Managing Multi-Agent Coordination, Planning, and Scheduling

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Abstract

Most research about multi-agent coordination is concentrated at a high level, e.g., developing coordination interaction protocols to be imposed on agents. There has been less concern about how the internal task structures of individual agents affect these higher-level coordination behaviors. In particular, agent planning and scheduling behaviors are inextricably linked to coordination behaviors. This paper proposes some extensions and restrictions to the expressiveness of traditional plan and schedule representations that allow the formal definition of the multi-agent coordination problem. We recast our GPGP coordination approach using this formalism, and present a set of general rules relating task environment characteristics and this implemented set of GPGP coordination mechanisms.

1. Introduction

Multi-agent coordination, defined as *managing interdependencies between activities*, addresses the special issues arising from the dependency relationships between multiple agents' tasks. We define an *inter-dependency* as a relationship between a local and non-local task where the execution of one changes some performance-related characteristics associated with the other. We represent the interdependencies using an extended Hierarchical Task Network (HTN) [6] formalism and manage the inter-dependencies using an extended set of GPGP (Generalized Partial Global Planning) [4] coordination mechanisms.

We extend the expressiveness of traditional HTNs to represent agent tasks' characteristics by annotating tasks and actions like TÆMS (Task Analysis, Environment Modeling, and Simulation) [5], an abstract modeling representation that represents task inter-dependencies quantitatively. Given the extended HTNs for representing tasks and environments, we recast our GPGP coordination mechanisms [3, 4] within this formalism. Previously, planning and scheduling were often studied separately from coordination. We state that planning and scheduling can be incorporated to help agents improve their coordination behaviors. We also introduce a scheduling-coordination problem and an associated algorithm for handling this problem.

2. Extending HTNs

Traditional HTNs are not expressive enough to represent worth-oriented goals, contingencies, or the uncertainties that arise when task plans are distributed over multiple agents. Several previous approaches have tried to address parts of this problem. It has been stated [1] that in practice the standard AI representations and algorithms survive because real "problems commonly possess structure . . . [therefore] specialized representations, and algorithms employing these representations, can achieve computational leverage by exploiting these various forms of structure."

We base our formal definition of the coordination problem on the well known work of Erol, et al.[6], who first formalized HTN planning, and focus primarily on the differences here. Note that we are only concentrating on an agent's (partially) *local* view—primitive or compound tasks at other agents are represented locally as *non-local tasks* (NLTs). The vocabulary is expanded with novel language constructs: a finite set of *non-local task* symbols, a finite set of input provision symbols, a finite set of outcome symbols including "OK" and "FAIL" to represent contingencies, and a finite vector of domain-dependent task/action characteristics. We re-define the following terms with the new vocabulary: *primitive task*, *function*, *goal task*, *compound task*, *task networks*, etc. New terms are also introduced: non-local tasks, links, etc. With the extended HTNs, it is easy to represent the characteristics of agents' tasks (task structures, information flow, control flow, etc.) for assisting the coordination process. Details can be found in [2]. Based on the extended HTNs, we present an *expressiveness theorem* demonstrating that *the vocabulary of our extended HTNs is strictly more expressive than that of traditional HTNs*.

3. Formalizing the Coordination Problem

Agents must decide on an appropriate course of actions to achieve their goals (planning), integrate actions in service of multiple goals and shepherd their limited local resources (scheduling), and finally execute the actions. One key is to solve the *scheduling-coordination problem*: an agent's local scheduler cannot make good schedules in the face of large amounts of uncertainty within the task representation.

The key problem for coordination is that there exists *uncertainty* in non-local tasks, which can lead to bad schedules, low efficiency, and resource misuse. We state a base assumption first: *Each agent is capable of reasoning locally about its schedule of activities and possible alternatives*, which guarantees an appropriate local schedule *without* uncertainty within task executions. In the presence of uncertainty, the *scheduling-coordination problem* addresses how to provide information to the local scheduler, remove uncertainty and thus allow the construction of better schedules. The general idea is to find a way to fill the uncertainty information in the uncoordinated task structures for the local agent. Our solution is that a specific GPGP coordination mechanism is applied to remove the uncertainty, which often results in information sent from a remote agent.

We alter the agents' architecture by inserting a GPGP (coordination) module in between the planner and the scheduler. The information flow among these components in our agents' internal structure is as follows: The planner provides uncoordinated plans (with uncertainty) to the GPGP coordination module; the GPGP coordination module takes the uncoordinated plans as input, applies one or a combination of appropriate coordination mechanisms to the uncoordinated plans and produces coordinated plans, which are the input to the scheduler; the scheduler uses the coordinated plans to make better schedules. We present a scheduling-coordination algorithm as follows (further explanation in [2]):

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Given: $(P, M, R)$

        Input: $P$, an uncoordinated plan represented using the extended
        HTNs; $M$, the extended set of GPGP coordination mechanisms;
        $R$, the role of this agent in a particular coordination process. Out-
        put: $S$, a coordinated schedule with uncertainty removed.

    1. Apply the function GPGP$_{\text{Detect}}$ to $P$ to find out a set of $k$ coordination
       points, $CP = \{nlt_i \mid i = 1, \dots, k\}$;
    2. While $(CP \neq \phi)$
           • Select a coordination point $nlt_i$ from $CP$; $CP \leftarrow CP -$
             $\{nlt_i\}$;
           • if ($nlt_i$ is avoidable) $\{P \leftarrow P -$ Branch$(nlt_i)$; continue; $\}$
           • else $\{$ select $m_j \in M$ and apply it to $nlt_i$:
             $P \leftarrow$ ApplyMechanism$(P, \{nlt_i\}, m_j, r)$; $\}$
    3. Generate better schedule, $S$, based on a selected utility function;
    4. Return S.
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Each of the extended GPGP mechanisms consists of two parts: *a pattern-directed re-writing of the extended HTN* and *a coordination communication protocol* (specified as a HTN) specific to the mechanism. The task re-writing of our extended set of GPGP coordination mechanisms has been recast using the extended HTNs [2]. Based on the analysis of the application of the mechanisms, we prove that *the GPGP processes for those coordination problems that can be represented with the extended HTNs are deterministic*.

In dynamic environments, it is key for an agent to autonomously select the best coordination mechanisms according to its knowledge of its own capabilities, its belief about the other agents, and the dynamic environmental features. That is, given k inter-dependencies, nlt, in a coordination problem environment and our extended set of GPGP coordination mechanisms, M, for each nlt_i, according to a performance evaluation function, EV, we must select a certain mechanism, m_j, such that EV is maximized. The above problem is called *coordination strategy problem*. A viable solution is to apply the mechanisms, M, to various domain applications, and apply learning techniques over the experimental results to extract certain mappings, or rules, between environmental factors and the coordination mechanisms, so that the rules can be employed to select appropriate mechanisms in similar environments.

4. Implementation

We implemented a novel set of GPGP coordination mechanisms and followed the general procedure in the last part of Section 3 to explore the potential relationships between these mechanisms and the environmental characteristics. The detection of the coordination relationships is domain-independent, which is advantageous compared to the earlier approach in [5]. An example rule, learned through the experimental results in our implemented Emergency Medical Systems (EMS) using a standard learning program, C4.5 (details in [3]), is shown here: If (deadline is the user's main concern), apply *Coordination by Reservation*—one of our extended set of GPGP coordination mechanisms (further explained in [2, 3]).

References

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