S(P)$ **sound** for problems with width $\leq i$
2. **New planner** $T1$ based on $K^1_S(P)$ **improves** upon $T0$ planner based on $K_1(P)$
   - **Belief space** planner
   - Two heuristics
     - **Reachability** heuristic h_C derived from $K^1_S(P)$
     - **Certainty** heuristic h_K

Outline for the rest of the talk

1. **Translation** $K_S^i(P)$
2. **Planner** $T1$
3. Experimental **Results**

Idea for the $K_S^i(P)$ translation

$K_{S0}(P)$ is $K_{T,M}(P)$ with $T = S_0$.

- $K_{S0}(P)$ sound and complete, but **exponential** on $|F|$

Define K_S to be like K_{S0}, **but** $T = S \subseteq S_0$

- S **set of samples** of S_0
- $K_S(P)$ is **complete** but not necessarily **sound.**

$K_S^i(P)$ like $K_S(P)$ but with a **specific** sample set S

- **Sound** when width of problem P **bounded** by i
- $|S|$ **exponential** on i

Bases for Conformant Problems

Definition

A **set of states** S, $S \subseteq S_0$ is a **basis for problem** P, iff any conformant plan that conforms with S also conforms with S_0

Theorem (Palacios & Geffner, JAIR 2009)

If problem P has width i, then there exists a basis S for P of size **exponential in** i**.**

The $K_S^i(P)$ translation

$K_S^i(P)$ is $K_S(P)$ with **sample set** $S \subseteq S_0$ s.t. S guaranteed to be a basis for P if width of $P \leq i$

$K_S^i(P)$ is **always** complete and **sound** if width$(P) \leq i$,

Computation of sample sets S **exponential** in i, provided that I compiled into d–DNNF (Darwiche, 2002)

See paper for details

$T1$ planner

Belief space planner $T1$ **implicitly** represents **beliefs.**

Search **node** $n = \langle \pi, \ S_n, \ R \rangle$

- π is the **plan prefix** to reach n from **root node** $\langle \emptyset, \ S^1, \ R_0 \rangle$
- S_n is sample set S^1 progressed through π
- R set of **known** literals

SAT solver used to check literals true in R

Two heuristics:

- $h_C(n) = h(K_S(P))$, where $S = S_n$
- $h_K(n)$ . . . in next slide

Certainty heuristic h_K

Given node $n = \langle \pi,\ S_n,\ R \rangle$, $h_K(n)$ defined as:

\# of literals L in *oneof* **invariants** overlapping G s.t. $\neg L \notin R$

Related to

- **Landmark** heuristic (Richter, Helmert & Westphal, 2008)
- **Belief cardinality** heuristic (Bertoli & Cimatti, 2002)

$T1$ planner: Search Engine

- Multi-queue best first search algorithm (Helmert, 2004)
- 3 open lists Q1,Q2, Q3:
  - **Q1**: nodes for helpful actions or that decrease certainty heuristic h_K, ordered with h_C
  - **Q2**: nodes for helpful actions or that decrease certainty heuristic h_K, ordered with h_K
  - **Q3**: nodes for non-helpful actions, ordered with h_C
- We alternate expansion from Q1 and Q2, $^1/_{10}$ of the expansions are from Q3.

Experimental Evaluation

$T1$ compared with

- $T0$ (Palacios & Geffner, 2007)
- DNF (To, Son & Pontelli, 2010)

over instances from various sources (IPC, Conformant–FF, $T0$)

$T1$ has a **higher coverage** than both $T0$ and DNF.

$T1$ is **slower** than $T0$, faster (in average) than DNF.

Heuristics comparison: $h_C(b)$ vs. $h_K(b)$

		h_C				h_K				T1			
Domain	I	S	T	E	L	S	T	E	L	S	T	E	L
Bomb	9	7	71	4k	101	7	11	773	101	**8**	2	100	101
Cube(Ctr)	12	6	84	32k	188	10	1	890	61	**12**	0.1	61	58
Cube(Cor)	11	8	92	219k	271	10	4	26k	88	**11**	12	15k	269
Dispose	11	7	664	8k	349	**9**	57	2k	190	8	134	1k	491
Logistics	4	2	0.2	546	30	2	544	1613k	30	**4**	0.1	554	78
Ring	7	6	1	1k	17	5	571	58k	17	**8**	0.2	214	31
UTS-k	15	**15**	0.06	26	7	2	0.05	154	7	13	0.04	10	9

- The **combination** of h_C and h_K in T1 performs generally better

Summary

1. A method to for defining and computing a **sample set** $S^i \subseteq S_o$ s.t.
   - S^i is exponential in i
   - translation $K^i_S(P)$ based on S^i is sound and complete if $width(P) \leq i$
2. A **Planner** $T1$ based on new translation, extended with certainty heuristic, **competitive** with state–of–the–art.

Thank you!

$T1$ Planner: Belief Tracking

Action a **applicable** on node n when $Pre(a) \subset R$

Resulting node $n' = \langle \pi', \ S', \ R' \rangle$

- $\pi' = \pi \cup \{a\}$
- $S' = \{s' | s' = f(a, s), \ s \in S\}$
- R' results from
  1. Applying $K_0(P)$ **support** and **cancellation** rules (Palacios & Geffner, 2009; Baral & Son, 1997)
  2. **If** width ≤ 1, lits true in all $s \in S$ added to R'
  3. **Otherwise**, lit entailment checked with SAT solver as in Conformant–FF (Brafman & Hoffman, 2005)

Duplicate detection

- **If** width ≤ 1, **direct comparison** of S and R suffices
- **Otherwise**, belief equivalence checked with **one SAT solver call**

$T1$ planner: Reachability heuristic $h_C(b_n)$

$h_C(n)$ is the **sum** of costs of actions in relaxed plan π^+.

π^+ extracted from $h_{add}(G)$ computation (Keyder & Geffner, 2008) **over classical problem** $K_S(P)$

- S are samples S^1 progressed through prefix π

Helpful actions def. analogous to that in (Hoffman & Nebel, 2001)

$T1$ planner: Epistemic Landmarks

Idea

If robot needs to end at location x with certainty, then certainly it can't be at locations $x' \neq x$

Epistemic landmarks are G along with **negation** of lits **mutex** with $g \in G$

$oneof(x_1, \ldots, x_m)$'s in problem description checked for **invariance**

- All pairs x_i,x_k **mutex** for $i \neq k$
- Every a with eff $C \rightarrow \neg x_i$, has eff $C \rightarrow x_k$, $1 \leq i, k \leq m$

if not, it is attempted to extend $oneof(\ldots)$ with additional literals (Helmert, 2009)