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Heuristic Planning for Hybrid Systems*

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Abstract

Planning in hybrid systems has been gaining research interest in the Artificial Intelligence community in recent years. Hybrid systems allow for a more accurate representation of real world problems, though solving them is very challenging due to complex system dynamics and a large model feature set. We developed DiNo, a new planner designed to tackle problems set in hybrid domains. DiNo is based on the discretise and validate approach and uses the novel Staged Relaxed Planning Graph+ (SRPG+) heuristic.

Introduction

Over the years, Automated Planning research has been continuously attempting to solve the most advanced and complex planning problems. The standard modelling language, PDDL ((McDermott et al. 1998)), has been evolving to accommodate new concepts and operations, enabling research to tackle problems more accurately representing real-world scenarios. A recent version of the language, PDDL+ ((Fox and Long 2006)), enabled the most accurate standardised way yet, of defining hybrid problems as planning domains.

Planning in hybrid domains (also known as hybrid systems) is currently one of the fastest growing and most interesting subfields of Automated Planning. Hybrid domains are models of systems which exhibit both continuous and discrete behaviour. They are amongst the most advanced models of systems and the resulting problems are notoriously difficult for planners to cope with due to non-linear behaviours and immense search spaces. Indeed, planning in hybrid domains is challenging because apart from the state explosion caused by discrete state variables, the continuous variables cause the reachability problem to become undecidable.

We introduce DiNo, a new planner designed to solve problems set in hybrid domains. DiNo uses the planning-as-model-checking paradigm ((Bogomolov et al. 2014)) and relies on the Discretise & Validate approach ((Della Penna, Magazzeni, and Mercorio 2012)). The Discretise & Validate approach works by approximating the continuous dynamics of the system and handling the resulting discretised model with uniform time steps and step functions. Discretised model and a finite-time horizon ensures a finite number of states in the search for a solution. Solutions to the discretised problem are validated against the original continuous model using VAL ((Howey, Long, and Fox 2004)). If the plan at a certain discretisation is not valid, the discretisation can be refined and the process iterates.

DiNo, based on UPMurphi, extends its capabilities by using a novel relaxation-based domain-independent heuristic, Staged Relaxed Planning Graph+ (SRPG+). The heuristic guides the Enforced Hill-Climbing algorithm ((Nebel 2001)). In DiNo we also exploit the deferred heuristic evaluation ((Richter and Westphal 2010)) for completeness (in a discretised search space with a finite horizon). The SPRG+ heuristic improves on the Temporal Relaxed Planning Graph and extends its functionality to include information gained from PDDL+ features, namely the processes and events.

DiNo is currently the only heuristic planner capable of handling non-linear system dynamics combined with the full PDDL+ feature set.

Related Work

Various techniques and tools have been developed to deal with hybrid domains. More recent approaches in this direction have been proposed by ((Bogomolov et al. 2014)), where the close relationship between hybrid planning domains and hybrid automata is explored, and ((Bryce et al. 2015)) where PDDL+ models are handled using SMT.

Nevertheless, none of these approaches are able to handle the full set of PDDL+ features, namely non-linear domains with processes and events. To date, the only viable approach in this direction is PDDL+ planning via *discretisation*. UPMurphi ((Della Penna, Magazzeni, and Mercorio 2012)), which implements the discretise and validate approach, is able to deal with the full range of PDDL+ features. The main drawback of UPMurphi is the lack of heuristics, and this strongly limits its scalability. However, UPMurphi was successfully used in the multiple-battery management domain ((Fox, Long, and Magazzeni 2012)), where a domain-*specific* heuristic was used.

Staged Relaxed Planning Graph+

The Staged Relaxed Planning Graph+ is designed for hybrid domains with continuous change and PDDL+ features. The

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DOMAIN	PLANNER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
LINEAR GENERATOR	DiNo	0.34	0.40	0.50	0.60	0.74	0.88	1.00	1.16	1.38	2.00	1.84	2.06	2.32	2.46	2.88	2.94	3.42	3.54	3.76	4.26
	UPMurphi	140.50	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
NON-LINEAR GENERATOR	DiNo	3.62	0.78	2.86	59.62	1051.84	X	X	X	X	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	UPMurphi	X	X	X	X	X	X	X	X	X	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LINEAR SOLAR ROVER	DiNo	0.70	0.92	1.26	1.52	1.80	2.04	2.28	2.64	2.98	3.30	3.50	3.74	4.00	4.38	5.20	5.40	5.08	5.64	6.12	6.02
	UPMurphi	203.26	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
NON-LINEAR SOLAR ROVER	DiNo	1.10	2.58	4.74	7.10	9.58	12.86	16.48	21.38	26.74	29.90	35.96	42.54	48.06	55.46	62.84	74.50	86.96	95.66	102.86	117.48
	UPMurphi	288.94	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
POWERED DESCENT	DiNo	0.68	1.04	1.88	3.52	2.88	3.14	5.26	3.82	1.58	2.26	11.24	42.24	14.90	61.94	19.86	80.28	2.94	2234.88	X	X
	UPMurphi	0.18	0.74	2.98	7.18	30.08	126.08	322.16	879.52	974.60	X	X	X	X	X	X	X	X	X	X	X

Table 1: Results for DiNo and UPMurphi (time in seconds) for each problem in our test domains (”X” - planner ran out of memory, ”N/A” - problem not tested)

SRPG+ is closely based on the successful and well-known Temporal Relaxed Planning Graph (TRPG) ((Coles et al. 2012)). In the TRPG, the original problem is relaxed and does not account for the delete effects of actions on propositional facts. Numeric variables are represented as upper and lower bounds which are the theoretical highest and lowest values each variable can take at the given fact layer. Each layer is time-stamped to keep track of the time at which it occurs.

The Staged Relaxed Planning Graph+ follows the TRPG relaxation but significantly differs in handling time as well as processes and events. There are 3 key elements to the SRPG+ heuristic which make it unique:

Time Staging The Staged Relaxed Planning Graph is built with all successive fact layers separated by the discretised time step, Δt. This differs from the Temporal RPG where fact layers exist only at the earliest time of occurrence of happenings.

Time Passing DiNo depends on an additional action to advance time (tp) in the search. tp is crucial to discretised search as it is used to handle continuous change (i.e. actions' continuous effects, processes and events are applied through tp). We decided to exploit this approach to extract useful information and increase the performance of the planner.

The time-passing action can be helpful (prioritised), if its effects help in achieving the goal. However, we found that designating tp as helpful in the absence of any other helpful actions at a given state, can yield improved performance of our heuristic and propagate the search forward more quickly.

Processes and Events The Staged Relaxed Planning Graph+ is the first heuristic which explicitly reasons with processes and events. This results in the evolution of the system in the SRPG more closely resembling the concrete system, and thus the SRPG+ yields a more accurate heuristic estimate.

Evaluation

We evaluated the performance of DiNo on PDDL+ benchmark domains. Note that the only planner able to deal with the same class of problems as DiNo, is UPMurphi. This comparison is useful for our evaluation as it highlights the benefits of the Staged Relaxed Planning Graph+. Table 1 summarises the times taken by DiNo and UPMurphi to solve problems in our test suite. Note that for all domains we used the same time discretisation $\Delta t = 1.0$, except non-linear generator where it had to be refined to $\Delta t = 0.5$ for problems with 3, 4 and 5 tanks.

Conclusion

We have presented DiNo, the first heuristic planner capable of reasoning with the full PDDL+ feature set and complex non-linear systems. DiNo is based on the Discretise & Validate approach, and uses the novel SRPG+ domain-independent heuristic introduced in this paper. We have empirically proved DiNo's superiority over its competitors for problems set in hybrid domains. Enriching discretisation-based planning with an efficient heuristic, that takes processes and events into account, is an important step in PDDL+ planning. Future research will expand DiNo's capabilities to deal with larger problem instances and infer more information from processes and events.

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