On the Use of Width-Based Search for Multi Agent Privacy-Preserving Planning (Extended Abstract)*

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Abstract

The aim of decentralised multi-agent (DMA) planning is to coordinate a set of agents to jointly achieve a goal while preserving their privacy. Blind search algorithms, such as width-based search, have recently proved to be very effective in the context of centralised automated planning, especially when combined with goal-oriented techniques. In this paper, we discuss a recent line of research in which the usage of width-based search has been extensively studied in the context of DMA planning, addressing the challenges related to the agents' privacy and performance.

Introduction

Decentralised multi-agent (DMA) planning deals with the problem of coordinating multiple agents to jointly achieve a goal. In this context, the knowledge of the model is distributed among the agents who are characterised by a private and a public component. During the synthesis of a plan, agents do not want to exchange information regarding their private part, thus making the DMA planning a challenging problem. Many approaches in the literature differ in how they handle privacy issues.

Recent work in classical planning has shown that width-based search algorithms can solve planning problem instances of many existing domains in low polynomial time when they feature atomic goals. Width-based search relies on the notion of *novelty*. The novelty of a state s has been originally defined as the size of the smallest tuple of facts that hold in s for the first time in the search, considering all previously generated states (Lipovetzky and Geffner 2012).

Research efforts have recently been invested in investigating how width-based techniques can be successfully employed in the context of multi-agent planning. Some underlying challenges of the multi-agent setting prevent a straightforward adaptation of the aforementioned techniques in this context. For example, the effectiveness of the width-based search for DMA planning can be negatively affected by the guarantee that privacy is preserved.

*The extended abstract reports on the work previously appeared in the papers (Bazzotti et al. 2018; Gerevini et al. 2019b,a).

To preserve privacy, the private knowledge shared among agents can be encrypted: an agent α_i shares with the other agents a description of each reached search state in which all the private facts of α_i that are true are substituted with a single string obtained by encrypting all the private fact names of α_i. This encryption has an impact on the measure of novelty, and hence for DMA planning, it can also affect the effectiveness of the width-based search algorithms.

In this paper, we summarise how these problems have been tackled in some previous work (Bazzotti et al. 2018; Gerevini et al. 2019a,b).

Width-Based Search for DMA Planning

The first algorithms we consider for DMA planning are Iterative Width search (IW) and Serialized Iterative Width search (SIW) (Lipovetzky and Geffner 2012). Essentially, IW consists of a sequence of breadth-first search episodes (BFS) with an increasing integer value k for which all states with novelty greater than k are pruned. The success of this simple pruning technique derives from the fact that usually any action in optimal plans achieves a tuple of at least k facts that were not true in any preceding state on the solution path (Lipovetzky and Geffner 2012). SIW is a variant of IW that restarts the Iterative Width search from each reached state which satisfies at least one atomic goal that had not previously been achieved. SIW proved to be more effective for planning problems featuring multiple-goal propositions and, being a blind search scheme, is more suitable to preserving the privacy of agents w.r.t. other approaches to multi-agent planning that exchange heuristic information between agents.

Bazzotti et al. (2018) propose a search procedure, MA-SIW which is a variant of SIW for DMA planning. The generalisation of SIW to the multi-agents context may arise some synchronisation problems. This could happen because different agents are aware of different sets of actions. Then, at a given time, the search tree depth reached by the agents' BFS episode can differ quite a bit from the depth reached by the BFS episode of another agent. In MA-SIW when an agent α_i reaches a state achieving a new problem goal, all the agents should restart a new IW search from that state, but accidentally a state s generated by α_i after the restart may arrive to another agent α_j before that agent restarts its own

IW search. In such a case, when α_j restarts its IW search, to synchronise itself, with α_i, state s will be discarded and will not be visited by α_j's restarted search.

The combination of goal-oriented search and pure exploration methods, like IW and SIW, yields a family of search procedures, called best-first width search (BFWS). This approach exploit an evaluation function $f = \langle h, w \rangle$ where h is the heuristic function and w the novelty measure function. In this setting, the nodes to be expanded primarily are those with lower h and, in the case of ties, those that are the most novel (i.e., having the smallest novelty measure w). For this purpose, it was necessary to define and compute the novelty in a slightly different fashion, taking multiple heuristics functions, into account (Lipovetzky and Geffner 2017).

Gerevini et al. (2019b) propose a new search procedure, namely MA-BFWS, which leverages width-based exploration in the form of novelty-based preferences to provide a complement to goal-directed heuristic search. The authors explore different sequences of arbitrary estimates, both novelty-based and heuristic-based, to break ties.

In the multi-agent setting, the agents' coordination is achieved through the exchange of messages in which the private facts are encrypted. This exchange could expose the system to malicious behaviour, e.g., an external and hostile agent can gather these messages to infer information about actions and search states. Gerevini et al. (2019a) study how to exploit the notion of novelty in order to reduce the amount of exchanged messages, evaluating its effect within MA-BFWS. Essentially, each agent retains, i.e., does not share to other agents, the search states whose *outgoing novelty*, exceeds a given threshold. Such a novelty is computed by considering the public part of search states which have been previously transmitted to other agents. The benefit of such a technique is twofold, on the one hand, it strengthens the privacy of MA-BFWS, by exposing less information, and at the same time, it speeds up the search since fewer messages are exchanged.

Experimental Results

In this section, we present a selection of the experimental results which were provided by the width-based search. We compare the MA-SIW and MA-BFWS performance against two existing approaches, namely PSM (Tožička, Štolba, and Komenda 2017) and the best configuration of MAPLAN (Fišer, Štolba, and Komenda 2015). As benchmarks, we used the same suite used in (Gerevini et al. 2019b).

Since the behaviour of MA-SIW and MA-BFWS depends on how the exchanged messages between agents are scheduled over time, we performed 5 runs by considering an instance solved if for at least 3 out of 5 runs it has been solved by the considered approach. Given a DMA planning problem, for each agent in the problem, we limited the usage of the available resources to 3 CPU cores and 8 GB of RAM.

Table 1 summarised the results we got in terms of coverage over the different tested approaches. Results show that overall MA-BFWS outperforms MA-SIW and performs better than MAPLAN and PSM. Remarkably, our approaches share only information about the search states, while MAPLAN also requires sharing the information for the computation of the search heuristics. In this sense, as well as solving a wider range of problems, MA-BFWS exposes less private knowledge to other agents.

Domain	MA-BFWS	MA-SIW	MAPLAN	PSM
Blocksworld	**20**	**20**	**20**	**20**
Depot	17	8	12	17
DriverLog	**20**	**20**	16	**20**
Elevators	**20**	**20**	8	12
Logistics	**20**	18	18	18
Rovers	**20**	**20**	**20**	19
Satellites	**20**	**20**	**20**	13
Sokoban	13	4	**17**	16
Taxi	**20**	**20**	**20**	**20**
Wireless	2	0	**4**	0
Woodworking	12	1	15	**18**
Zenotravel	**20**	**20**	**20**	10
Overall (240)	**204**	171	190	184

Table 1: Number of problems solved by MA-BFWS, MA-SIW, MAPLAN and PSM for the considered benchmark.

Conclusions

In this paper, we explored how the width-based search, originally designed for addressing centralised planning problems, can be successfully exploited in a multi-agent setting. In such a setting preserving the privacy of agents is a crucial issue. MA-SIW addresses the synchronisation issues that may arise when SIW is adapted to the multi-agent setting and, since it does not exchange heuristic information during the search, provides a privacy stronger than the other existing heuristic-based approaches. MA-BFWS incorporates the width-based techniques under the form of novelty-based preferences which provide an effective complement to goal-directed search. To preserve privacy, the public projection of actions is not shared, negatively impacting the informativeness of the heuristics. Despite this, the integration between poorly informed heuristics and novelty measures, also damaged by the privacy preservation, yields an effective search scheme for the multi-agent setting.

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