Automatic Generation of Theories of Coordination in Multi-Agent Systems

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INTRODUCTION

Coordination is defined as the process of managing dependencies between activities. Its fundamental components are the allocation of scarce resources and the communication of intermediate results. Coordination theory can be defined as the set of axioms, constructs and analytical techniques used to create a model of dependency management in multi-agent systems (MAS).

Multi-agent systems (MAS) represent a significant interest in a variety of disciplines, such as artificial intelligence (and other domains of activity in computer science), political science, international relations, public health, public policy, social welfare, economics, demography, anthropology, communication studies, geography, history, sociology, urban planning, control theory, electrical engineering, military science, and so forth. The present author and his students have worked on several systems in different domains of MAS, such as:

a. **Manmade Technical Systems:** The technical and economic aspects of distributed automated air traffic control; distributed automated control of urban street and highway ramp traffic signals; learning, planning and collaborating robots; distributed control of nationwide manufacturing operations; distributed decision support systems for optimum resource and task allocation over space and time.
b. **Natural Complex Systems:** The behavior of natural organisms, causality and temporal relations, social structures and coordination.
c. **Human Behavior and its Simulation:** Language development and studies of the properties of dictionaries; behavioral studies on reasoning and decision making; information, fact and knowledge retrieval; automatic teaching and evaluation of control operators; social networks, social and cultural anthropology aids; multi-agent systems simulating human societies.

One important concern is how to verify the correctness of the computer representation of MAS and how to optimize their operations. Theories of Coordination (ToC) should satisfy these requirements. However, such are currently ad hoc and amorphous, in that there is no unified model of coordination, though there exist many constructs describing specific phenomena in MAS. With the current advent of large-scale agent-based societies, there is a need for theories that builders can use in designing MAS, instead of being forced to learn from trial and error every time such a society is built. In addition to such design tools, we generate a trouble-shooting tool to diagnose problems with existing deficient systems. We envisage steady feed-back from this component to the user when the MAS malfunctions.

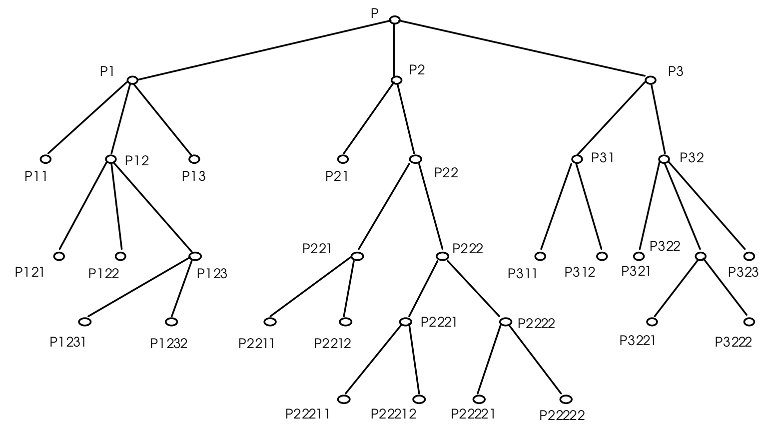
We are creating software tools and formal techniques to be used to analyze and design[1] systems of interacting intelligent agents. The concept is based on our experience gained in many projects, primarily in developing tactical and strategic decision support aids for use in dynamic command and control environments with multiple resources, multiple tasks, multiple sources of information and multiple human and machine decision makers that have different roles and responsibilities and belong to a hierarchy with overlapping jurisdictions. (This was completed during our multi-year collaboration with the U.S. Coast Guard in computerizing their tactical and strategic planning processes.)

BACKGROUND

Our approach to the above scenarios is to use intelligent agents as aides for human decision-makers, with each agent performing a small number of functions. The complex problem of designing a command and control system for such environments is greatly aided by automated support. A fundamental requirement for such automated support is a framework for modeling coordination in a way that can be used by automated tools. Our ongoing work is intended to satisfy this requirement.

We are adopting an empirical approach in developing theories of coordination. We are creating for benchmark tests a representative, easily modifiable and parametrizable simulation model of three large classes of MAS. We then observe and measure the effect of a set of control variables on the quality of coordination. We then form high-level, orthogonal emergent variables using the multivari-

Figure 1. The metaphorical production plan, the P-tree, is an AND-tree. Leaf nodes reference raw materials or sub-components provided. Higher level process nodes correspond to manufacturing/ assembly operations. Each process node may be associated with an OR-subtree (not shown).



ate statistical method principal factor/components analysis. (Note that nonlinear and cross-product terms are also to be included in the trial functions. The word "trial" has an important, well-meant property, indicating that preconceived artifacts have no a priori role in the approach.) The emergent variables directly and in a statistically significant manner affect the level of coordination, the system structure and functioning. We then produce on this basis theories of coordination applicable to the three classes of MAS to be discussed below. They will contribute to the creation of design tools and guidelines in the construction of new systems, and trouble-shooting tools for existing suboptimal MAS.

We note this method is analogous to theory formation in physics where experimental results may suggest novel conceptual frameworks that have relevance to phenomena beyond those appearing in the original experiments. We hope that the theory to be developed will help in understanding coordination in general as well as in the creation of models of coordination for specific applications.

THE THREE TYPES OF MULTI-AGENT SOCIETIES

The first experimental environment, the *P-System* (*P* stands for production), is a metaphorical and abstract version of our Distributed Control of Nationwide Manufacturing Operations system and will be used for the first set of benchmark tests. The model also has correspondence to industrial supply networks and has the following characteristics:

- Communication between agents is asynchronous and over limited bandwidth. It includes request for information, resource or action; task or resource allocation to agents; a piece of information; an acknowledgment, and so forth. Messages can be broadcasted at large, or sent to selected groups of agents or to an individual one on the basis of need-to-know and qualified-to-know.
- The sequence of "manufacturing operations" of a given product defines a hierarchical network of tasks, the *P-tree*, which corresponds (is homomorphic) to the problem-solving network needed by the planning process (see Figure 1). All agents share a global goal structure that forms the basis for the generation of individual goal structures. The agent society can assume an organizational structure ranging from a sharply defined multitier hierarchy to an egalitarian flat structure.
- Although the top layer of the P-tree is an AND-tree, each node can also be associated with an OR-subtree (alternative tasks can accomplish the given job at the respective process node).
- *Planning* is equivalent to assigning the (metaphorical) manufacturing/assembly operations to resources over space and time. An agent with a higher priority task (see below) can obtain a needed resource from another agent with a lower priority task. The latter task is performed with a less satisfactory

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