Multi-Agent Planning for Non-Cooperative Agents

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Background and Analysis

At least three major subproblems can be distinguished in a multi-agent planning problem: a *task allocation problem* (which agent performs which subtasks), an *individual planning problem* for each of the agents involved (how to ensure that the tasks allocated to me can be performed), and a *plan coordination problem* (how to ensure that the individual planning processes can be integrated into an overall solution). Undoubtedly, the interaction between these subproblems is heavily influenced by the willingness to cooperate between agents.

We concentrate on the interaction between these three subproblems if the agents involved are *strictly non-cooperative* due to their insistence on maintaining *full planning autonomy*. That is, in order to achieve a feasible joint plan, the agents are not willing to revise their plan during or after the planning process.[1]

Typical application areas where this requirement plays an important role are automated supply chain management, multi-modal transportation provided by independent companies, and patient-centered health care management systems. A common characteristic of such planning problems is the presence of a *complex task* to be solved by the agents, where such a task is specified as a set of interdependent subtasks and for every subtask some specific abilities required to perform the task. The agents involved each have specific abilities enabling them to solve specific subtasks, but not the complete task. Besides their abilities, agents may also differ in the costs they associate with performing a subtask. Performing subtasks will also deliver specific rewards to the executing agents and we suppose that each agent will aim at maximizing its profit.

Statements

Due to the planning autonomy required by the agents, we will make no assumptions about the specific planning methods used by them: each agent is completely free in choosing its own favorite planning system. It then remains to analyze the requirements for the task allocation mechanism and the plan coordination method that should be applied and their interrelationships. Our opinion with respect to these requirements are expressed by the following statements:

Statement 1 While most approaches to plan coordination are focussing on the coordination of already completed plans or iterative coordination of partially completed plans, multi-agent planning problems for non-cooperative agents (as state above) require a pre-planning coordination method.

Comment: Coordination of already completed plans (post-planning coordination) as for example in plan merging (von Martial 1992; Tonino *et al.* 2002), assumes that a collection of agents have already constructed plans to realize their individual goals. Here, coordination is focused on the computations within and between the agents after the planning of the individual agents. The aim is to achieve a common, conflict-free and less costly joint plan by exploiting positive interactions and resolving possible conflicts between independently generated individual plans. This means that revision of the original planning products is required. Coordination during planning approaches (Durfee 1991; Decker & Lesser 1994) allow coordination also to occur before every agent has completed its own plan: Here, coordination and planning are intertwined processes where planning information is continuously exchanged between the parties involved to arrive at a common feasible solution. The main difference with the first approach mentioned is that positive (negative) interactions between *partial* individual plans are exploited (resolved).[2] In both these approaches, it therefore is taken for granted that the individual agents are prepared to share information about their plans and, if necessary, to adapt and revise their individual plans after they have constructed their plans.

Statement 2 The only way a pre-planning method can ensure a feasible global solution to the multi-agent planning problem —whatever plan is chosen by the individual agent— is by providing (a minimal set of) additional constraints to the original planning problem.

[1] This insistence on autonomy might also be caused by external factors as the impossibility to communicate.

[2] For example, in the (G)PGP framework (Durfee 1991; Decker & Lesser 1994), planning and coordination are conceived as iterative processes, with plans of various levels of abstraction being exchanged (and modified) between agents to achieve a feasible and efficient coordinated plan.

Comment: This statement immediately follows from the requirement that the resulting joint plan should satisfy all the initial constraints. The additional constraints are needed to ensure the feasibility of the combination of the independently developed plans produced by the autonomous agents. Examples of this approach are the partitioning methods as applied by Valk (Valk 2005) and the temporal decoupling method as specified by Hunsberger (Hunsberger 2002).

Statement 3 Solving the preplanning coordination problem assumes that it is known which subtasks are allocated to which agents. On the other hand, the specific set of additional constraints resulting from the coordination process — and thereby the total plan cost for solving the multi-agent planning problem— heavily depends on the specific task allocation chosen. Current approaches to task allocation do not pay attention to complex task specifications and/or allocation of planning constraints. Current approaches to (preplanning) coordination do not take into account cost factors. Therefore, a careful integration of task allocation and plan coordination methods is called for in order to minimize the costs for the actors involved.

Comment: Quite a number of studies have concentrated on market-based approaches to task allocation in multi-agent systems. Typical examples of these studies are the study of (combinatorial) auctions for task allocation and coalition formation processes in multi-agent systems and its relations to combinatorial optimization problems (Gerkey & Mataric 2004). In most approaches, however, the tasks described are rather simple: often they consist of a set of atomic tasks and each of the actors receives one single task or a subset of tasks. Even if the task description is more elaborate, as in the Traderbots architecture (Dias & A.Stentz 2003), it is assumed that the set of subtasks does not require an elaborate planning process to execute. Therefore, the problem of identifying planning constraints and the problem of allocating them does not occur in this approach. At the same time, current plan coordination methods almost always assume that agents are fully cooperative and/or tasks already have been allocated to agents. As far as we know no attention has been paid to plan coordination and task allocation as intertwined processes where reallocation of tasks and subsequent replanning of the agents might be needed to obtain better results.

Summarizing, we conclude that although both task allocation and plan coordination have been given attention to separately, existing approaches seem to be less suitable to deal with the complete problem, since *(i)* task specifications often are too simple *(ii)* the interdependency between the subproblems mentioned is neglected, *(iii)* almost no interdependency of subtasks assigned to different agents is assumed and *(iv)* almost no attention has been paid to the mutual dependencies between task allocation and coordination of self-interested and competitive agents.

Recommendations We therefore would like to see future research to concentrate on the following issues:

1. To generalize both current market-based task and plan constraint allocation methods by taking into account complex tasks consisting of interdependent sets of hierarchically ordered subtasks, enabling the task to be decomposed at several levels of abstraction;
2. To generalize current task allocation methods by providing task allocation methods suitable for handling complex tasks, developing suitable cost models to handle the allocation of additional plan constraints identified by plan coordination methods;
3. to extend current methods for plan coordination by
   - developing methods for identification of plan constraints using complex task specifications;
   - developing cost models for plan constraints and methods to identify cost-minimal sets of plan constraints to be used by agents for their valuations;
4. to integrate both approaches in a common framework where task allocation and plan constraint allocation are considered as intertwined, iterative processes. Here, special attention will be given to incorporate adaptive (learning) strategies for agents suitable for repeated task (re)allocation problems and to re-evaluation methods for plan constraints aiming at the improvement of overall profits.

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