State-of-the-Art Survey

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Danny Weyns
H. Van Dyke Parunak
Fabien Michel (Eds.)

Environments for Multi-Agent Systems

First International Workshop, E4MAS 2004
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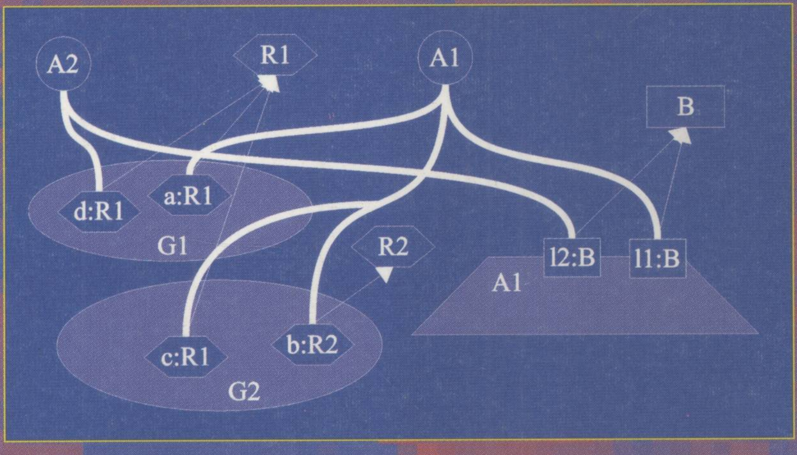

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Preface

The modern field of multiagent systems has developed from two main lines of earlier research.

Its practitioners generally regard it as a form of artificial intelligence (AI). Some of its earliest work was reported in a series of workshops in the US dating from 1980, revealingly entitled, "Distributed Artificial Intelligence," and pioneers often quoted a statement attributed to Nils Nilsson that "all AI is distributed." The locus of classical AI was what happens in the head of a single agent, and much MAS research reflects this heritage with its emphasis on detailed modeling of the mental state and processes of individual agents. From this perspective, intelligence is ultimately the purview of a single mind, though it can be amplified by appropriate interactions with other minds. These interactions are typically mediated by structured protocols of various sorts, modeled on human conversational behavior.

But the modern field of MAS was not born of a single parent. A few researchers have persistently advocated ideas from the field of artificial life (ALife). These scientists were impressed by the complex adaptive behaviors of communities of animals (often extremely simple animals, such as insects or even microorganisms). The computational models on which they drew were often created by biologists who used them not to solve practical engineering problems but to test their hypotheses about the mechanisms used by natural systems. In the artificial life model, intelligence need not reside in a single agent, but emerges at the level of the community from the nonlinear interactions among agents. Because the individual agents are often subcognitive, their interactions cannot be modeled by protocols that presume linguistic competence. The French biologist Grassé observed that these interactions are typically achieved indirectly, through modifications of a shared environment [1].

All interaction among agents of any sort requires an environment. For an AI agent whose interactions with other agents are based on speech act theory, the environment consists of a computer network that can convey messages from one agent's outbox to another agent's inbox. For an ALife agent, the environment is whatever the agent's sensors sense and whatever its effectors try to manipulate.

In most cases, AI agents (and their designers) can take the environment for granted. Error-correcting protocols ensure that messages once sent will arrive in due course. Message latency may lead to synchronization issues among agents, but these issues can be discussed entirely at the level of the agents themselves, without reasoning about the environment. As a result, the environment fades into the background, and becomes invisible.

Not so for ALife agents. Simon observed long ago that the complex behavior of an ant wandering along the ground is best explained not by what goes on inside the ant, but by what happens outside, in the structure of the ground over which the ant moves [2]. When a termite interacts with other termites by depositing and sensing pheromones, the absorption and evaporation of the pheromone by the environment plays a critical role in the emergent structure of the colony's behavior. There are no error-correcting protocols to ensure that an agent who tries to push a rock from one place to another will in fact be able to realize that objective. From the ALife perspective, the environment is an active participant in agent dynamics, a first-class member of the overall system.

One happy result of the confluence of AI and ALife in MAS is the emergence of hybrid agents that draw on the best of both earlier traditions. This volume, and the workshop of which it is the archival record, is evidence of that hybridization. The agents described in these papers are not artificial ants constructed to test a biologist's theories about insect behavior, but components of systems engineered to fly airplanes, or analyze sensor data, or produce plausible human-like behavior in a video game. Like AI agents, many of them have cognitive, symbolic internal structures. Like ALife agents, all of them interact explicitly and deliberately with the environment through which they coordinate their behaviors.

The notion of the environment in MAS is still young, but the number of papers contributed to this volume suggests the potential of this concept for engineered systems, and their breadth sketches the broad framework of what a mature discipline of environments for multiagent systems might resemble. The entire life cycle of environmental engineering is represented here: conceptual models and languages for the design and specification of environments, simulation environments that admit environments as first-class objects, analysis of the role played by an explicit environment in agent coordination, and examples of full applications that exploit the power of an active environment. The introductory survey pulls these themes together to offer an integrated overview of this emerging discipline.

This volume shows the wide range of exploration typical of a nascent discipline as pioneers discover the best ways to frame problems and approach solutions. It will enable other researchers to take build on this body of initial exploration, and should form the foundation for a fruitful new set of tools and methods for developing multiagent systems.

[1] Grassé, P.P.: La Reconstruction du Nid et les Coordinations Inter-individuelles chez Bellicositermes Natalensis et Cubitermes sp. La theórie de la Stigmergie: Essai d'Interpreétation du Comportement des Termites Constructeurs. Insectes Sociaux 6 (1959) 41-84
[2] Simon, H.A.: The Sciences of the Artificial. Cambridge, MA, MIT Press (1969)

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H. Van Dyke Parunak
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Organization

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Vol. 2892: F. Dau, The Logic System of Concept Graphs with Negation. XI, 213 pages. 2003.

Table of Contents

Mediated Coordination

Applications

Environments for Multiagent Systems State-of-the-Art and Research Challenges

Danny Weyns[1], H. Van Dyke Parunak[2], Fabien Michel[3], Tom Holvoet[1], and Jacques Ferber[3]

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Abstract. It is generally accepted that the environment is an essential compound of multiagent systems (MASs). Yet the environment is typically assigned limited responsibilities, or even neglected entirely, overlooking a rich potential for the paradigm of MASs.

Opportunities that environments offer, have mostly been researched in the domain of situated MASs. However, the complex principles behind the concepts and responsibilities of the environment and the interplay between agents and environment are not yet fully clarified.

In this paper, we first give an overview of the state-of-the-art on environments in MASs. The survey discusses relevant research tracks on environments that have been explored so far. Each track is illustrated with a number of representative contributions by the research community. Based on this study and the results of our own research, we identify a set of core concerns for environments that can be divided in two classes: concerns related to the structure of the environment, and concerns related to the activity in the environment. To conclude, we list a number of research challenges that, in our opinion, are important for further research on environments for MAS.

1 Introduction

There is a general agreement in the multiagent research community that environments are essential for multiagent systems (MASs). Yet most researchers neglect to integrate the environment as a primary abstraction in models and tools for MASs, or minimize its responsibilities. As a consequence, a rich potential of applications and techniques that can be developed using MASs is overlooked.

Popular frameworks such as Jade [9], Jack [44], Retsina [79] or Zeus [58] reduce the environment to a message transport system or broker infrastructure. Well-known methodologies such as Message [25], Prometheus [66] or Tropos [12] offer support for some basic elements of the environment, however they fail to consider the environment as a first-class entity. Standard literature on MASs

D. Weyns et al. (Eds.): E4MAS 2004, LNAI 3374, pp. 1–47, 2005.

used for education, including [73, 93, 45], only deals very briefly with the topic of environments. Even in the FIPA [34] specifications it is hard to find any functionality for the environment beyond message transport or broker systems. Restricting interaction to inter-agent communication neglects a rich potential of possibilities for the paradigm of MASs.

Researchers working in the domain of situated MASs traditionally integrate the environment as a first-class entity in a MAS. In situated MASs, the environment is an active entity with its own processes that can change its own state, independent of the activity of the embedded agents. Inspired by biological systems, several researchers have shown that the environment can serve as a robust, self-revising, shared memory for agents. This can unburden the individual agents from continuously keeping track of their knowledge about the system. Moreover, it enables the agents to use their environment as an excellent medium for indirect coordination. Gradient fields and evaporating marks in the environment can guide agents in their local context and as such facilitate the coordination in a community of agents in a decentralized fashion. Several practical applications have shown how the environment can contribute to manage complex problems. There are examples in domains such as supply chain systems, network support, peer-to-peer systems, manufacturing control, multiagent simulation etc. Since the exploitation of the environment in MASs results in better manageable solutions, it is a promising paradigm to deal with the increasing complexity and dynamism of future system infrastructure and more advanced problem domains, e.g. ad hoc networks or ubiquitous computing.

Despite the large amount of work in the domain of situated MASs, we are just at the very beginning of understanding the complex principles behind the concepts related to the environment and the interplay between agents and the environment. This paper aims to contribute in three ways. First we give an overview of the state-of-the-art on environments for MASs. Based on this study as well as the results of our own research, we identify a set of core concerns for environments, as a second contribution. Third, we outline a number of research challenges that, in our opinion, are important for the future development of environments for MASs.

2 Organization of the Paper

In Sect. 3, we start with an overview of the state-of-the-art on environments for MASs. Studying MAS literature with a focus on environments is a tough job. During our study, we encountered two types of difficulties: (1) the term *environment* has several different meanings, causing a lot of confusion, (2) the functionalities associated with the environment are often treated implicitly, or integrated in the MAS in an ad-hoc manner.

The confusion on what the environment comprises is mainly caused by mixing up concepts and infrastructure. Sometimes, researchers refer to the environment as the logical entity of a MAS in which the agents and other objects/resources are embedded. Sometimes, the notion of environment is used to refer to the software infrastructure on which the MAS is executed. Sometimes, environment even refers to the underlying hardware infrastructure on which the MAS runs.

The fact that functionalities of the environment are often treated implicitly, or in an ad-hoc manner, indicates that in general, the MAS research community fails to treat the environment as a *first-class entity.* [36] defines a first-class module as: "a program building block, an independent piece of software which [...] provides an abstraction or information hiding mechanism so that a module's implementation can be changed without requiring any change to other modules." Thus, the environment is in general not treated as an independent building block that encapsulates its own clear-cut responsibilities in the MAS, irrespective of the agents.

Starting from this perspective, the overview of the state-of-the-art on environments for MASs we discuss in Sect. 3 is not just a summary of representative papers on the topic of environments for MASs. In fact, the number of research papers that are devoted to the environment is very limited. The overview is rather a reflection on MAS research literature in which we have put the spotlight on models and concepts associated with the environment. The survey is structured as follows:

3.1 General models for environments (Russell and Norvig, Ferber, Odell et al., Environments for mobile agents)
3.2 Inter-agent facilities
  - Communication infrastructure (Huhns & Stephens, FIPA, Jade, Retsina)
  - Models for indirect interaction
    - Classical blackboard communication
    - Tuple-based interaction models (JavaSpaces, Lime)
    - Stigmergy (Synthetic ecosystems, Network routing)
    - Interaction models related to space in MASs (MMASS)
  - Environment as an organizational layer (AGR)
3.3 Agent-Environment interaction
  - Perception of the environment (Robocup Soccer Server, Model for active perception)
  - Dealing with actions in the environment (Synchronous model for action, Action model with regional synchronization)
  - Task-environments (Wooldridge, TAEMS)
3.4 Environments in agent-oriented methodologies (Gaia)

For each track we selected a number of relevant contributions from the research community, specified in brackets. It is not a primary goal of the survey to be complete, but rather to give an overview of the wide range of different conceptions associated with the environment for MASs and its various uses.

In Sect. 4, we extract, from the listed research tracks, a set of core concerns for environments in MASs. We have divided the concerns in two classes:

4.1 Concerns related to the structure of the environment (Structuring, Resources, Ontology)
4.2 Concerns related to the activity in the environment (Communication, Actions, Perception, Environmental processes)

Each concern represents a *logical functionality* for which the environment may have a *natural responsibility*. Our goal is to make the logical functionalities *explicit*, i.e. as concerns of environments as first-class entities. We want to underline that the proposed list of concerns is not intended to be complete. Our aim is to give an initial impetus to explore the rich potential of environments for MASs.

Next in Sect. 5 we outline a number of research challenges that, in our opinion, are important for the further development of environments for MASs. We have divided the list in three categories:

5.1 Definition and scope of environments
5.2 Agent-environment interrelationship
5.3 Engineering environments

Each category discusses a number of applicable research challenges. These challenges may serve as a source of inspiration for future exploration of environments for MASs.

Finally, in Sect. 6 we draw conclusions.

Conventions. In the remainder of the paper, we use the following style conventions:

- Quotations are put in "quotation marks."
- Specific terms used in literature are marked in `teletype`.
- Terms of concepts we want to emphasize are marked in *italic*.

3 Environments for MASs: A Survey of the State-of-the-Art

In this section we give an overview of a number of important research tracks that, in one way or another, include some notion of environment. We start with discussing a couple of general models for environments that have been proposed in literature. Then we zoom in on various concepts and functionalities related to inter-agent facilities in the environment and agent-environment interaction. We conclude the section by discussing the position of environments in agent-oriented software engineering. Each track is illustrated with a number of relevant contributions from the research community.

3.1 General Models for Environments

We start our study on environments for MASs with a number of representative models for environments that have been proposed in the research community.

Russell and Norvig. In chapter 2 of [73], S. Russell and P. Norvig discuss how an intelligent agent relates to its environment: "An agent is anything that can be viewed as perceiving its environment through sensors and acting upon the environment through effectors." This generally acknowledged relationship between an agent and its environment is schematically depicted in Fig. 1.

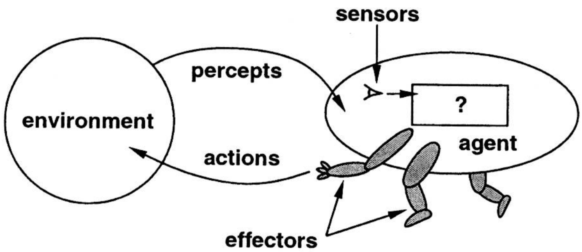

Fig. 1. Agent interaction with the environment [73]

Russell and Norvig discuss a number of key properties of environments that are now adopted by most researchers in the domain:

- Accessible versus inaccessible: indicates whether the agents have access to the complete state of the environment or not.
- Deterministic versus nondeterministic: indicates whether a state change of the environment is uniquely determined by its current state and the actions selected by the agents or not.
- Static versus dynamic: indicates whether the environment can change while an agent deliberates or not.
- Discrete versus continuous: indicates whether the number of percepts and actions are limited or not.

The most complex class of environments are those that are inaccessible, nondeterministic, dynamic and continuous. The first three properties of this list are properties typically occurring in MASs.

Russell and Norvig also define a "generic environment program", see Fig. 2. The program periodically gives the agents percepts and receives back their ac-

```
procedure RUN-ENVIRONMENT(state, UPDATE-FN, agents, termination)
  inputs: state, the initial state of the environment
          UPDATE-FN, function to modify the environment
          agents, a set of agents
          termination, a predicate to test when we are done

  repeat
     for each agent in agents do
        PERCEPT[agent] ← GET-PERCEPT(agent, state)
     end
     for each agent in agents do
        ACTION[agent] ← PROGRAM[agent](PERCEPT[agent])
     end
     state ← UPDATE-FN(actions, agents, state)
  until termination(state)
```

Fig. 2. A generic environment program [73]

tions. Next, the program updates the state of the environment based on the actions of the agents and of possibly other dynamic processes in the environment that are not considered as agents. This simple program for environments clearly illustrates the basic relationship between agents and their environment.

Ferber. In [28], J. Ferber discusses the modelling of environments for MAS at length. According to Ferber, an environment can either be represented as a single monolithic system, i.e. a centralized environment, or as a set of cells assembled in a network, i.e. a distributed environment. In a centralized environment, all agents have access to the same structure. In a distributed environment, each cell behaves like a centralized environment in miniature. However, a cell of a distributed environment differs in a number of ways from a centralized environment: (1) the state of a cell in a distributed environment depends on the surrounding cells, (2) the perception of agents in a distributed environment typically goes beyond one cell, (3) when agents move from cell to cell, the agent's link with the cells has to be managed and (4) the propagation of signals over the network of cells has to be managed. Orthogonal to the difference between a centralized or a distributed representation of environment, Ferber distinguishes between "generalized" and "specialized" models for environments. A generalized model is independent of the kind of actions that can be performed by agents. A specialized model is characterized by a well-defined set of actions. Ferber further distinguishes between purely communicative MASs (in which agents can only communicate by message transfer), purely situated MASs (in which agents can only act in the environment) and the combination of communicating and situated MASs.

Central to Ferber's model of an environment is the way actions are modelled. The action model of Ferber distinguishes between `influences` and `reactions` to influences. Influences come from inside the agents and are attempts to modify the course of events in the world. Reactions, which result in state changes, are produced by the environment by combining influences of all agents, given the local state of the environment and the laws of the world. This clear distinction between the products of the agents' behavior and the reaction of the environment provides a way to handle simultaneous activity in the MAS.

Ferber uses the BRIC formalism (Block-like Representation of Interactive Components) to model a MAS as a set of interconnected components that can exchange messages via the links. BRIC components encapsulate their own behavior and can be composed hierarchically. Fig. 3 depicts a model for a combined communicating and situated MAS in BRIC notation. In the BRIC model depicted in Fig. 3, the activity cycle of the MAS starts when the environment sends "perceptions" to the agents. As soon as the Synchronizer sends "synchronization of perceptions" signals to the agents, the agents are triggered to interpret the perceptions. Then, each agent produces an influence in the environment and possibly transmits a message to another agent. Next, the agent informs the Synchronizer it has finished its action by sending an "synchronization of actions" message. When all agents have sent their "synchronization of actions" messages, the Synchronizer sends a "synchronization of reactions" message to the Environ-