Exploiting optimizations in SAT-based planning: minimal-#actions plans and “soft” goals

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Context

SAT-based planning is the best approach for “optimally” solve planning problems by

1. constructing a SAT formula ϕ_n for a fixed *makespan* n;
2. verifying if ϕ_n is satisfiable; if not, n is increased.

Main advantages:

- simplicity
- effectiveness, can take advantage on the continuous progress in the SAT area
- optimal makespan guaranteed

International Planning Competitions

SATPLAN has been the winner of the IPC-4 and co-winner of the IPC-5 in the optimal tracks.

On the other hand . . .

SATPLAN's deficiency

- it can only handle a very limited part of the PDDL language; and
- it does not take into account other "plan quality" issues, e.g., number of actions in the plan and the possibility to express "soft" goals.

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Contribution of the work

We present SATPLANP, modification of SATPLAN, which returns plans

1. having minimal number of actions;
2. having maximal number of “soft” goals satisfied.

w.r.t. both

- subset inclusions (qualitative)
- cardinality (quantitative)

Planning as Satisfiability

Planning problem

Is a triple $\langle I, tr, G\rangle$ where (given the sets of fluents $\mathcal{F}$ and actions $\mathcal{A}$)

- I is a SAT formula over $\mathcal{F}$ and represents the set of *initial states*;
- tr is a SAT formula over $\mathcal{F} \cup \mathcal{A} \cup \mathcal{F}'$ where $\mathcal{F}' = \{f' : f \in \mathcal{F}\}$ is a copy of the fluent signature and represents the *transition relation*
- G is a SAT formula over $\mathcal{F}$ and represents the set of *goal states*.

Plan

The *planning problem* Π *with makespan* n is the SAT formula Π_n

$$I_0 \wedge \wedge_{i=1}^{n} tr_i \wedge G_n \qquad (n \geq 0) \tag{1}$$

- tr_i is the formula obtained from tr by substituting each symbol $p \in \mathcal{F} \cup \mathcal{A}$ with p_{i-1} and each $f \in \mathcal{F}'$ with f_i
- I_0 and G_n are obvious

A *plan for* Π_n is an interpretation satisfying (1).

```
function SATPLAN(Π_n)
    return DLL(cnf(Π_n),∅)

function DLL(φ,S)
    if (∅ ∈ φ) return FALSE;
    if (φ = ∅) return S;
    if ({l} ∈ φ) return DLL(φ_l, S ∪ {l});
    l := ChooseLiteral(φ);
    return DLL(φ_l̄, S ∪ {l̄}) or
    return DLL(φ_l̄, S ∪ {l}).
```

φ_l

φ_l returns the formula obtained from φ by (*i*) deleting the clauses containing l, and (*ii*) deleting $\bar{l}$ from the others.

Qualitative SATPLANP's algorithm

function QL-SATPLANP(Π_n,P,$\prec$)
  return OPT-DLL($cnf(\Pi_n \wedge \wedge_{p \in P}(v(p) \equiv p))$,$\emptyset$,$v(P)$,$v(\prec)$)

function OPT-DLL(φ,S,P',$\prec'$)
  if $(\emptyset \in \varphi)$ **return** FALSE;
  if $(\varphi = \emptyset)$ **return** S;
  if $(\{l\} \in \varphi)$ **return** OPT-DLL($\varphi_l, S \cup \{l\}, P', \prec'$);
  $l := ChooseLiteral(\varphi, S, P', \prec')$;
  $V :=$ OPT-DLL($\varphi_l, S \cup \{l\}, P', \prec'$);
  if ($V \neq$ FALSE) **return** V;
  return OPT-DLL($\varphi_{\bar{l}}, S \cup \{\bar{l}\}, P', \prec'$).

where

- for each $p \in P$, $v(p)$ is a newly introduced variable;
- $v(P)$ is the set of new variables, i.e., $\{v(p) : p \in P\}$;
- $v(\prec) = \prec'$ is the partial order on $v(P)$ defined by $v(p) \prec' v(p')$ iff $p \prec p'$;

Qualitative SATPLANP's algorithm: Example

Going at work from home

$$\neg AtWork_0, \quad AtWork_1 \equiv \neg AtWork_0 \equiv (Car_0 \vee Bus_0 \vee Bike_0), \quad AtWork_1, \tag{2}$$

If we have two preferences

1. $p_1 = (\neg Bike_0 \wedge \neg Bus_0 \wedge \neg Car_0)$
2. $p_2 = (\neg Bike_0 \wedge \neg Bus_0)$

with $p_1 \prec p_2$. OPT-DLL on (2) returns the plan corresponding to $\{Car_0\}$ determined while exploring the branch extending $\{\neg v(p_1), v(p_2)\}$.

function QT-SATPLANP(Π_n,P,c)
16 **return** OPT-DLL($cnf(\Pi_n \wedge adder(P,c))$,$\emptyset$,$b(c)$,$p(c)$)

$adder(P,c)$ is a SAT formula, e.g., (Warners, IPL 1999)

- if $n = \lceil log_2((\sum_{p \in P} c(p)) + 1) \rceil$, $adder(P,c)$ contains n new variables $\{b_{n-1}, \ldots, b_0\} = b(c)$; and
- for any plan π satisfying Π_n, there exists a unique interpretation μ to the variables in $\Pi_n \wedge adder(P,c)$ s.t.
  1. μ extends π and satisfies $\Pi_n \wedge adder(P,c)$;
  2. $\sum_{p \in P: \pi \models p} c(p) = \sum_{i=0}^{n-1} \mu(b_i) \times 2^i$, where $\mu(b_i)$ is 1 if μ assigns b_i to true, and is 0 otherwise.
- $p(c)$ is the partial order $b_{n-1} \prec b_{n-2} \prec \cdots \prec b_0$.

Quantitative SATPLANP's algorithm: Example

Going at work from home

$$\begin{array}{c} \neg AtWork_0, \\ AtWork_1 \equiv \neg AtWork_0 \equiv (Car_0 \vee Bus_0 \vee Bike_0), \\ AtWork_1, \end{array} \quad (3)$$

If we have two preferences

1. $p_1 = (\neg Bike_0 \wedge \neg Bus_0 \wedge \neg Car_0)$
2. $p_2 = (\neg Bike_0 \wedge \neg Bus_0)$

with $c(p_1) = 2$ and $c(p_2) = 1$, then two bits b_1 and b_0 are sufficient as output of $adder(\{p_1, p_2\}, c)$. OPT-DLL returns the plan corresponding to $\{Car_0\}$ determined while exploring the branch extending $\neg b_1, b_0$.

Rational and utility of SATPLANP's algorithms

Rational

- we preferentially (and in order) split on variables (literals) defining
  1. preferences, in the qualitative case
  2. the sum of the weights of preferences, in the quantitative case
- for minimizing actions, the preferences are the atoms related to actions and the split is forced to FALSE
- for maximizing soft goals satisfied, the preferences are the soft goals and the split is forced to TRUE

Utility

- if we want that as few as possible actions are executed, then we have to find an assignment in QT-SATPLANP;
- if we want that no redundant sequence of (possibly parallel) actions is executed, then we have to find an assignment in QL-SATPLANP.

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Experimental analysis: Goals

1. Evaluate SATPLANP w.r.t. the state-of-the-art on problems with "SimplePreferences", like "soft" goals
   - SATPLANP vs. SGPLAN
2. Evaluate the reductions that can be obtained with SATPLANP over SATPLAN
3. Evaluate the computational costs of such reductions
   - SATPLANP vs. SATPLAN
4. Evaluate what kind of *adder*() works better
   - (Warners, IPL 1999) vs. (Bailleaux & Boufkhad, CP 2003)

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Experimental analysis: 1.

	SGPLAN	SATPLAN	SATPLANP(w)	SATPLANP(b)	SATPLANP(s)
pipe	0/0	0/7	0/18	0/18	0/17
pipet	0/0	0/5	0/11	0/11	0/11
sat	0/10	0/4	0/4	0/4	0/4
air	0/23	0/9	0/11	0/11	0/11
phil	29/0	0/29	0/464	0/464	0/464
opt	12/0	0/12	0/90	0/90	0/90
psr	12/157	0/48	0/231	0/231	0/231
dep	2/3	0/4	0/7	0/7	0/7
driv	0/71	0/10	0/54	0/54	0/50
zeno	0/44	0/9	0/24	0/24	0/24
free	0/12	0/3	0/8	0/8	0/8
log	0/51	0/10	0/33	0/33	0/33
block	0/33	0/9	0/12	0/12	0/12
mpr	0/0	0/4	0/4	0/4	1/3
myst	0/0	0/2	0/2	0/2	0/2
path	7/0	0/7	0/21	0/21	0/21
stor	0/30	0/9	0/10	0/10	0/10
TPP	5/14	0/9	0/27	0/27	0/27
truck	3/0	0/3	0/3	0/3	0/3
Total	70/448	0/193	0/1034	0/1034	1/1028

Table: Results on domains coming from IPCs. x/y stands for x time outs or segmentation faults, y soft goals satisfied.

Experimental analysis: 2. and 4.

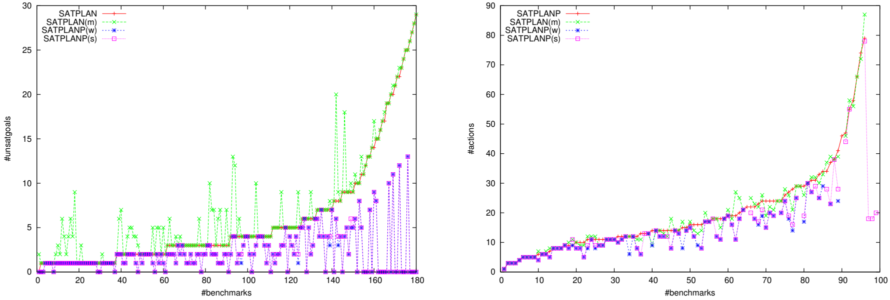
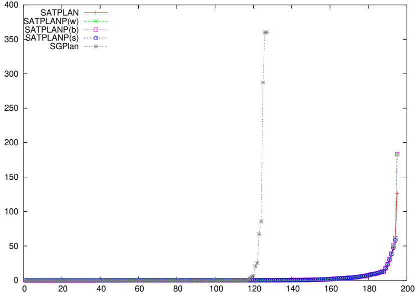


Figure: Left: Number of unsatisfied soft goals by SATPLAN, SATPLAN(m), and SATPLANP(w)/(s). Right: Number of actions in the returned plan for SATPLAN, SATPLAN(m), and SATPLANP(w)/(s).

Experimental analysis: 3. and 4.



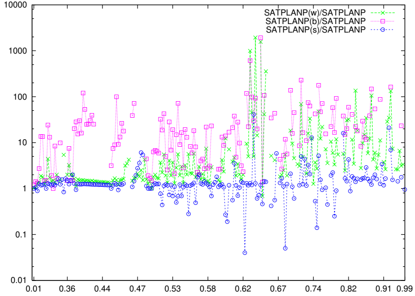


Figure: Left: Performances of SGPLAN, SATPLANP/(w)/(b)/(s). Right: Performances of SATPLANP(w)/(b)/(s) w.r.t. SATPLAN as a function of the ration between the number of preferences and the number of variables.

Further experiments

	#actions					Makespan	
PB	SATPLAN	SATPLAN(m)	SATPLANP(w)	SATPLANP(s)	SGPLAN	SATPLANP	SGPLAN
log6-0	33	30	25	25	26	9	26
log6-1	28	21	14	16	15	9	15
log6-9	41	39	24	28	28	11	28
block6-0	12	12	12	12	12	12	12
block6-1	10	10	10	10	16	10	16
block6-2	20	20	–	20	32	20	32
stor9	14	14	12	12	11	7	11
stor11	–	–	–	18	17	11	17
stor12	22	25	–	20	17	9	17
sat1	9	9	9	9	9	8	9
sat2	13	–	–	13	13	12	13
psr33	21	21	21	21	21	16	21
psr40	20	20	20	–	20	15	20
psr42	30	30	30	30	30	16	30
driv1	14	18	8	8	7	6	7
zeno5	15	14	14	14	11	5	11
zeno6	14	13	12	12	13	5	13
zeno8	16	17	15	15	12	5	12
free1	9	11	9	11	10	5	10
free2	18	18	–	18	14	8	14
free3	21	21	21	21	19	7	19
air7	41	41	41	41	41	21	41
air9	71	71	–	71	73	27	73
air12	39	39	39	39	39	21	39

Table: #actions and makespan for SATPLAN, SATPLANP and SGPLAN.

Conclusions and future work

Done . . . We have

- √ extended SAT-based planning to deal with (other) issues related to plan quality;
- √ showed that our approach is viable and competitive, often without sacrificing efficiency;
- √ evaluated different minimalities and *adder*()s

To be done . . .

- × relaxe the optimality in the makespan for further improve the plan quality;
- × experiment with other encodings, other than the "action-based".

More on this work . . .

- SATPLANP's web page at
  `http://www.star.dist.unige.it/~marco/SATPLANP/`
- Our ECAI 2006 and AAAI 2007 papers:
  - "Solving Optimization Problems with DLL"; and
  - "Planning as Satisfiability with Preferences"
- Enrico's invited talk at ICAPS'06