Plan Merging in Asprilo's m-Domain

Leo Pinetzki Jarek Liesen

University of Potsdam

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What is *asprilo*?

- Framework for intra-logistics & warehouse automation based on Answer Set Programming (ASP)
- Consists of
  - domain specifications (a, b, c and m)
  - plan checker
  - instance generator
  - visualizer
- Goal: Allow for generation of plans, that account for robot movement and fulfillment of orders

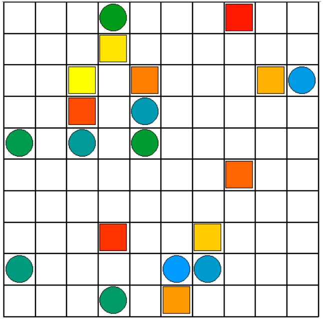

Figure: an asprilo warehouse in its visualizer

asprilo's m-Domain

- The simplest domain, “movement only”

square
: A robot

circle
: A destination for any robot

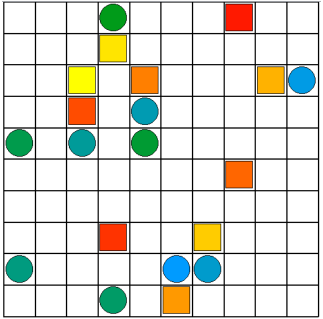

Figure: an asprilo instance of the m-domain

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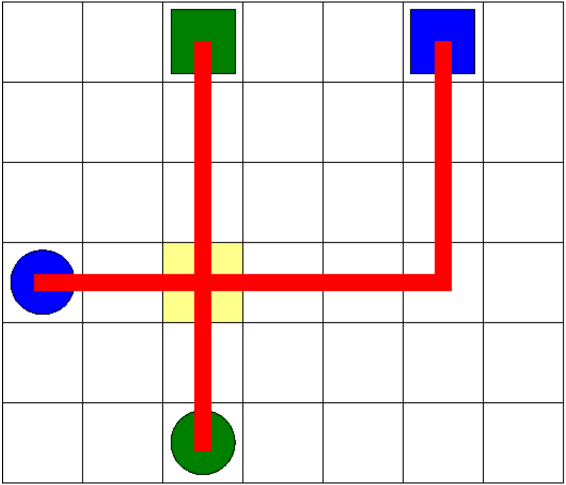
What is Plan Merging?

Unlike global planning, distributed planning needs plan merging



What is Plan Merging?

Unlike global planning, distributed planning needs plan merging

Advantages of plan merging are:

- Reduced complexity and computation time
- Avoiding re-planning when adding plans
- Plans can be computed in parallel

Important considerations are:

- Conflicts between single plans, such as robot collisions
- Plan has to stay valid
- Optimization of merged plan

Our Approach for Plan Merging

Standard, global approach:

1. **Centralized Plan generation**
   . . . for all robots by allowing arbitrary movements and forbidding collisions and unfulfilled orders

Our distributed approach:

1. **Target assignment**
   . . . optimizing for the smallest single distance between robot and shelf
2. **Plan generation**
   . . . without collision constraints
3. **Plan merging**

Target Assignment

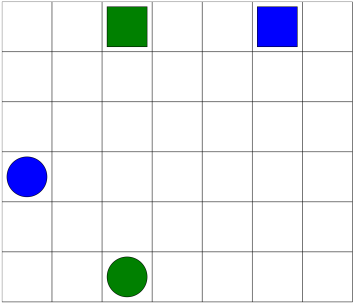
```
{ assigned(R,S) : isShelf(S) } = 1 :- isRobot(R).

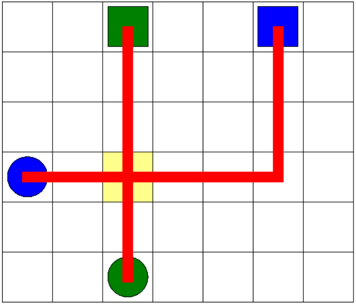
distance(R,S,D) :- position(R,(RX,RY),0),
                   position(S,(SX,SY),0),
                   assigned(R,S),
                   D = |RX - SX| + |RY - SY|.

#minimize { D : distance(R,S,D) }.
```

`assigned(R,S)` : robot `R` is assigned to shelf `S`

- Standard m-encoding but without collision constrains
  - assignes each robot a destination
  - plans moves without avoiding collisions
- Parallel independent planning for all robots at once





`planmov(R,D,T)` : robot `R` plans to take step in direction `D` at time step `t`

`planpos(R,C,T)` : robot `R` plans to be at cell `C` at time step `T`

Plan Merging

- We generally allow for arbitrary movement, but forbid certain moves using different strategies
- Strategies add constraints based on the plans
- Strategies can be freely combined to further reduce the search space

atoms after mergin of all plans:

`move(R,D,T)` : robot `R` takes step in direction `D` at time step `t`

`position(R,C,T)` : robot `R` is at cell `C` at time step `T`

Plan Merging: *basefile.lp*

- Merge baseline, and included in every merge call
- Contains move generation and position calculation
- Avoids moves that would lead to crashing of robots
- Generates itself a valid plan

```
{ move(R,D,T) : direction(D) } 1 :- isRobot(R),
        time(T).
:- error(_).

...
```

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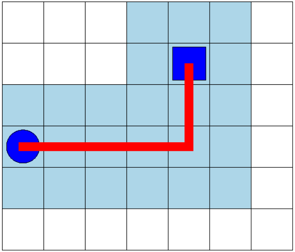
Corridor

```
1  surrounds((-s..s,-s..s)).
2  possible(R,(X+DX,Y+DY)):-
       planpos(R,(X,Y),_),
       surrounds((DX,DY)).
3  :- isRobot(R), position(R,C,_),
       not possible(R,C).
```



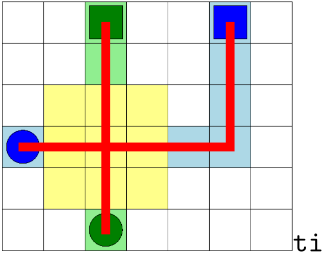
s = 1

time(0)

Idea: Allow each robot only to move to squares close to its planned trajectory

Bottleneck

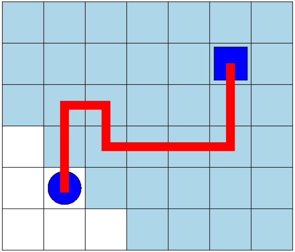
```
1  possible(R,C) :- planpos(R,C,_).
2  possible(R1,(X+DX,Y+DY)) :-
       planpos(R1,(X,Y),_),
       planpos(R2,(X,Y),_),
       R2 != R1, surrounds((DX,DY)).
3  :- isRobot(R), position(R,C,_),
       not possiblePosB(R,C).
```



Idea: Constraint moves even further than corridor, by only allowing to deviate from the plan at conflict cells

Deathlaser

```
1  :- position(R,(X1,Y1),T),
       planpos(R,(X2,Y2),T),
       assigned(R,S),
       position(S,(SX,SY),0),
      D1 = |SX-X1| + |SY-Y1|,
      D2 = |SX-X2| + |SY-Y2|,
      D1 > D2.
```



time(0)

Idea: Disallow robot to fall behind its plan in terms of distance to its goal

Deathlaser

```
1  :- position(R,(X1,Y1),T),
       planpos(R,(X2,Y2),T),
       assigned(R,S),
       position(S,(SX,SY),0),
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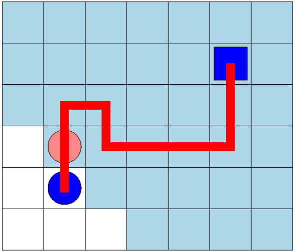

time(1)

Idea: Disallow robot to fall behind its plan in terms of distance to its goal

Deathlaser

```
1 :- position(R,(X1,Y1),T),
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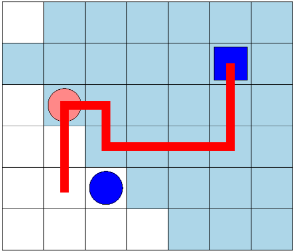
```



time(2)

Idea: Disallow robot to fall behind its plan in terms of distance to its goal

Deathlaser

```
1  :- position(R,(X1,Y1),T),
       planpos(R,(X2,Y2),T),
       assigned(R,S),
       position(S,(SX,SY),0),
       D1 = |SX-X1| + |SY-Y1|,
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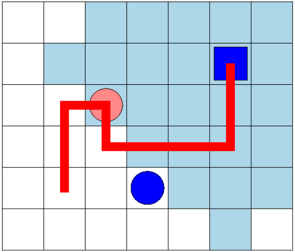

time(3)

Idea: Disallow robot to fall behind its plan in terms of distance to its goal

Deathlaser

```
:- position(R,(X1,Y1),T),
    planpos(R,(X2,Y2),T),
    assigned(R,S),
    position(S,(SX,SY),0),
    D1 = |SX-X1| + |SY-Y1|,
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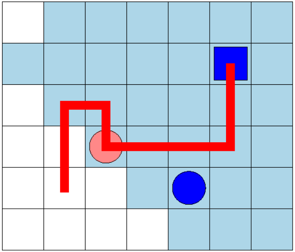
    D1 > D2.
```

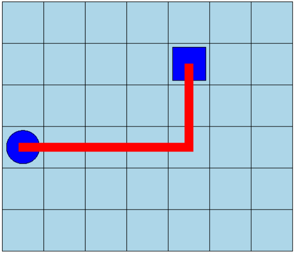


time(4)

Idea: Disallow robot to fall behind its plan in terms of distance to its goal

Homesick

```
1  homesick(T) :- time(T),
       T \ interval = 0.
2  :- homesick(T), isRobot(R),
        position(R,C,T),
        not planpos(R,C,_).
```



`interval = 3`
`time(0)`

Idea: Make robots converge to their original trajectory every few moves

Homesick

```
1 homesick(T) :- time(T),
      T \ interval = 0.
2 :- homesick(T), isRobot(R),
      position(R,C,T),
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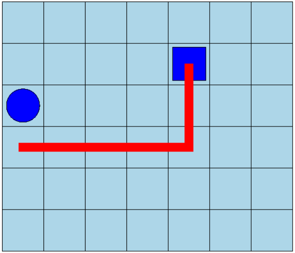
```



```
interval = 3
time(1)
```

Idea: Make robots converge to their original trajectory every few moves

Homesick

```
homesick(T) :- time(T),
    T \ interval = 0.
:- homesick(T), isRobot(R),
     position(R,C,T),
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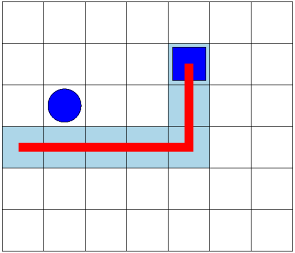
```



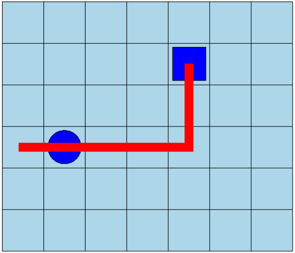
`interval = 3`

`time(2)`

Idea: Make robots converge to their original trajectory every few moves

Homesick

```
homesick(T) :- time(T),
    T \ interval = 0.
:- homesick(T), isRobot(R),
     position(R,C,T),
     not planpos(R,C,_).
```



`interval = 3`

`time(3)`

Idea: Make robots converge to their original trajectory every few moves

Homesick

```
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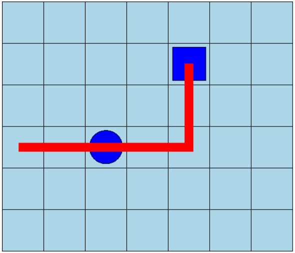
```

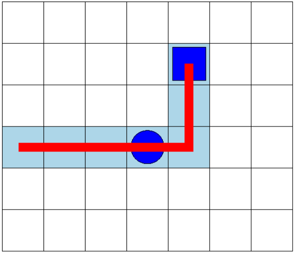


interval = 3
time(4)

Idea: Make robots converge to their original trajectory every few moves

Homesick

```
1  homesick(T) :- time(T),
       T \ interval = 0.
2  :- homesick(T), isRobot(R),
       position(R,C,T),
       not planpos(R,C,_).
```

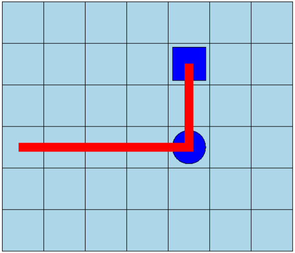


`interval = 3`
`time(5)`

Idea: Make robots converge to their original trajectory every few moves

Homesick

```
homesick(T) :- time(T),
     T \ interval = 0.
:- homesick(T), isRobot(R),
     position(R,C,T),
     not planpos(R,C,_).
```



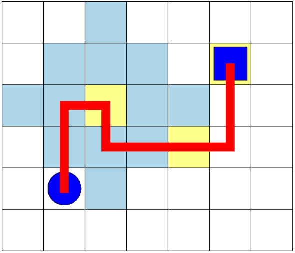
interval = 3

time(6)

Idea: Make robots converge to their original trajectory every few moves

Checkpoints

```
1 :- checkpoint(R,CP,C),
       position(R,CP,T),
       not reached(R,CP,T),
       T = CP*step.
2 :- goalpoint(R,CP,C),
       reached(R,CP,T1),
       move(R,D,T2), T1 > T2.
```



```
interval = 3
time(0)
```

Idea: Force robots to visit their planned cell every few moves

Checkpoints

```
1 :- checkpoint(R,CP,C),
     position(R,CP,T),
     not reached(R,CP,T),
     T = CP*step.
2 :- goalpoint(R,CP,C),
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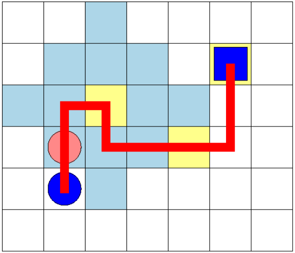
```

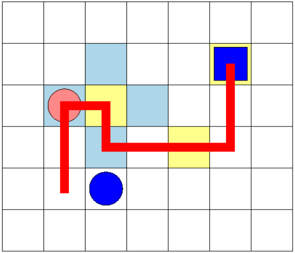


interval = 3
time(1)

Idea: Force robots to visit their planned cell every few moves

Checkpoints

```
1 :- checkpoint(R,CP,C),
      position(R,CP,T),
      not reached(R,CP,T),
      T = CP*step.
2 :- goalpoint(R,CP,C),
      reached(R,CP,T1),
      move(R,D,T2), T1 > T2.
```

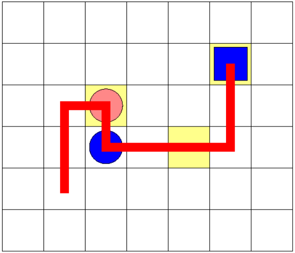


`interval = 3`
`time(2)`

Idea: Force robots to visit their planned cell every few moves

Checkpoints

```
1 :- checkpoint(R,CP,C),
      position(R,CP,T),
      not reached(R,CP,T),
      T = CP*step.
2 :- goalpoint(R,CP,C),
      reached(R,CP,T1),
      move(R,D,T2), T1 > T2.
```



interval = 3

time(3)

Idea: Force robots to visit their planned cell every few moves

Checkpoints

```
1  :- checkpoint(R,CP,C),
      position(R,CP,T),
      not reached(R,CP,T),
      T = CP*step.
2  :- goalpoint(R,CP,C),
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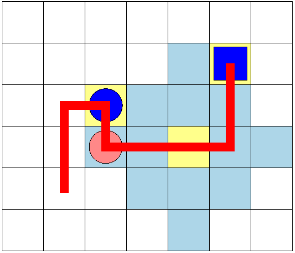


```
interval = 3
time(4)
```

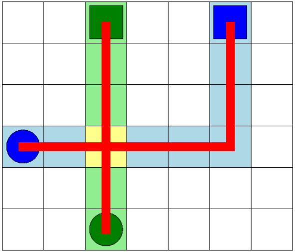
Idea: Force robots to visit their planned cell every few moves

Crossroad

```
1  :- not orderedPlan(R,_,O,D),
      orderedMoves(R,_,O,D).

2  :- not orderedMoves(R,_,O,D),
      orderedPlan(R,_,O,D).

3  :- orderedPlan(R,T,O,_),
      orderedMoves(R,T',O,_),
      |T - T'| > maximumOffset.
```



`time(0)`

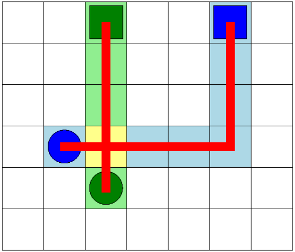
Idea: Allow to change the timeing of moves but keep their order

Crossroad

```
1  :- not orderedPlan(R,_,O,D),
      orderedMoves(R,_,O,D).

2  :- not orderedMoves(R,_,O,D),
      orderedPlan(R,_,O,D).

3  :- orderedPlan(R,T,O,_),
      orderedMoves(R,T',O,_),
      |T - T'| > maximumOffset.
```



time(1)

Idea: Allow to change the timeing of moves but keep their order

Crossroad

```
1  :- not orderedPlan(R,_,O,D),
      orderedMoves(R,_,O,D).

2  :- not orderedMoves(R,_,O,D),
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3  :- orderedPlan(R,T,O,_),
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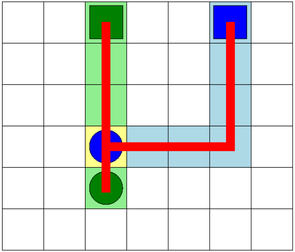
```



time(2)

Idea: Allow to change the timeing of moves but keep their order

Crossroad

```
1  :- not orderedPlan(R,_,O,D),
      orderedMoves(R,_,O,D).

2  :- not orderedMoves(R,_,O,D),
      orderedPlan(R,_,O,D).

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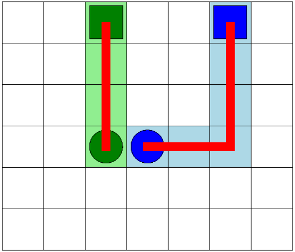
      orderedMoves(R,T',O,_),
      |T - T'| > maximumOffset.
```



time(3)

Idea: Allow to change the timeing of moves but keep their order

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Benchmark Setup

- Executed on V-Server with the following specs:
  - 16 VCores Intel Xenon E5-2680-v3
  - 32GB RAM
  - Debian 18.04.4 LTS
  - Python 3.7.7
  - clingo 5.4.0
- Additional strategy "replan" was benchmarked:
  complete replanning after target assignment and plan generation
  $\rightarrow$ Baseline for other strategies
  Only basefile.lp without any strategy

Benchmark Instances

- Three types of quadratic instances according to asprilo's m-domain specifications:

Sparse	10% of edge length as robots
Normal	100% of edge length as robots
Cluttered	10% of number of cells as robots

- 10 instances each for edge lengths of 10, 20, 30, . . . , 100
- For cluttered edge lengths of over 50 were infeasible to ground, so we have generated additional instances between 30 and 50

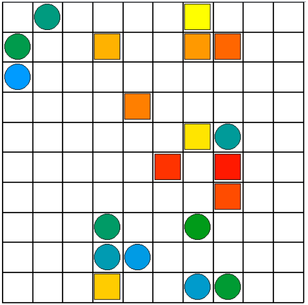


Figure: cluttered 10x10

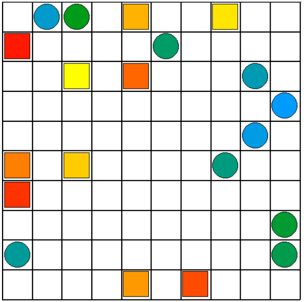


Figure: normal 10x10

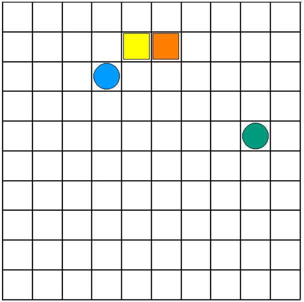


Figure: sparse 10x10

Hypothesis on Single Strategies

Corridor	Bottleneck	Checkpoints
$\sim$ ok performance	$+$ better than Corridor	$\sim$ ok performance

Homesick	Deathlaser	Crossroad
$+$ very good performance	$+$ very good performance	$-$ bad performance

Configuration Clingo 5.4.0 + baseline.lp + Strategy

Hypothesis on Strategy Combinations

	Corridor	Bottleneck	Checkp.	Homesick	Deathlaser
Bottleneck	$-$ Corridor redundant				
Checkp.	$+$	$-$ Checkpoints redundant			
Homesick	$\sim$	$-$ Homesick redundant	$\sim$ Highly depends on hyper-parameters		
Deathlaser	$+$	$+$	$-$ Deathlaser redundant	$+$ $=$ Checkpoints	
Crossroad	$-$ no benefit	$-$ no benefit	$-$ no benefit	$-$ no benefit	$+$

Configuration Clingo 5.4.0 + baseline.lp + Strategies

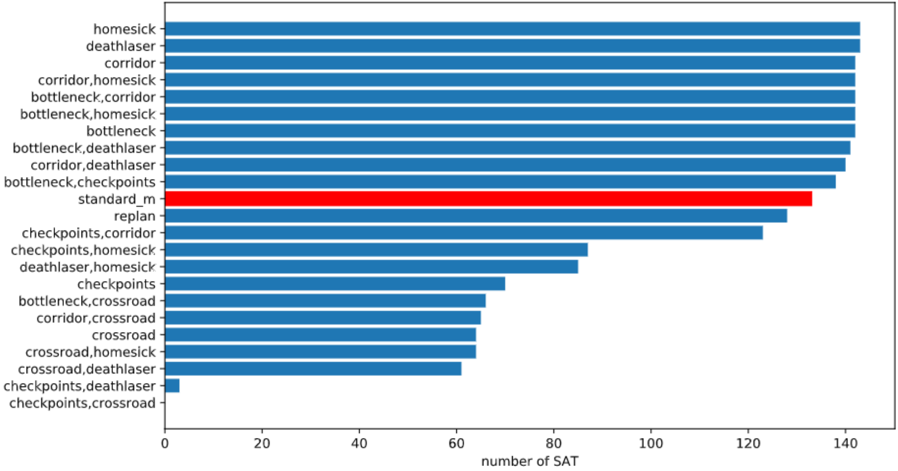
General Benchmark Results

- Total time determined by grounding time of merge step
- Combining strategies did not improve the performance
- Strategies performed very differently on different instance types
- Solving time of the merge is strongly correlated with number of rules and choice rules

General Benchmark Results

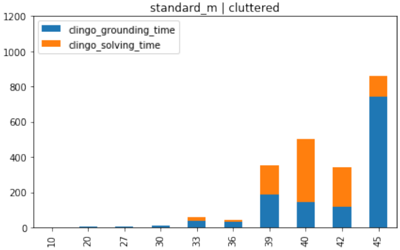
- Checkpoints strategy almost always timed out, combinations with checkpoints performed very poorly
- Combination of checkpoints and crossroad solved no instances
- Crossroad is the worst non-combined strategy
- Standard m-encoding performed the best on cluttered instances

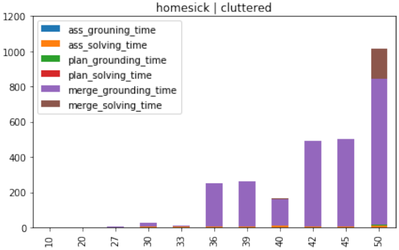
Benchmark Results



timeout 20min

Comparison with Standard m-Encoding





- Best performance on cluttered instances
- By far the lowest grounding times of all strategies on cluttered, comparable on other types
- Generally a much higher solving time than well-performing strategies

Comparison with Hypothesis

Corridor	Bottleneck	Checkpoints
+ good performance	+ worse than Corridor	— bad performance

Homesick	Deathlaser	Crossroad
+ best performance	+ second best performance	— worst performance

Comparison with Hypothesis

	Corridor	Bottleneck	Checkp.	Homesick	Deathlaser
Bottleneck	+ good for normal and sparse				
Checkp.	— limited by implementation of checkpoints	— worse than Bottleneck on ist own			
Homesick	∼ works well on normal and sparse	∼ works well on normal and sparse	∼ performed well on sparse		
Deathlaser	+ good on cluttered	+ very good for normal and cluttered	—	—	
Crossroad	—	—	—	—	—

Brief comparrison of stats

Grouding related stats (means):

strategies	grounding time	merge constraints	merge variables
homesick	124	42301.9	225590.7
standard-m	125	1353323	6227959

Solving related stats (means):

strategies	solving time	merge conflicts
homesick	3.226768	148.2
standard-m	29	559.2105

We have much more detailed information. If one is interested we can show them afterwards!

Conclusion

- Combining strategies is not worth
- No strategy performed well on all instance types
- Using normalized scores, homesick and bottleneck alone performed the best, checkpoints and its combinations performed the worst
- The m-encoding performed surprisingly well due to small grounding times
- Our hypothesis focused on the performance of solving rather then grounding

Future Work

- Optimization of grounding in merge step!
- Implementation of more strategies that ground faster
- Optimization of hyperparameters