Transactions in GIS, 2007, 11(4): 483–506

Review Article

Geospatial Agents, Agents Everywhere . . .

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Abstract
The use of the related terms "agent-based", "multi-agent", "software agent" and "intelligent agent" have witnessed significant growth in the Geographic Information Science (GIScience) literature in the past decade. These terms usually refer to both artificial life agents that simulate human and animal behavior and software agents that support human-computer interactions. In this article we first comprehensively review both types of agents. Then we argue that both these categories of agents borrow from Artificial Intelligence (AI) research, requiring them to share the characteristics of and be similar to AI agents. We also argue that geospatial agents form a distinct category of AI agents because they are explicit about geography and geographic data models. Our overall goal is to first capture the diversity of, and then define and categorize GIScience agent research into geospatial agents, thereby capturing the diversity of agent-oriented architectures and applications that have been developed in the recent past to present a holistic review of geospatial agents.

1 Introduction

Intelligent agents originated as an extension of artificial intelligence (AI) research in the late 1980s and early 1990s. The term refers to relatively autonomous software that manages information searching/retrieval and simulation in complex and changing operating environments such as the Internet. Since their inception, agents have become a popular technology for a variety of computer applications, ranging from managing human-computer interactions to simulating social interactions. Agents have become very popular in Geographic Information Science (GIScience). Recent special issues and editorials in the journals *Ecology and Society* (Janssen and Ostrom 2006), *International Journal of Geographic Information Science* (Brown and Xie 2006), and *Transactions of GIS* (Albrecht 2005) highlight this trend.

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Numerous reasons explain why agent research and modeling resonate with GIScience. With the increasing availability of finer grained spatial data, agent models offer a high level of disaggregation. They address scale concerns at a conceptual and functional level; agents eliminate the modifiable areal unit problem by creating objects that operate at the lowest unit of analysis. At the same time, agents can move across spatial scales and extents, whether these are simulated landscapes or computer networks. Agent models allow for interactions with the environment because they sense landscape characteristics and interact with other agents of like or different types. Agents also are appealing because they are dynamic (in terms of temporality), can move across different data repositories and platforms, and can be designed to understand properties of geospatial data, thereby addressing issues of interoperability which have long stymied the integration of GIS and spatial modeling. Taken together, these characteristics ensure that the intelligent agent paradigm is one that will continue to attract GIScience researchers.

Despite its appeal to a wide variety of GIScience applications, individual researchers tend to cluster their definition of an agent around its applications to geographic modeling. Primarily, agents in GIScience are viewed as existing solely in the realm of geosimulation (e.g. Benenson and Torrens 2004). These researchers have taken the first step to engaging the community on the integration of GIS and dynamic simulation modeling. A broader view of multi-agent systems that encompasses a range of autonomous software entities in a range of conceptions of geographic space (e.g. simulated real places, neutral or hypothetical landscapes, distributed spatial databases, computer networks, and IP addresses) is still necessary. We argue that a broader view will bring coherence to agent research in the GIScience literature and move the field forward. Additionally, some writers assume that their readers are well-versed with the origins of agents, and understate the value in further developing these two historical frameworks upon which the uniqueness of these systems rest. As a consequence, a compendium of applications of agents to GIScience is hard to find in a single paper. To overcome these lacunae, this paper defines and categorizes the range of agent applications in GIScience in terms of AI research. It then presents a concise and inclusive definition of a Geospatial agent.

1.1 Defining an Intelligent Agent

In early AI research, the term ‘agent’ was a “buzzword” that described a wide range of software with different structural and functional characteristics, a situation mirrored to some degree in GIScience. Nwana (1996) hypothesized that this confusion arose because the label ‘agent’ is generic with no claim over it by agent researchers. The confusion proved detrimental to initial agent research because of indiscriminate application of the term to any and all software (e.g. disaggregated dynamic models), which in turn diminished the significant complexity of agent-based systems (which require significant knowledge structure and internal reasoning mechanisms).

Subsequent consensus amongst AI researchers suggested that to be considered an intelligent agent, the software/computer model must possess the following four properties: (1) autonomous behavior; (2) the ability to sense its environment and other agents; (3) the ability to act upon its environment alone or in collaboration with others; and (4) possession of rational behavior (Woolridge and Jennings 1995, Woolridge 1999). To aid in inter-agent collaboration and communication, specific Agent Communication Languages, for example, the Knowledge Query and Manipulation Language (Labrou et al. 1999), have also been developed. Additionally, researchers have pointed out that intelligent agents should not only be able to respond to, but also learn from, their environment (Maes 1994). Humanistic characteristics such as beliefs, desires, intentions (Shoham 1993), and emotions and trust (Maes 1994) also could form a part of agent behavior. Some form of rational behavior may be dictated by using heuristic models of decision-making within the agent, which can be used to capture some (but not all) of the additional characteristics ascribed above.

Following from the AI definition provided above, two key questions must guide a literature review of agent applications in GIScience. First, are the commonalities of representation and behavior that define AI agents transferable to agents in the GIScience literature? The second question is more fundamental to the existence of GIScience as an area of enquiry: Is an agent used for GIScience applications sufficiently distinct from AI agents that we can call it a "geospatial" agent? The answer to these questions lies in comparing existing GIScience agent research against the established characteristics of an 'agent' in AI research and in identifying, if any, similarities and differences.

Towards this goal, we evaluate the two common frameworks of intelligent agent research in GIScience for evidence of agency. These two common frameworks are distinguished as artificial life agents (most closely akin to geosimulation) and software agents.

1.2 Intelligent Agent Frameworks in GIScience

Franklin and Graesser (1996) developed an extensive classification scheme for the wide variety of agent research in the AI literature (Figure 1). This classification scheme has become an influential guide in framing agent-based research.

We systematically reviewed the GIScience literature and identified two general traditions for the use of the term agents. One definition of agents in GIScience focuses on modeling an individual's action in a social world (Parker et al. 2003). Another body of agent applications in GIScience defines agents as autonomous software designed to reduce work and information overload during Human-Computer Interactions (HCI) (Tsou and Buttenfield 2002, Sengupta and Bennett 2003). Specifically, the former perspective emphasizes the modeling of social interactions among people (or other biological beings), whereas the latter promotes interaction among software components to provide assistance to users. According to Franklin and Graesser's (1996) diagram, the

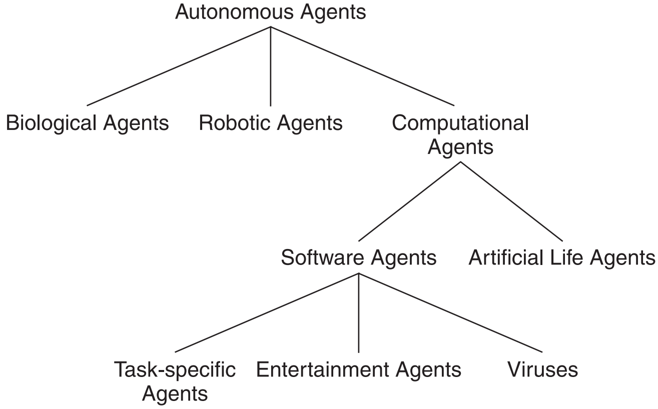

Figure 1 Classification of agents proposed by Franklin and Graesser (1996)

Table 1 Terms used for categories of agents in GIScience (Franklin and Graesser 1996)

Authors	Artificial Life Agents	Software Agents
Rodrigues et al. 1997	Spatial Simulation Agents	Interface Agents
O'Sullivan and Haklay 2000	Agent-based Models	Multi-Agent Systems
Koch 2000	Social Simulation Research Agents	Multi-Agent Systems
Parker et al. 2003	Multi-Agent Systems	
Hare and Deadman 2004	Agent-based Modeling	Multi-Agent Simulation

two categories of agent-research in GIScience fall under the category of computation agents and are denoted by the terms "artificial life agents" and "software agents", respectively. GIScientists employ slight variations in the actual terminology. Synonyms proposed for these two categories of agents by GIScience researchers are captured in Table 1.

Although the exact names of what have emerged as two distinct strains of intelligent agent research in GIScience have not troubled researchers in the past, researchers should take into account the semantic and ontological confusion of the early years of AI research. Public hype over promising new technologies (e.g. expert systems in the mid-1980s) was soon followed by disillusionment with their true potential in mirroring human intelligence (Nwana 1996). Fuelling this disappointment were developers who touted "intelligence" in their software when there was none. Indeed, it was the need to distinguish the computer program from an agent and the desire to capture the diversity of agent programs in the current literature, which prompted the article by Franklin and Graesser (1996). Doing so has enabled the AI community to rally around a common ontology and significantly advance the field in recent years.

The remainder of this paper is directed at reviewing the predominant applications of agents in GIScience, to potentially discover a common set of properties applicable to all geospatial agents.

2 A Review of Agents in GIScience

We refer to the two types of agents that predominate in GIScience as Artificial Life Geospatial Agents (ALGAs) and Software Geospatial Agents (SGAs), respectively. Whereas ALGAs focus on modeling social interactions and response to stimuli of (primarily) biological organisms, SGAs act as software assistants to computer users, managing and automating specific hardware/software tasks. These two categories of agents as used in GIScience are further defined below.

2.1 Artificial Life Geospatial Agents

ALGAs are computer models, either independent programming code interacting with other code or a single piece of software. They mimic the perceived or measured behavioral response of an individual to an external stimuli using one of the many available computational models of boundedly rational decision-making behavior as impacted by social networks. ALGAs span conceptions of entities: from atoms and animals to people and organizations (Parker et al. 2003). They change over time and respond to stimuli through a variety of mechanisms, such as genetic algorithms/programming, heuristic methods (e.g. expert systems), game theory, linear programming, and reinforcement learning (Berger 2001, Balmann et al. 2002, Gimblett et al. 2002, Hoffman et al. 2002, Lim et al. 2002, Sasaki and Box 2003). The development of various software platforms to facilitate the modeling of ALGAs, for instance SWARM (Terna 1998), Cormas (Bosquet et al. 1998), and RePast along with its ArcGIS extension called Agent Analyst (Najlis and North 2004), indicates their growing popularity in the social sciences. The reader is referred to an extensive overview of the various ALGA platforms by Gilbert and Bankes (2002).

O'Sullivan and Haklay (2000) suggest that the roots of ALGA lie in research on the flocking behavior of birds and animals (Reynolds 1987, Levy 1992, Resnik 1994, Westervelt and Hopkins 1999) and simulations of social behavior and interactions among people (Esptein and Axtell 1996, Gimblett et al. 1998, Gilbert and Troitzsch 1999, Janssen and Jager 2000, Berger 2001). ALGAs also parallel the development of Individual-Based Models (IBMs) in the ecological literature (McGlade 1999, Ahearn et al. 2001, Bian 2003). It should be noted that ALGAs have even deeper social-science roots. These include game-theory approaches that model risk-minimizing strategies (Gould 1963, Gotts et al. 2003). They also include discrete choice theory (Ben-Akiva and Lerman 1985) and other decision making models (Smith et al. 1984, Fischer and Nijkamp 1985, Couclelis 1986, Mohammadian and Kanaroglou 2003) that simulate response to stimuli, process cognitive information and decide among alternatives in space.[1] Additionally, ALGAs borrow concepts from cellular automata, for example models of urban sprawl (Batty 1996, Batty and Xie 1997, Clarke and Gaydos 1998, White and Engelen 2000).[2] Consequently there is a rich tradition upon which to model the behavior of and interactions among individual agents. The ALGA community of researchers rarely, if ever, refers to AI research in computer science. Perhaps the unstated perception, according to O'Sullivan and Haklay (2000), is that whereas the term agent originated in distributed AI research, the growth of agent research was significantly impacted by post-war English language social science (e.g. discrete choice models).

Table 2 describes current research on ALGAs, showing the authors, a description of their work and a thematic categorization based on the processes modeled with agents. Based on both mobility of and information exchange between agents, we have grouped the papers into five main themes, which are: (A) adoption of agricultural practices/subsidy, (B) patterns of human movement (and settlement, if necessary), (C) human social collaboration (or networks), (D) movement of animals, and (E) Land Use and Land Cover Change (LUCC).

These five themes were chosen because geographers focus on studying interactions in the biosphere (i.e. people, animals and their environments) and therefore research tends to be restricted to this domain. In addition, the behaviors being modeled (i.e. hunting/foraging, recreation, locating homes, making land use decisions, fighting forest-fires, movement of pedestrians and shoppers) all utilize some form of individual decision making within a social matrix.

In addition to thematic similarity, ALGAs share two broad characteristics at the operational level. First, they possess mobility in the virtual landscape. This may be expressed by, for example, recreators in a national park (Deadman and Gimblett 1994) and predator-prey interactions (Westervelt and Hopkins 1999). Mobility can be used to

Table 2 Artificial life geospatial agents

Author	Brief Description	Themes (letters in parentheses refer to categories in Table 1)
Balmann et al. 2002, Happe et al. 2006	Modeling effects of reducing subsidy for livestock-fodder co-production; structural changes (interest rates, technology) resulting from new payment structures	Adoption of agricultural practices/subsidy and human social networks (A, C)
Batty et al. 2003	Pedestrian movement in carnivals and parades	Patterns of human movement (B)
Benenson 1999, Benenson et al. 2002	Modeling mobile and immobile urban objects; agents in the context of real-estate development	Patterns of human movement and settlement (B)
Bennett and Tang 2006	Modeling elk migration patterns in Yellowstone National Park	Movement of animals (D)
Berger 2001	Diffusion of innovation and resource use changes in agriculture	Adoption of agricultural practices/subsidy and human social networks (A, C)
Bosquet et al. 2002	Hunting of wild meat in Cameroon	Patterns of human movement and settlement; Human social collaboration (B, C)
Brown and Robinson 2006, Fernandez et al. 2005, Omer 2005	Preference of residential agents for moving to their present location; residential segregation	Patterns of human movement and settlement (B)
Box 2002, De Vasconcelos et al. 2002	Forest fire-spread and fire-fighting	Human social collaboration (C)
Castella et al. 2005	Landuse change model for Vietnam derived from role-playing games to identify and represent driving forces	Land Use and Land Cover Change (LUCC) (E)
Cavens et al. 2003, Gloor et al. 2003	Pedestrian movements in virtual Alpine Landscapes	Patterns of human movement (B)
Deadman 1999	Common-pool resource management	Human social collaboration (C)
Deffuant et al. 2002	Modelling of organic farming conversion	Adoption of agricultural practices/subsidy and human social networks (A, C)

Table 2 *Continued*

Author	Brief Description	Themes (letters in parentheses refer to categories in Table 1)
Gimblett et al. 2002	Recreational uses of forest lands	Patterns of human movement (B)
Harper et al. 2002	Control of parasitic "cowbirds"	Movement of animals (D)
Heppenstall et al. 2005	Identifying petrol pricing strategies on UK Motorways	Human social networks (C)
Hoffman et al. 2002, Evans and Kelley 2004	Reforestation of agricultural lands in Indiana	LUCC (E)
Huigen et al. 2006	Farm expansion and settlement patterns in Phillipines resulting from demographic changes	LUCC (E)
Itami 2002	Behaviour of recreators on trails	Patterns of human movement (B)
Jepsen et al. 2006	Clustering of agricultural fields around villages	LUCC (E)
Jiang and Gimblett 2002	Pedestrian movements, isovist fields, viewshed analysis, watershed analysis and wildfire diffusion	Patterns of human movement (B)
Koch 2000	Shopping behaviour	Patterns of human movement (B)
Lei et al. 2005	Interaction of decision-makers with land owning agents to simulate impacts of policy	Human social collaboration and LUCC (C, E)
Li et al. 2005	Impact of the growing rural population on forests and the Wolong Nature Reserve for Giant Pandas	LUCC (E)
Ligtenberg et al. 2001, 2004	Complex land use planning process by local, regional, national authorities involving collaboration; agent-based models of stakeholders in simulating urban land allocation	LUCC, Human social collaboration (C, E)
Lim et al. 2002, Deadman et al. 2004	Decisions regarding use of land in Brazil; Land use behaviour of farming families along the Transamazon highway in Brazil	LUCC, Patterns of human movement and settlement (B, E)

Table 2 *Continued*

Author	Brief Description	Themes (letters in parentheses refer to categories in Table 1)
Manson 2005	Variations in agricultural land use in the Yucatan Peninsula of Mexico as a function of institutional and environmental predictor variables	LUCC (E)
Parker et al. 2002, Parker et al. 2003	Overview and categorization of various LUCC agent models	LUCC (E)
Sasaki and Box 2003	Exploration of Von Thunen's models	Patterns of human movement and settlement (B)
Sengupta et al. 2005	Adoption of conservation payments by farmers in Southern Illinois	Adoption of agricultural practices/subsidy and human social networks (A, C)
Torrens 2002	Agents and cellular automata for urban planning	Patterns of human movement and settlement (B)
Van Dyke Parunak et al. 2006	Exploration of possible paths through virtual environments	Patterns of human movement, Movement of animals (B, D)
Westervelt and Hopkins 1999	Interaction of individuals of a species with each other and a simulated landscape/habitat	Movement of animals (D)

further distinguish between ALGAs. If during a simulation, an ALGA is immobile and perceives and acts upon information obtained at a specific location in the virtual landscape, like cells in cellular automata, then its behavior is usually tied to the properties of the location and is significantly influenced by immediate neighborhood effects (although it is not immune from global changes). This strategy is employed by most land use-land cover change models and examples include those described by Ligtenberg et al. (2001), Torrens and O'Sullivan (2001), Berger (2001), Bosquet et al. (2001), Balmann et al. (2002), Deffuant et al. (2002), Hoffman et al. (2002), Parker et al. (2002), and Torrens (2002).

Conversely, an ALGA may "roam" the virtual landscape such that its actions vary based on the location of other agents and perception of available resources on a regional scale (e.g. predator-prey avoidance models and foraging models). Examples of ALGAs that describe such artificial life agents include Deadman (1999), Jiang (1999), Box (2002), Harper et al. (2002), Jiang and Gimblett (2002), Itami (2002), Gimblett et al. (2002), and Sasaki and Box (2003). Hybrid agent simulations, those that incorporate both mobile and immobile agents at different stages of the simulation, are also possible. A mobile ALGA may first decide on a patch to deforest, and then make a patch-specific decision about the type of crop to be planted on that patch (Lim et al. 2002).

A second feature of ALGAs is that they possess a computational structure to simulate individual behavior as well as social interactions. For individual behavior, the reader is referred to Parker et al. (2003), who indicate that bounded rational decision-making behavior can be modeled using genetic algorithms, heuristics (i.e. rules-based methods), simulated annealing, classifier systems, and reinforcement learning. To this group could be added recursive linear programming (Berger 2001, Balmann et al. 2002). For social interactions, models for information passing between agents have been developed based on spatial adjacency or using social/spatial networks (Auer and Norris 2001, Gilbert et al. 2001, Dibble and Feldman 2004, Ziervogel et al. 2005). This information exchange can subsequently affect behavior of an individual agent, thereby altering the outcome of a simulation.

ALGAs continue to dominate the GIScience literature on agents, and are increasingly popular, partly because researchers see ALGAs as an important tool for social science modeling (Brown et al. 2005b). One can expect that, in the future, an even larger set of interactions and behaviors between humans, animals and the natural environment will be modeled using ALGAs.

2.2 *Software Geospatial Agents*

SGAs serve a quite different purpose from ALGAs. ALGAs model the behavior of entities, whereas SGAs assist people more directly in managing information and making decisions in hardware and software environments. Broadly defined, SGAs are designed to act autonomously on behalf of an entity to manage geographically explicit information. An entity can be a person, another software agent, a piece of software like GIS, or hardware such as cellular phone towers.

Software agent research, of which SGAs are an instance, arose from the distributed AI community. This community was disillusioned by monolithic approaches to modeling human intelligence and believed that knowledge could be distributed into elemental components that generated emergent and intelligent behavior through interaction (Hayes-Roth and Hayes-Roth 1979, Hayes-Roth 1985, Huhns 1987, Bond and Graesser

1988). Current research on this topic builds on recent advances in user/software interface development from distributed AI research (Etzioni and Weld 1994, Maes 1994), network mobility (Kotz and Gray 1999) and Internet data- and information-mining algorithms (Knapik and Johnson 1998).

SGAs share three common features, which are spatial information handling, distributed problem solving and the ability to facilitate interoperability. SGAs are designed with knowledge about spatial data models and geospatial issues (e.g. scale, georeferencing, representation, extent, metadata, and accuracy) so that they can handle spatial information. In terms of distributed problem solving, SGAs are identical to software agents; they work over the networked environments using disparate pieces of information located on multiple machines. SGAs possess interoperability. They can work across platforms (different software and hardware platforms as well as forms of geospatial data representation) that allow them to seamlessly integrate spatial data and process models. This links SGAs to a rich GIScience literature on ontology, representation, and semantics.

Instead of arranging SGAs by themes (as done with ALGAs), we divide them by tasks. Rodrigues and Raper (1999), originally described the potential of SGAs to handle four crucial types of spatial activities: (1) using knowledge of the users' interests and preferences to manipulate and display geospatial data (for brevity, we abbreviate such agents as "personal agents"); (2) assisting users interact with GIS and other spatially explicit external software packages (agent-assisted HCI); (3) locating and retrieving spatial data from the Internet; and (4) assisting decision-making in collaborative spatial tasks such as environmental planning (SDSS agent). Personal agents are best described by Campos et al. (1996) where their user-interface agents provide assistance to users of the Arc/Info GIS software. Examples of agent-assisted HCI combined with spatial data retrieval functionality include Sengupta and Bennett (2003) and Nute et al. (2004), both of whom detail agent-based environments that use multiple interacting agents to retrieve and manipulate spatial data and models for decision-making environments. Medeiros et al. (2001) provide an example of SDSS agents that assists a group of decision-makers reach consensus.

Rodrigues and Raper's (1999) typology provides an initial framing. We believe it requires some additions, the prime example being the absence of mobile agents (i.e. softbots that traverse across networked computers) in their typology. This omission understates the potential role that GIScience has and can play to intelligent agent research in understanding how agents physically move across networks or devices (e.g. topology in mobility). Tsou and Buttenfield (2002) describe a distributed geospatial analysis environment that uses mobile agents as a key characteristic of its operation. Possible future GIScience applications will likely necessitate the use of mobile agents to navigate a computational grid (Armstrong et al. 2005) or search through large information repositories with different ontologies and interpret semantically different material.

Rodrigues and Raper's (1999) typology also needs to be further expanded to cover the spectrum of emerging GIScience applications. Based on a review of the literature, we add seven categories to their four. Table 3 describes these new categories of tasks, which may overlap in an agent architecture. For example, an agent-based system may retrieve geospatial information for the user from a distributed data repository and then carry out multiple tasks related to data mining and knowledge discovery, data fusion, geocomputation resources monitoring, and semantic interoperability.

Table 4 summarizes the various researchers working on developing agents for GIScience applications. Each instance provides a brief description and categorizes applications based on task.

Table 3 Task-based categorization of software geospatial agents

1. Personal Assistants (agents use knowledge of the users' interests and preferences to manipulate and display geospatial data)
2. Agent-assisted HCI (agents assist users interact with GIS)
3. Spatial data retrieval (agents assist users locate and retrieve spatial data from Internet)
4. SDSS agents (assisting decision-making in collaborative spatial tasks such as environmental planning)
5. Contextual visualization of geospatial information (agents knowledgeable about scale and rules of cartographic generalization)
6. Data mining and knowledge discovery (agents extract useful information from very large or distributed geospatial databases)
7. Data fusion (agents capable of integration of multiple geospatial datasets from a variety of sources and sensors)
8. Location Based Services (LBS) (agents identify services based on current location and individual preferences on hand-held devices)
9. Management of mobile devices (agents discover new resources such as available IP addresses on a mobile network; Hodes and Katz 1999)
10. Grid computing support (agents monitor available geocomputing resources and manage load distributions on a large, grid computing environment)
11. Semantic interoperability (agents ensure interoperability among digital repositories and software platforms)

3 Fitting Geospatial Agents back into the Mainstream

As shown in the above typologies and breadth of literature, intelligent agents provide a powerful frame for geospatial analysis and representation as well as data and model management. Agents are everywhere in GIScience. But are they truly agents from the perspective of AI research? And do they deserve the moniker "geospatial"? We delve into these two unanswered questions below.

3.1 Are ALGAs and SGAs really AI Agents?

Woolridge and Jennings (1995) provide perhaps the most comprehensive and accepted definition of agents within AI research. To be designated an "agent", the hardware or software must exhibit properties of autonomy, interaction and/or collaboration (with other agents or with humans) and rationality, combined with an ability to sense and act upon their environment (i.e. reactivity and pro-activity). To these may be added heuristics to specify rational behaviour in open environments, coupled with a degree of mobility within these environments.

An initial distinction can be drawn between agents and geospatial software programs (including spatial simulation models). Compared to an agent-based model, the program's output does not affect what the program senses later. Software programs also largely fail to possess temporal continuity. In other words, "it runs once and then goes into a coma, waiting to be called again" (Franklin and Graesser 1996, p. 8). This distinction underscores the ability of agents to respond to uncertainties, and is crucial in separating geospatial agents from regular geospatial software or dynamic spatial modeling.

Table 4 Software geospatial agents

Author	Brief Description	Themes (numbers in parentheses refer to categories listed in Table 3)
Ambite et al. 2002	Optimal selection of routes from among several alternatives for travel planning	Personal assistant (1)
Chen et al. 2003, Zipf and Aras 2002	Provision of LBS on mobile devices such as e-coupons	LBS agent (8)
Ferrand 2000	Automated generalization of features for cartographic visualization at different scales	Contextual visualization (5)
Goodenough et al. 1999	Estimation of forest parameters from data-fusion of remotely-sensed information	Data fusion and knowledge discovery (7)
Guan et al. 2000	Accessing distributed GIS resources from mobile devices with limited communication bandwidth and unstable connectivity	Management of mobile devices, Grid computing (9, 10)
Hodes and Katz 1999	Discovery of new resources (e.g. Domain Name Services) by mobile devices	Mobile device management (9)
Kretschmer et al. 2001	Interactive digital storytelling and multi-media visualization for tourism	LBS agent; Personal assistant (1, 8)
Lokuge and Ishizaki 1995	Interactive visualization of complex geospatial information	Agent-assisted HCI (2)
Luo et al. 2003	Quick navigation of spatial data located on a computer network	Spatial data retrieval (3)
Maamar et al. 1999	Navigation of large geospatial digital libraries with distributed resources	Agent-assisted HCI; Spatial data retrieval (2, 3)
Malaka et al. 2004	Identification of LBS services, selection and booking of services for user	LBS agent; Personal assistant (1, 8)
Medeiros et al. 2001	Coordination among users of group SDSS to reach consensus	SDSS agent (4)
Mustiere et al. 1999	Development of cartographic generalization rules using automated knowledge acquisition	Contextual visualization (5)

Table 4 *Continued*

Author	Brief Description	Themes (numbers in parentheses refer to categories listed in Table 3)
Nolan et al. 2001, Shahriari and Tao 2002, Purvis et al. 2003	Searching and management of distributed processing of geospatial data and imagery	Spatial data retrieval (3)
Rahimi et al. 2002, Rana et al. 2002	Conflate data from multiple sources (different scales, accuracy and projection; multi-spectral and multi-sensor data)	Data mining and knowledge discovery; Data fusion (6, 7)
Ray and Claramunt 2002	Load-balancing of computational resources in distributed heterogeneous geographic information processing environments	Grid computing (10)
Rodrigues et al. 1997	Assistance in interacting with geographical elements and environmental quality parameters for decision-making	Agent-assisted HCI; SDSS agent (2, 4)
Saarloos et al. 2001, 2005	Assistance during the planning process and development of consensus	Agent-assisted HCI (2)
Santos et al. 1998	Automated analysis of crime-pattern distributions	Data fusion and knowledge discovery (7)
Sengupta et al. 1996, Sengupta and Bennett 2003, Nute et al. 2004	Integration of models and spatial data located on Internet using standardized models and metadata for spatial decision-support	Spatial data retrieval; SDSS agent; Semantic interoperability (3, 4, 11)
Sheth et al. 2003, Stroe and Subrahmanian 2003	Development of ontology-based retrieval mechanism for spatial information	Semantic interoperability (11)
Tsou and Buttenfield 1998, 2002	Access to Internet-based repositories of geospatial data for provision of GIS data layers to mobile devices	Spatial data retrieval (3)
West and Hess 2002	Decreasing system learning costs for SDSS using well-structured metadata	Agent-assisted HCI; SDSS agent (2, 4)
Zhang and Gruenwald 2001	Retrieval of spatial information from distributed servers for display on mobile devices	Spatial data retrieval; Mobile devices (3, 9)

A further distinction between agents and geospatial software/modeling should, however, be made on the basis of a key characteristic of agents, autonomy. A weak notion of autonomy suggests that agents must, in addition to being reactive, be in control of their state and persist beyond the completion of a single task (Tosic and Agha 2004). However, this is true of many common software applications such as firewalls and virus scanners and, in the geospatial realm, of Internet Map Servers. A strong notion of autonomy requires that agents have goal-directed behavior and be proactive in achieving those goals. Humans or applications instantiate them but agents continue to run even after the instantiation mechanism has been terminated or is no longer present. Once instantiated, the agent must have knowledge of its goals, be in control of its actions, be able to make rational decisions in uncertain and open environments without prior knowledge about each and every situation they encounter, and require no assistance from human operators.

It should be recognized that unlike biological agents, autonomy for the SGAs and ALGAs are restricted to their operating environments. The operating environment can be the environment of computer operating systems or an artificial GIS environment (e.g. Najlis and North 2004, Brown et al. 2005a). Excepting this restriction, SGA and ALGA programmers strive to maintain a strong notion of autonomy. In the world of computer networks or code in a device, most SGAs by design follow the dictates of autonomy, interaction/collaboration, rationality, mobility, and sensing/perceiving of their environment. ALGAs also share similar characteristics, being designed to operate independently, and perceive/respond rationally to new situations and other agents within their GIS-based 'virtual worlds'.

Thus conceptualized, both ALGAs and SGAs can be situated within the general agent literature. In a classification scheme most likely to resonate with GIScience researchers, Franklin and Graesser (1996) suggest that artificial life and software agents are subsets of computational agents (see Figure 1) and are more similar than the categorization of such software into ALGAs and SGAs suggest. Both can be defined as "situated within and a part of an environment that senses that environment and acts upon it, over time, in pursuit of its own agenda and so as to effect what it senses in the future" (Franklin and Graesser 1996, p. 7). Both agents can be designed to possess a strong notion of autonomy, in that they sense features of their environment, have specific goals and react autonomously on the features to achieve these goals. Further, they can act continuously over time, until they expire or choose to stop. In doing so, both ALGAs and SGAs can fulfill the definition of a computational agent from distributed AI.

The characteristics we posit above are the minimum requirements for a piece of software code to be called an "agent" in the AI literature. Additional distinctions may be made about the complexity of an agent's decision-making process to distinguish between a planned, that is cognitive, response versus a purely reactive response (Ferber 1999), and between agents that have the capacity to learn and adapt to those that do not (Tan 1993). These categorizations do not distract from the original definition. Researchers may contest whether or not the complex nature of the open environment in which these agents operate necessitates planning and learning by agents. However, emergent properties (i.e. the formation of complex patterns from simple rules) observed as a result of inter-agent interactions in a simulated environment needs neither complex behaviors nor learning ability (e.g. Schelling 1971, 1978). Instead, emergent patterns depend on initial conditions of an environment (e.g. Parker and Meretsky 2004) and result from the positive and negative feedbacks that operate on and amongst agents in that environment.

3.2 Is there a Geospatial Agent?

In the first instance, we asked whether ALGAs and SGAs fit within the AI paradigm of agents. Here, the broader question is whether applications of agents in GIScience deserve the moniker of "geospatial agents" (i.e. do they deserve a separate researchable entry in AI research)? Let us revisit one definition of agents in GIScience. According to Rodrigues et al. (1997, p. 114) spatial agents are autonomous software entities that can reason over representations of the environment. Instead of spatial agents, we utilize the more precise term geospatial agent because we believe that geography must be explicit and, unlike Rodrigues et al. (1997) who consider only SGAs or Hare and Deadman (2004) who consider only ALGAs, the term must encompass all types of agents in GIScience. Explicit geography includes both ALGAs that utilize geospatial data to create a representative model of the real world and SGAs that possess an inherent knowledge of geospatial data and its idiosyncrasies. Because they must be cognizant of geospatial data and its constructs, the initial answer to whether there are "geospatial agents" appears to be 'yes'.

ALGAs and SGAs without a notion of geographic space or spatial constructs would be severely limited in their functionality. For example, agents in agent-based computational economics (Tesfatsion 2002) are not explicitly geospatial; whereas, ALGAs are tied to a location in a geospatial environment, and preferably to locations in the real world (Deadman et al. 2004, Evans and Kelley 2004, Sengupta et al. 2005). SGAs must handle a lack of standards over data and software in GIScience, all of which pose a special challenge for semantic interoperability. Lacking a knowledge of the nuances of geospatial data and spatial constructs, most AI software agents would fail to function in a GIS environment. Both of these cases call for the explicit use of the term "geospatial" to define both ALGAs and SGAs.

The use of the moniker "geospatial" also may yield technological benefits from a functional perspective. For example, the Internet lacks geographic topology, that is, it is easy for intelligent agents to find two adjacent IP addresses but not their relationship in Euclidean space. As yet, there are no widely adopted standards for expressing this topology. This causes a significant hurdle for mobile SGAs. Appreciating the nuances of geography and introducing geographic coordinates as a part of IP specifications could not only benefit the SGAs but also the Internet community, for example, this knowledge can be used to automate the downloading of data from the nearest mirrored server.

Heretofore, we have focused on what AI offers to GIScience. However, GIScience offers to AI research on geospatial agents an enormous and nuanced literature on human behavior and a more general critique of models. Previously we mentioned discrete choice and decision making models (e.g. Smith et al. 1984, Ben-Akiva and Lerman 1985, Fischer and Nijkamp 1985, Couclelis 1986, Mohammadian and Kanaroglou 2003). Such models would allow AI, which presumably models human behavior with agents, to incorporate decision-making strategies within their framework. To this we add the critiques of modeling and GIS (Pickles 1995). GIScience research draws on human geography methods to interrogate the cultural and positivist assumptions that can be embedded in the design of systems. Some of this research could apply to AI agents, giving AI the ability to better contextualize interactions over space.

3.3 The Future of Geospatial Agents

Currently, various researchers are working on methodology suitable for developing SGAs for a variety of GIScience applications, including agents for geocollaboration, that is, developing map categories and field-research planning by groups of individuals (MacEachren et al. 2004), for automated choice of interpolation methods and parameters (Jarvis et al. 2003), and for creation of multi-criteria class intervals in choropleth mapping (Armstrong et al. 2003). Efforts are also underway to develop ALGAs that integrate cellular automata and agents for the modeling of complex geographic systems (Torrens and Benenson 2005), and to create new applications such as modeling the effectiveness of greenbelts in reducing urban sprawl (Brown et al. 2004).

Our last point is that ALGA and SGA represent a thin slice of the agent classification taxonomy proposed by Franklin and Graesser (1996). Figure 1 shows the tiny corner that they occupy. Considerable research is being conducted in robotic agents and virus protection. A broader perspective of geospatial agents would consider these categories as well as interaction among the multiple categories, and GIScience would have much to offer to the expanded research agenda. For example, the use of Global Positioning Systems (GPS) technology to position robots in the real world, is a growing and important area of research (DARPA 2006). Certainly, geographic research on naïve wayfinding (e.g. Egenhofer and Mark 1995, Golledge 1999) by biological agents (i.e. humans) could inform the positioning of robots by means other than GPS signals, and enable robots to autonomously traverse regions without accurate signals, such as urban canyons and inside buildings.

In the future, GIScience research on intelligent agents in areas such as real-time resource management systems likely will necessitate some convergence of ALGAs and SGAs (consider that most SGAs already are hybrids). A hypothetical example that combines and integrates ALGAs and SGAs could include a dynamic taxation scheme for reducing congestion on roads in major metropolitan areas. Such a system would vary tolls on different highways according to traffic density and number of cars at various locations, and would require interaction of the system with agents that are guiding individual users to their destination. A current example is the creation of the software application called Multi Agent-based Behavioral Economic Landscape (MABEL) by including distributed processing (i.e. outsourcing simulation tasks to remote computers on a network) as a part of their ALGA architecture (Lei et al. 2005). ALGAs and SGAs are likely to benefit from close linkages between each other and with AI.

4 Conclusions

Clearly geospatial agents are here to stay. They have broad applicability in modeling behavior, whether it involves human patterns in space or organizational actions in choosing land uses. They hold out the opportunity to help us manage geospatial information and heuristically manage connections among physically dispersed data management systems and spatial process models.

Our review of the literature has revealed that prior definitions in GIScience (O'Sullivan and Haklay 2001, Tsou and Buttenfield 2002, Parker et al. 2003, Sengupta and Bennett 2003) embody ALGA or SGA but not both. This reflects the different origins and trajectories of agent development. Whereas ALGAs and SGAs share computational similarities (i.e. both are software objects that respond to external stimuli and modify their operating environments) and can be defined as agents, there are significant ontological differences between the categories. However, ALGAs and SGAs can be viewed as similar and complementary research streams that may converge in the near future, and these two streams should be clarified to ensure future innovations in this direction.

The question is, can GIScience lay claim to a geospatial agent that represents a distinct instance of intelligent agents? We believe the answer is yes, because of the explicitly geographic or spatial nature of agents and the tools with which geographers can bring to examine them (e.g. scale, extent, proximity, and topology).

Additionally, geospatial software, spatial simulation models, or AI technologies such as expert systems, do not constitute agent-based systems. Geospatial agents must: (1) have a strong notion of autonomy; (2) contain explicit geospatial locations; and (3) handle the unique qualities of geospatial data. Thus, ALGAs move between specific places in a virtual space, whether it is an idealized landscape or a representation of actual geography. SGAs are concerned with spatial locations, such as cell phone locations or map extents. To some degree, this is a matter of emphasis: instead of geography being a component of the process, in GIScience it is brought to the foreground. Just as important, geospatial agents must handle the unique characteristics of geospatial data, that is geographic topologies, spatial distributions, representations (e.g. features), data structures (e.g. raster and vector), and geographic concepts (e.g. projection, coordinate systems, and scale). It is insufficient to move across space; geospatial agents must possess an intelligence of that space. In doing so, geospatial agents will continue to play an important and critical role in GIScience research and define a niche separate from both AI and social science simulation research.

Notes

1 We are grateful to Helen Couclelis for suggestions on the roots of ALGA.
2 Torrens and Benenson (2005) distinguish between ALGAs and cellular automata. In ALGAs, "individual automata are free to move within the spaces that they 'inhabit'. With cellular automata, *information* moves between cells".

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