Multi-agent Planing Based on Causal Graph

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Abstract. Multi-agent planning is a kind of difficult but not fully studied planning problem. In the cooperative assumption, previous approaches either find a globally consistent plan by the backtrack-based solution, or make the local plans first, and then merge them. However, local planning between agents is inconsistent and conflicting in most case, in this case finding a globally consistent plan is time-consuming and costly. In this paper, we propose a novel approach to get causal-links graph from causal constraints between agents in solving multi-agent planning problems to reduce the effort of repeatedly searching agents' consistent local plans. Theoretical analysis show that our approach can efficiently solve multi-agent planning problems with tightly degree of coupling level.

1. Introduction
Multi-agent related problems are important in the intelligence planning, which draw more and more attention by domestic and foreign scholars recently. It has a wide range of application in different industrial areas, including factory assembly line [1], unmanned aerial vehicles [2], unmanned surface vessels [3], and autonomous underwater vehicles [4]. Further, in real life there are many examples of multi-agent collaboration to complete the task. Typically these examples have some common features, for example, each agent has a different ability to perform, and construct its local plans while preserving privacy. They plan independently, and need to interact with other agents to achieve the global goals. Therefore, how to effectively achieve the global goals for the multi-agent planning is that we must face and solve.

There have been many approaches designed to solve the multi-agent planning problems. For example, Jamroga use planning graph to handle the possible relationships between agents' individual goals [5]. Dimopoulos and Moraitis dealt with coordination and cooperation in the multiple agents planning [6]. Zhang combine graph planning with distributed constraint satisfaction techniques to solve the multi-agent replanning problems [7]. Other work focused on conducting iterative backward search [8], etc. More recently, Brafman and Domshlak proposed a novel notion of multi-agent Planning as CSP+Planning [9], which was later extended to a fully distributed multi-agent planning approach called Planning-First [10]. These work either did not realize the real distributed multi-agent planning, or rely on a shared information in the way of memory.

In this paper, we present a novel approach to solve the multi-agent planning problems, and Our basic idea is to get the causal-links for the multi-agent planning problem first, then allow agents to expand the goals iteratively during the backward planning search. Further we detect the ordering constraints of agents' partial plans, and exploit the structure graph to make plans efficiently. We also
allow agents to work under fully distributed setting where their private information is not shared by other agents.

2. Problem Formulation

The cooperative multi-agent systems is based on a formalization which is minimally extends STRIPS-style language model under the problem of deterministic domains and fully-observable information. In the following we briefly introduce the definitions and notation in multi-agent planning problem that we will rely on in the rest of this paper.

We consider planning for multi-agent system where agents must coordinate their efforts to the set of global goals. Specifically, we restrict our attention to multi-agent's STRIPS formalism which slightly extended to STRIPS representation of classical planning language. Intuitively multi-agent planning consists of several (≥ 2) agents, of which each local agent planning to work together to complete the specified global goals. Intuitively, multi-agent planning problem has more than one independent agent, which each of these agents must make local plan independently, coordinate their individual plans to achieve global goals under given their initial state and own actions. What is more, each agent can only plan in its own actions and local area.

In MA-STRIPS model, states of the world are described by limited proposition subset and action is defined as tuples $(p, a, e)$, where $p$ and $e$ denote the precondition and the effect( add and delete effect ) of the action, respectively. We say that there exists an action $a$ can be executed state $s$ iff $p(a) \subseteq s$. Formally, our multi-agent planning formalism is heavily based on MA-STRIPS model which were first introduced by [9] and the notations are as follows.

Definition 1 An MA-STRIPS problem $\mathcal{P}$ for a set of planning agents $\{\phi_i\}_{i=1}^l$ is given by a quadruple $\mathcal{P} = \langle \mathcal{F}, \{ \mathcal{A}_i \}_{i=1}^l, \mathcal{I}, \mathcal{G} \rangle$, where

- $\mathcal{F}$ is a finite set of propositions (or fluents), $\mathcal{I} \subseteq \mathcal{F}$ is the initial state of the world, and $\mathcal{G} \subseteq \mathcal{F}$ is the specification of the goal conditions,
- For $1 \leq i \leq l$, $\mathcal{A}_i$ is the finite set of actions available to agent $\phi_i$. Each action $a \in \mathcal{A}_i$ is given by the notation above that has the well known STRIPS syntax and semantics.

Note that MA-STRIPS model turns into STRIPS formalism exactly when $l = 1$ and the individual agent has private information which is not available to someone else. Before describing our characterization for multi-agent planning problem, we need to introduce a brief description of related definition such the notions of internal and public actions of agents. The dependencies between local planning for agents in a MA-STRIPS problem induce several key characteristics. First, assuming that we already have the multi-agent planning model definition, we can use the set of fluents $\mathcal{F}_i = \bigcup_{a \in \mathcal{A}_i} \mathcal{P}(a) \cup \mathcal{E}(a)$ to denote which part of fluents relate to agent $\phi_i$. Then, the above mentioned fluents can be further partitioned into the subsets $\mathcal{F}_i^\phi = \mathcal{F}_i \setminus \bigcup_{\phi_j \neq \phi_i} \mathcal{F}_j$ and $\mathcal{F}_i^e = \mathcal{F}_i \setminus \mathcal{F}_i^\phi$, which represent its internal fluents and public fluents, respectively. It induces directly from this notion of agent's internal fluents that agent $\phi_i$ actions $\mathcal{A}_i$ can be partitioned into $\mathcal{A}_i^\phi$ and $\mathcal{A}_i^e$ as its internal and public actions.

To better understand the MA-STRIPS model, we use a problem from the well-recognized logistics domain as a representative example, which is often used for multi-agent planning problem. The task is to transport a set of packages from their initial to their target location. A package can be moved from one location on the map to another location by the vehicles (truck or airplane). Each vehicle can move along a certain subset of roadmap segments in or between the cities. As shown in Figure 1, assume initially there are five agents in the roadmap, four trucks (agents) can transport packages through a roadmap in each city as well as that one airplane (agent) can do between two cities. The global goals
are to have the agents move package p1 from the initial location pgh-po to the destination location ny-po and package p2 from abc-po to def-po, respectively. Each vehicle can execute three different actions: load and unload a package in the vehicle and move between the roadmap in the city. There are two public actions (e.g., load (p1, pgh-truck, pgh-airport) and unload (p1, pgh-truck, pgh-airport)) in MA-STRIPS planning problem, these actions were seen as coordination points. There also has certain actions that are internal to an agent such as the action move (pgh-truck, pgh-po, pgh-airport) or fly (airplane1, pgh-airport, ny-airport).

Figure 1. An example of multi-agent planning problem.

3. The Proposed Method

As mentioned above, we divide the actions and propositions of the multi-agent planning problem into the two types of public and private. Coordination points are the public actions or propositions which are the key steps in collaboration between the agents to achieve the global goal. In general, the actions and the state of propositions are corresponding one by one in the planning graph. So we can get the state propositions based on the actions in the analysis of multi-agent planning (or vice versa). To facilitate the representation and analysis, we use the actions in the causal-links graph. As shown in Figure 2, there are five coordination points $\alpha_1, \alpha_2, \alpha_3$ and eleven internal points $\beta_1, \beta_2, \beta_3, \beta_4$ which in three agents' local plans. These coordination points are arranged in order of precedence $<\alpha_1, \alpha_2, \alpha_3>$ (e.g., execute $\alpha_1$ before $\alpha_2$). All the sub-plans compose a solution $<\gamma_1, \gamma_2, \gamma_3>$ to the problem of multi-agent planning. There is a monotone mapping function $f$ mapping the action $\alpha_i$ in the coordination points into $<\gamma_1, \gamma_2, \gamma_3>$, such that $r_{f(i)} = \alpha_i$.

How to determine the coordination points and their order of execution is a critical issue. Here we propose to use a "Goal-oriented" approach to building the planning causal graph, which is the key to solving collaboration between agents in the multi-agent planning problem. Simply speaking, the "Goal-oriented" method is to make a plan to achieve the given goal state, and performing this plan requires the relevant conditions.

Causal-links has the simplest form sub-plan$_1$ $\rightarrow$ sub-goal$_1$ $\rightarrow$ sub-plan$_2$ $\rightarrow$ goal. This causal link indicates that performing sub-plan$_1$ is to obtain sub-goal$_1$, whose objective is to enable sub-plan$_2$ to
achieve the goal. The common form of causal-links is a finite sequence
\( sub-plan \rightarrow sub-goal_1 \rightarrow sub-goal_2 \rightarrow L \rightarrow sub-goal_m \rightarrow sub-plan \rightarrow goal_1 \rightarrow goal_2 \rightarrow goal_n \)
where the sub-link \( sub-goal \rightarrow sub-goal \) denotes that \( sub-goal \) involved in achieving \( sub-goal \) without the need to perform a further local plan. Further, if \( sub-goal \) is conjunctive, then \( sub-goal \) can be one of its conjuncts.

Destructive interference: Given a planning solution \( \alpha, \alpha_3, \alpha_4, L, \alpha_n \), if only \( \alpha_i \) supplies the precondition \( p \) for \( \alpha_i \), and someone \( \beta_i \) destroys \( p(\sim p \in \text{add}(\beta_i)) \) between the time points of their execution.

When solving multi-agent planning, "Goal-oriented" uses null-plan can determine whether the goal has been satisfied. Then we have the following statements about Generate-null-plan.

Generate-null-plan: During the solutions of "Goal-oriented", if seeking for the goal which already held, make a null-plan for achieving the goal.

Here we give a formal formulation of the "Goal-oriented" method. To achieve a given goal \( G \), we need to perform a local planning \( L \) under the condition \( C \). "Goal-oriented" is formulated as a form \( L \rightarrow PC G \). Assuming \( P_C \) is a sub-plan for obtaining conditions \( C \), we construct the new plan \( P_N \) by the following way:
• Adding a new local plan \( P_L \) to the end of sub-plan \( P_C \).
• Ordering all the actions that in the local planning \( P_L \) after the sub-plan \( P_C \), and
• Adjusting the causal-links appropriately.

When multi-agent planning in the use of "Goal-oriented" to solve the problem, the goal \( G \) is often conjunctive form. Then we can decompose \( G \) into several different conjunctive items, that is \( G=G_1 \land G_2 \land L \land G_4 \). Each conjunctive item represents a sub-goal \( G_i \) to be achieved. What is more, consider the simplest conjunctive form \( G=G_1 \land G_2 \), then we can further decompose the form \( L \rightarrow PC G \) into \( P_{h_i} / G \rightarrow G_1 \) and \( P_{h_2} / C \rightarrow G_2 \). Suppose \( P_1 \) and \( P_2 \) is planning to achieve \( G_1 \) and \( G_2 \) respectively, their corresponding causal-links are \( sub-plan \rightarrow sub-goal \rightarrow L \rightarrow G \rightarrow finish \rightarrow G \) and \( sub-plan \rightarrow sub-goal \rightarrow L \rightarrow G \rightarrow finish \rightarrow G \) respectively. \( P_1 + P_2 \) is their joint planning for obtaining the conjunctive goal \( G \). Then we make the appropriate changes to the form of their causal-links, which become the following form \( sub-plan \rightarrow sub-goal \rightarrow L \rightarrow G \rightarrow G \rightarrow finish \rightarrow G \) and \( sub-plan \rightarrow sub-goal \rightarrow L \rightarrow G \rightarrow G \rightarrow finish \rightarrow G \). If there is no destructive interference between the synthetic planning, then \( P_1 + P_2 \) can achieve the goal \( G \). More precisely, we have the following expression of "Solve-conjunctive-goal".

Solve-conjunctive-goal: For a given conjunctive goal \( G=G_1 \land G_2 \). If there are plans \( P_1 \) and \( P_2 \) to achieve the sub-goal \( G_1 \) and \( G_2 \), respectively, and these plans don't destroy each other. Then we propose the plan \( P_1 + P_2 \) to achieve the goal \( G \).
When solving global planning solution, it is necessary to make each local planning solution consistent. Therefore, we define the following constraints.

(R1) Causal-links Restriction
A complete causal-links of \( n \) coordination points \( < \alpha_1, \alpha_2, L, \alpha_n > \) satisfies (R1) iff, for \( 1 \leq i \leq n \), \( P_{\alpha_i} / C_{\alpha_i} \), and \( \alpha_i \in P_{\alpha_i} \), the following conditions are true:

a) \( i = 1 \), and agent \( \phi_i \) who performs \( P_{\alpha_i} \) can supply the condition \( C_1 \);

b) \( 1 < i < n-1 \), and \( P_{\alpha_i} \) can achieve \( G_i \) which is either \( G_i \) or a conjunct of \( G_i \), and for \( i < j < n \), \( P_{\alpha_i} / C_{\alpha_i} \) doesn't hold;

c) \( i = n \), and \( P_{\alpha_n} \) can achieve \( G_n \), and the sub-plans \( \{ P_{\alpha_j} \} (1 < j < n - 1) \) which produce \( < \alpha_1, \alpha_2, L, \alpha_{n-1} > \) can supply \( C_n \).

(R2) Local-planning Restriction
The agents' sub-plans \( P_i, (1 \leq i \leq l) \) satisfies (R2) iff, for each \( P_i = < \alpha_i1, \alpha_i2, L, \alpha_i > \), the local planning problem with action landmarks \( < F, A^e, I \cap F, P, < \alpha_i1, \alpha_i2, L, \alpha_i > > \) can be solved.

The Causal-links Restriction (R1) ensures consistency between the local plans, and no destructive interference with each other. This external constraints make the local planning between the various agents without conflicts. The Local-planning Restriction (R2) ensures that each agent can perform the coordination points, and to meet their preconditions. That is, the agent \( \phi_i \) make local plans to produce certain conditions, which are internal preconditions for its public actions.

4. Theoretical analysis
Theoretically, we prove the correctness properties of Our approach below.

Theorem 1 (Soundness) Given a multi-agent planning problem \( \Gamma = \langle F, \{ A_i \}_{i=1}^l, I, G \rangle \), there exists a causal-links of \( n \) coordination points \( < \alpha_1, \alpha_2, L, \alpha_n > \), which achieves the global goal \( G \), then we can extend it into a satisfied plan \( P \) for \( \Gamma \).

Proof We give a straightforward proof of the Theorem 1. (R1) Causal-links Restriction can achieve the sub-goals, and Solving the sub-goals which execution conditions are supplied by the agents' local planning, while these conditions are verified by (R2) Local-planning Restriction.

Theorem 2 (Completeness) Given a solvable multi-agent planning problem \( \Gamma = \langle F, \{ A_i \}_{i=1}^l, I, G \rangle \), Our approach can certainly find a solution \( P \) for \( \Gamma \).

Proof The steps of the proof are similar to the theory 1. The same proof part no longer tautology, the different is Our approach does local planning will first try to relax the conditions, so the legal plan \( P \) must be in.

5. Conclusion
In this paper, we present a novel approach to improve the efficiency of solving multi-agent planning problems in the MA-STRIPS model with a fully distributed setting. Our approach can be easily deal with various types of multi-agent planning problem including those with complex interactions between agents.

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