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A review of agent-based systems applied in environmental informatics

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EXTENDED ABSTRACT

During the last few years, agents and agent-based systems have attracted a significant amount of attention from researchers in environmental informatics. Agent-based approaches have been adopted for developing environmental systems for data management, decision support or simulation purposes. In order to identify the degree of penetration of agent technology in environmental software systems, over twenty applications reported in the recent literature have been reviewed from a software engineering perspective. These applications use agent-based approaches and methods, either as metaphor for software design or as an abstraction for software development.

As a software design metaphor, agents are considered as the building blocks of a system. Agent related technologies for software design include techniques for system requirements specification, software modelling, specification and verification. Taking a step ahead, agent technology has moved to agent-oriented software engineering that adopts agents in the whole software design process, as for example in GAIA.

On the second front (that of software implementation) there is a plethora of agent deployment strategies that might vary from object oriented programming and custom multi-agent systems to agent platforms. The latter have emerged as the evolution of object-oriented programming and distributed computing, and utilize agents as the basic software unit for developing systems.

This paper attempts to summarize recent developments in environmental informatics that exploit agent technology. All the applications presented in this paper have been evaluated from a software point of view, i.e. the adoption of agent technologies for software design or/and implementation is in the focus.

The result of this survey provides an outlook of agent use in environmental software, illustrated graphically in Figure 1. The main conclusion of this presentation is that agent technology has been only partially adopted in environmental informatics. There is still space for exploiting agent technology in environmental software, by adopting agent-oriented software engineering and agent programming techniques in future developments.

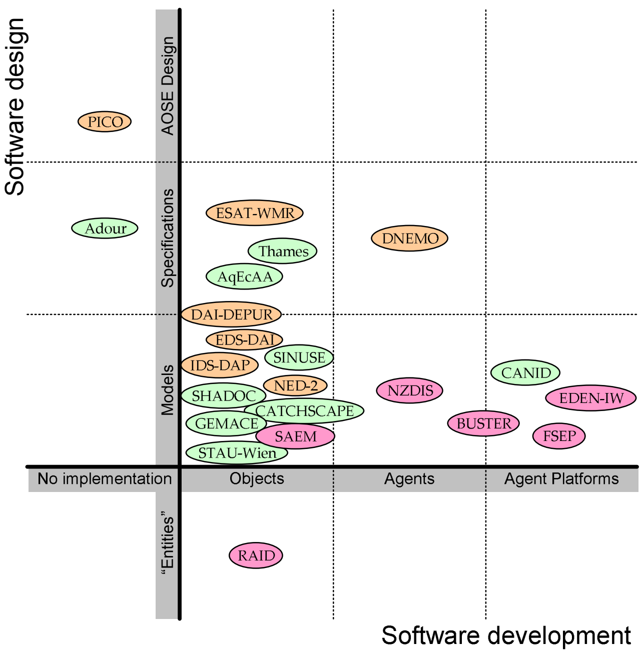

Figure 1. Qualitative illustration of the systems reviewed with respect to the techniques adopted for software design and software implementation

1. INTRODUCTION

1.1. Motivation

According to Parunak (2000), software agents are best suited for applications that are *modular*, *decentralized*, *changeable*, *ill-structured*, and *complex*. Parunak draws this conclusion, by ascertaining industrial and commercial applications, mainly in the fields of control systems, enterprise resource planning systems and electronic services. However, it is evident that environmental software applications bear similar characteristics: Environmental software is often required to provide services targeting multiple users and service levels, to integrate data and information from heterogeneous sources, to deal with data with spatial and temporal reference and to adapt to changing conditions. Also, environmental applications inherit both the uncertainty and the complexity involved in the natural environment. Thus, typically environmental software is characterized by involving uncertainties both at data, model and decision-making levels, and complexities related to the conflicting requirements and values of the involved users and stakeholders. Consequently, one could claim that the area of environmental informatics fits well with the competences of the agent-based systems. Thus, several agent-related approaches can be found in the literature for developing environmental software applications.

1.2. Related work

This paper aims to summarize the recent developments in the field, to assess the current status of progress and trace directions for future research, from an agent-based software engineering perspective. Such an overall review is currently missing from the bibliography. Tobias and Hofmann (2004) compare four java-based platforms for agent-based modeling from the end-user's perspective, i.e. their aim is to "determine the simulation framework that is the best suited for theory and data based modeling of social interventions, such as information campaigns". In contrast, this paper considers the various applications reviewed from an agent-oriented software modeling and implementation perspective. Also, this work has a broader scope than this of Hare and Deadman (2004) which "provides an overview of agent-based simulation in environmental modelling", as it considers applications for environmental data management and environmental decision support – not only agent-based simulation systems.

The rest of this paper is structured as follows: Section 2 presents more than twenty systems reported recently that exploit agent technologies. Section 3 discusses systems characteristics from a software engineering viewpoint and, finally, Section 4 draws some conclusions and proposes future work.

2. BIBLIOGRAPHIC SURVEY

This section provides a review of agent-based applications in environmental informatics. Applications that are either under development or not fully targeted on environmental problems have been included in the survey for reasons of completeness, but also for investigating the synergy of agents in environmental informatics. For the facilitation of the presentation initially the applications are distinguished in three categories (even in the boundaries between them might be little bit fuzzy):

(a) those that deal with environmental information management,
(b) those that are related with decision support in environmental problems, and finally
(c) those that simulate environmental or ecological systems and processes.

The rest of this section presents applications grouped in these three categories.

2.1. Environmental data management systems

Software agent approaches have been applied in a variety of systems for managing, integrating or disseminating environmental data.

Such a system is ***EDEN-IW*** (*Environmental Data Exchange Network for Inland Water*) that aims to provide citizens, researchers and other users with existing inland water data, acting as an one-stop-shop (Felluga *et al*. 2003). EDEN-IW exploits the technological infrastructure of Infosleuth system (Nodine *et al*. 2000, Pitts and Fowler 2001), in which software agents execute data management activities and interpret user queries on a set of distributed and heterogeneous databases. Also, InfoSleuth agents collaborate for retrieving data and homogenizing queries, using a common ontology that describes the application field.

A quite similar system that uses software agents for accessing environmental data is ***NZDIS*** (*New Zealand Distributed Information System*). NZDIS (Cranefield and Purvis 2001, Purvis *et al*. 2003) has been designed for managing environmental meta-data in order to service queries to heterogeneous data sources.

In the Australian Bureau of Meteorology, ***FSEP*** (*Forecast Streamlining and Enhancement Project*) is being developed, which uses agents for detecting and using data and services available in open, distributed environment. In FSEP (Dance et al. 2003), agents manage weather monitoring and forecasts data.

In the same category fall the following systems, even if they are either not developed with agents or they don't deal solely with environmental applications:

– The ***BUSTER*** system (*Bremen University Semantic Translator for Enhanced Retrieval*) utilizes ontologies for retrieving information sources and semantic translation into the desired format (Neumann *et al*. 2001). BUSTER prototype is to be redesigned using software agents.
– The ***MAGIC*** system (*Multi-Agents-based Diagnostic Data Acquisition and Management in Complex Systems*), which even if it does not targeted only for environmental applications, its objective is to develop a flexible multi-agent architecture for the diagnosis of progressively created faults in complex systems, by adopting different diagnostic methods in parallel. MAGIC has been demonstrated in an automatic industrial control application (Köppen-Seliger *et al*. 2001). A similar application, developed by the same team is the ***DIAMOND*** (DIstributed Architecture for MONitoring and Diagnosis) architecture, which adopts an agent-based architecture for distributed monitoring and diagnosis (Albert *et al*. 2003). DIAMOND will be demonstrated for monitoring of the water-steam cycle of a coal fire power plant.
– The ***SAEM*** system (A Society of Agents in Environmental Monitoring) proposes the use of robotic agents that collaborate for monitoring and evaluating the pollution on a power plant chimney (Seco et al. 1998). Specifically, a simulated application of small flying robotic agent societies (helicopter models) is assigned to monitoring a pollutant cloud.
– The ***RAID*** system (Rilevamento dati Ambientali con Interfaccia DECT) deals with pollution monitoring and control in indoors environments. *RAID* exploits the general architecture of ***Kaleidoscope*** that uses "entities" for the dynamic integration of sensor (Micucci 2002).

2.2. Environmental decision support systems

Most agent-based environmental decision support systems found in the literature, utilize agent technology from a distributed artificial intelligence perspective. In most cases, agent technologies are not used throughout the whole software development cycle; rather they are used only in a distributed decision-making fashion. Such kinds of applications include the following:

The ***D-NEMO*** experimental prototype, installed in the Athens Air Quality Monitoring Network, uses agents for the management of urban air pollution (Kalapanidas and Avouris 2002). *D-NEMO* agents incorporate classification and regression decision trees, case based reasoning and artificial neural networks for forecasting collaboratively air pollution episodes.

In ***EDS*** *(Environmental Decision Support)* application an agent community is used for supporting the decision-making process related with environmental assessment, planning, and project evaluation. Specifically, the ***EDS*** system provides assistance to project developers in the selection of adequate locations, guaranteeing the compliance with the applicable regulations and the existing development plans as well as satisfying the specified project requirements (Malheiro and Oliveira 1996, 1997).

The ***NED-2*** application, developed by the University of Georgia and the USDA Forest Service, deals with the simulation of forest ecosystems management plans and the evaluation of alternatives. In *NED-2* agents use growth and yield models to simulate management plans, perform goal analyses, and generate result reports (Nate 2004).

In ***PICO project***, Perini & Susi (2004) adopted agent-based requirement analysis for a decision support system in the field of integrated production in agriculture. This work focuses on design issues, using Tropos methodology (Giunchiglia, Mylopoulos & Perini 2002), while authors mention that they will continue their developments using software agents.

In ***ESAT-WMR*** system (*Expert System and Agent Technology to Water Mains Rehabilitation*), the agent-based decision support tool reported intents to support a U.K. water company in its water mains rehabilitation decision making processes. A community of collaborative agents models the tasks and interactions of the water company and its associates, and, ultimately, assesses alternative strategies for the pipes network rehabilitation (Davis and Sharp 1999, Davis 2000).

Another decision support system, applied for the selection of agricultural product penetration strategy is reported by Matsatsinis *et al.* (1999, 2003). The ***IDS-DAP*** system (*Intelligent decision support system for differentiated agricultural products*) incorporates distributed multi-criteria analysis models into consumer agents participating in a particular market research.

Last, but not least, the ***DAI-DEPUR*** system, which was developed in the University of Catalunia, applies distributed artificial intelligence techniques in a decision support system for supervising a wastewater treatment plant. The processes of the plant are represented by agents, which collaborate in a layered architecture (Sànchez *et al.* 1996).

2.3. Environmental simulation systems

In this category, applications that use agents as their building blocks for modeling processes and interactions within a system were gathered. Such systems usually utilize purely reflective agents, typically for simulating ecological or social systems. Systems that fall in this category are summarized below.

The ***SHADOC*** system (Barreteau & Bousquet 2000) uses agents for simulating the behavior of the stakeholders and the farmers involved in the irrigation of Senegal valley. In a follow-up effort, the ***CATCHSCAPE*** system (Becu *et al*. 2003) deals with the irrigation of northern Thailand, using agents for representing all entities related with the hydrologic basin. Agents incorporate models for the determination of aquatic reservoirs. Relative to those to systems (with regard to the field of application) it is the ***SINUSE*** application (Feuillette *et al*. 2003), that employs agents to model the Kairouan water basin. *SINUSE* agent-based system investigates the consequences of human behavior in the availability of aquatic resources by simulating physical and socio-economic interactions on a free access water table.

The ***STAU-Wien*** application (City–Suburb relations and development in the Vienna Region) aims to study the urban growth of Vienna city and its suburbs. The objective of this work is to simulate prior and future landscape transition processes for the suburban region in the surroundings of Vienna, Austria. A spatial agent model is used for stimulating regional migration and allocation decisions of households and commercial enterprises (Loibl & Toetzer 2003).

The multi-agent model ***GEMACE*** *(Multi-agent model to simulate agricultural and hunting management of the Camargue and its effects)* simulates the interactions between hunters, farmers and duck population of a habitat. The system investigates the correlations between human activities and the environment and their impacts to the land use and the population of ducks.

A bargaining model to simulate negotiations between water users for the hydrologic basin ***Adour***, in reported by Thoyer *et al.*2001. Seven agents are employed to represent farmers, water utility, taxpayers and non governmental organisations that negotiate alternatives of water use.

In Recknagel (2002) an Aquatic Ecosystem Simulation with Adaptive Agents (***AqEcAA***) is reported. This work presents an conceptual framework simulating the aquatic food web and species interactions by using adaptive agents.

Significant contribution to the management of aquatic resources with agents had the ***FIRMA*** project (Freshwater Integrated Resource Management with Agents). FIRMA applied agent-based modeling for the integration of natural, hydrologic, social and economic aspects of freshwater management. A variety of agent-based models has been developed for simulating consumers, suppliers, and government, and their interactions at different scale of aggregation. One of the FIRMA test cases has been applied on the Thames river to explore the effects of precipitation and temperature on water availability and household demand (Barthelemy et al. 2001). In this case, water consumer agents communicate with each other, sharing perspectives in the form of endorsements (Moss et al 2000).

Finally, another system that models territoriality and dominance of canid populations and their effects on population dynamics was developed by Pitt et al. 2003. The ***CANID*** system employes autonomous agents for simulating the population dynamics of coyotes using the Swarm platform (Swarm Development Group 2001), that supports agent interaction with variable schedules and hierarchies.

3. SYNOPSIS AND DISCUSSION

In the previous section twenty three systems that utilize agent technology have been discussed. A summary of these systems are presented in Table 1. In order to assess the penetration of agent technologies in environmental software, we evaluated the characteristics summarized in Table 1 from two perspectives. The first is related to agent-based software design and the second is related to agent-based software development.

3.1. Software design

From this aspect we evaluated use of agent-related technologies in software design and modeling. The notion of an agent can be used in four levels. At the lowest level, we gathered systems that use some agent-alike "*entities*". In the second level, we have systems that are modeled using agents, typically involving UML design. The third level involves agents for software specification, by adopting BDI (Rao & Georgeff, 1995), LORA (Wooldridge 2000) or similar techniques. Finally, in the upper level we clustered systems that adopt a sophisticated agent-oriented software design process, as Gaia (Zambonelli *et al*., 2003) and Tropos (Giunchiglia *et al*.2002).

3.2. Software development

From a software implementation perspective, we identified three levels of penetration of agent-related technologies:

– Implementation with objects.
– Implementation with software agents, typically confronting with FIPA standards (FIPA, 1999).

#	Acronym	Main tasks and objectives	Application field	Related technologies	Agents (names or types)	Related publications
1	***EDEN-IW & InfoSleuth***	Data integration and homogeneous access provision services	Water resources data	JADE, FIPA-ACL, SQL, RDF	DB resource agent, query decomposition agent, ontology agent, broker agent	Nodine et al. 2000, Pitts *and* Fowler 2001, Felluga et.al 2003
2	***NZDIS***	Integrated querying services in an open, distributed environment of heterogeneous databases	Environmental data	FIPA-ACL, UML, OQL, RDF	ontology agent, resource agent, query processing agents, broker agent	Cranefield and Purvis 2001, Purvis et al. 2003
3	***FSEP***	Survailance, forecasting and alert of weather conditions	Meteorology	JACK, RDF-S, DAML+OIL	wrapper agents, interface agents	Dance et al. 2003
4	***BUSTER***	Data integration and filtering, querying services	Geographical information sources	OIL, [FIPA-OS]*	Wrapper, mediator, mapper	Neumann et al. 2001
5	***MAGIC & DIA-MOND***	Fault detection in industrial process	Water treatment process and Water-Steam cycle a power plant	XML, CORBA, FIPA-ACL	diagnostic agents, data acquisition agent, knowledge acquisition agent, wrapper agents, monitoring agent	Köppen-Seliger et al. 2001, Albert et al. 2002, Albert et al. 2003.
6	***SAEM***	Monitoring the pollutant cloud emitted by a power plant chimney	Atmospheric pollution	robotic agents	helicopter agents	Seco et al. 1998
7	***RAID & Kaleido-scope***	Pollution monitoring and control in indoor environments	Indoor air quality	"entities"	-	Micucci 2002
8	***D-NEMO***	Air pollution incident forecasting	Atmospheric pollution	LALO, KQML	station agents, model agents	Kalapanidas and Avouris 2002
9	***EDS-DAI***	Project evaluation and assessment with respect to alternative locations that comply with legal regulations, development plans and satisfy custom requirements	Environmental project evaluation	[Distributed Belief Revision]*	evaluation agents, GIS agents	Malheiro and Oliveira 1996
10	***NED-2***	Forest ecosystem management simulation and goal-driven decision support	Forest management	C++, Prolog, HTML	Interface agent, Simulation agent, Goal analysis planning agent, GIS agent, Report generation agents	Nute et al. 2004
11	***PICO***	Design system requirements, analysis of organizational complexity, dealing with all the dependencies between the domain stakeholders, and study of natural plant protection techniques.	Integrated production in agriculture	[Tropos, WEKA]*	GIS agent, Disease Behavior Learner, wraper agents	Perini and Susi 2004
12	***ESAT-WMR***	Modeling and analysis of elective strategies for urban water supply pipe network rehabilitation	Water supply networks	KIF, KQML, Object-oriented programming	Interface agent, Heuristics agent, Information agent, Datamining agent, Database agent	Davis and Sharp 1999, Davis 2000
13	***IDS-DAP***	Market penetration of agricultural products investigation, using multicriteria analysis	Differentiated agricultural products marketing	UML, Visual Basic, TCP-IP	Data analysis agent, Brand Choice agent, Market expert agent	Matsatsinis *et al.* 1999, 2003
14	***DAI-DEPUR***	Simulation and control of the physical, chemical, micro-biological aspects of the activated sludge processes	Waste water treatment plants	LISP, G2, GAR, LINNEO+	knowledge base agents, case-based reasoning agents, supervisory agents	Sànchez *et al.* 1996
15	***SHADOC***	Farmer behavior and water allocation simulation	Water catchment management	UML, SmallTalk, Object-oriented programming	PumpStation, Reach, Watercourse, Plot, Farmer	Barreteau & Bousquet 2000
16	***CATCHSCAPE***	Simulation of the whole catchment features as well as farmer's individual decisions	Water catchment management	UML, SmallTalk, Object-oriented programming	Plot, Crop, Farmer, Canal, Weir, Canal Manager, River,	Becu *et al.* 2003
17	***SINUSE***	Physical and socio-economic interactions modeling for simulating demand management negotiations on a free access water table	Integrated management of a water table	UML, SmallTalk, Object-oriented programming	Plot, Water table, Farmer	Feuillette *et al.* 2003
18	***STAU-Wien***	Simulation of rural development patterns in the Vienna Region	Rural development	UML, ArcInfo, Cellular automata, Object-oriented programming	enterprises, households	Loibl & Toetzer 2003
19	***GEMACE***	Simulation of interactions between duck population, farming decisions and leasing of hunting rights	Environmental planning	UML, Smalltalk, Object-oriented programming	hunting manager agents, farmers agents	Mathevet et al. 2003
20	***Adour***	Stakeholder negotiation over water use	Water management	[BDI]*	farmers, environmental lobbies, water manager, taxpayer	Thoyer et al. 2001
21	***AqEcAA***	Simulation of aquatic food webs and plankton species interactions	Food chain	Echo	phytoplankton species, zooplankton species	Recknagel 2003
22	***FIRMA & Thames***	Agent-based modeling for the integration of natural, hydrologic, social and economic aspects of freshwater management.	Water resource management	SDML	Policy agent, citizens	Barthelemy et al. 2001, Moss et al 2000
23	***CANID***	Agent-based simulation of territoriality and dominance of canid populations	Biodiversity – Population dynamics	Swarn	coyote	Pitt *et al.* 2003

Note: Applications marked with a star (*) are reported to be in the design phase or partially implemented.

Table 1. Summary of the systems reviewed.

– Implementation using agent-platforms, such as JADE, ZEUS, JACK, etc, reviewed in Mangina (2002).

3.3. Geometrical implementations

In an effort to qualitatively geometrize the degree of adoption of agent technologies in the reviewed applications, Figure 1 has been sketched. The horizontal axis tries to capture the use of agent techniques for software development, while the vertical one depicts the adoption of agent-related software design methods. Such an illustration could be considered quite subjective[1], however it provides an outlook of the efforts reported in the recent literature and can lead to some valuable conclusions, discussed below.

4. CONCLUSIONS

The main conclusion of this presentation is that agent technology has been adopted in environmental informatics in a limited, rather fragmented way. It becomes evident that agent-based design techniques is somehow admired in environmental decision support and simulation systems, and that agent based programming is popular for environmental management systems. However, agent technology is not homogeneously adopted in environmental software developments. The sole application that reports an agent-oriented software engineering technique throughout the whole design process is *PICO***,** while software development using agent-based programming techniques is not accompanied with agent-based design to a great extend. Therefore, it can be inferred that agent technology hasn't been diffused at the greatest extend and there are underexploited tools and techniques, available for future work. For example, socio-economic agent-based models and simulations could adopt agent technology both for software modeling and implementation, as we described elsewhere (Athanasiadis *et al*. 2005). Finally, we identify the lack of generic methodology for adopting agent technology in environmental software, which will set the frame of work under the particular needs of environmental informatics.

NOTE

Some of the project acronyms used in the paper have been devised by the author for enhancing the presentation of Table 1 and Figure 1. Also, the our prior works in the field were not included in the review.

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[1] For example, the most advanced agent-related technologies (as agent-oriented software engineering and agent-based programming) were not available at the time some systems have been developed.

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