An Agent-oriented software engineering paradigm and the design of a new generation of spatial information system

Yuxiao Li[1]*, George Benwell*[2]*, Peter Whigham*[3]*, Nick Mulgan*[4]

[1,2,3]Spatial Information Research Centre
University of Otago. Dunedin, New Zealand
Phone: +64 3 479-8301 Fax: +64 3 479-8311
Email: yli, gbenwell, pwhigham@infoscience.otago.ac.nz

[4]Compudigm International, Wellington, New Zealand
Phone: +64 4 499 9881 Fax: +64 4 499 9853
Email: nick.mulgan@compudigm.co.nz

Presented at SIRC 2000 – The 12th Annual Colloquium of the Spatial Information Research Centre
University of Otago, Dunedin, New Zealand
December 10-13th 2000

ABSTRACT

The aim of this paper is to explore the connection between an agent-oriented software development paradigm and the task of designing a third generation of spatial information system. The paper provides an argument that the adoption of an agent-oriented system design approach is a significant advancement for the spatial information system design problem. These conclusions are drawn from both theoretical and practical considerations. Existing research using the concept of computing agents in some spatial data handling domains are also reviewed and generalised. Based on an understanding of spatial information systems, agent-oriented ideas as well as the exploration of existing works involving intelligent agents in the domain of spatial data handling, a design consideration using intelligent computing agents as the basic building block for a new generation of spatial systems is outlined.

Keywords and phrases**:** computing agent, agent-based system, spatial information system, spatial representation, spatial reasoning

1.0 INTRODUCTION

1.1 Spatial information systems – the problem faced

Spatial information systems (SIS) are computer based systems for the representation, management, manipulation and reasoning of spatial features in the real world, entities or phenomena. Studies of the *states, relationships* and *behaviours* of selected features are the main issues in those space-related research domains, such as administration and management, spatial decision support, navigation system, image processing in medical science and geoscience to name a few. Spatial concepts like *position, shape, size, direction, distance, proximity, accessibility* are important properties. They influence all aspects of the implementation of spatial information in SIS.

1.1.1 The issue of static spatial representation and spatial reasoning

The *static* issue of present systems can be seen both in spatial representation and spatial reasoning. The *static* problem of data representation of a spatial feature is related to the map originated representation style of spatial information. This paradigm has changed little since its first adoption. Spatial information is only, in its broadest context, an *approximate* model of world, which is built on our spatial cognition, conceptualisation and abstraction of reality. Restrictions are inherent in the model because of the uncertainty and our subjectivity of natural processes. Except for the *selective constraints* from the viewpoint of the relevancy and importance of the features in a particular problem in a domain, the most pervasive conditions on the represented features are their *spatial* and *temporal constraints*. Specifically, the correctness and value of the spatial representation is on a specific time point or period temporally and on a particular scale specification spatially. Data need to be updated frequently in order to avoid being obsolete, and single-scale spatial representations need to be replaced by multi-scale spatial representations for different users with different requirements and different levels of detail (Burrough and Frank, 1995).

The *static* nature of present SIS causes many problems, both theoretical and practical. For example, the quality control of spatial data and error modelling has become an important research area in spatial information theory. Although the error from the measurement and pre-processing stages may be controlled, the seriousness of time limits and scale affects on data quality inherent in the conceptualisation, abstraction, generalisation and representation do not match well with a map model paradigm.

Because the manual updating of spatial information is a time consuming and resource-demanding job, methods are currently being developed to help automatically update old maps in SIS. The brute force solution by storing multi-scale representations seems an *ad-hoc* choice for dealing with the scale effect. It not only greatly increases the amount of data that needs to be handled in the *static* SIS, (where large amount of information may be duplicated), but also makes the data suppliers expectations difficult due to different demands by different potential data users.

1.1.2. The issue of lacking complex spatial data analysis functions

The static nature of spatial reasoning directly links to another important conceptual issue pertaining to present SIS — the lack of complex spatial data analysis functions, especially complex process modelling functions (Burrough and Frank 1995, Openshaw, 1996, Openshaw, 1997a, 1997b, Openshaw and Turton, 1998, Openshaw, 1998)

The *static* nature of spatial reasoning is a challenge to both the designers of the system and the user. There are three main issues. First, the applicability of a particular function has restrictions from both the feature and features in the real world system and their representations in the digital world. Second, a model of the system needs to adaptive as no two situations are exactly the same. A good approach in one situation may not be suited to another situation without major changes, even though the situations are outwardly similar. Third, it is difficult to build and implement a model and simulation function in a *static* way if there is not a complete knowledge of the processes of the world. An impossibility of course!

In many cases a SIS is no more than just a spatial data store. The requirements for complex exploratory spatial data analysis (such as those in Anselin, 1998) and process modelling (such as those in Burrough, 1998 and in Openshaw, 1998) are expediently solved by the loose integration of SIS with other spatial analysis, modelling and simulation systems. As the indispensable component of spatial analysis, the spatial reasoning abilities of complex exploratory spatial data analysis and the process modelling and simulation should be considered during the design stages, either internally built or tightly integrated in a generic way. These abilities are crucial for the future of SIS.

1.1.3. The summary

The problems emerging in spatial information science research may appear multifarious, but in essence all the problems stem from the *static* software engineering approach. The assumptions of complete knowledge about the problem lead to many ad-hoc approaches and difficulties. Although the observations of nature lead to descriptions that are complex, nonlinear and recursive, the concepts of spatial information and spatial data analysis in present SIS are static and linear.

It is to consider discarding the old *static* paradigm and seek a new *dynamic* approach where the nature of the SIS domain is explicitly captured by the data model and analysis representations. It is understood in the new paradigm that completeness is impossible and that adaptation must occur, and that knowledge must be continually acquired over time and space.

1.2 Agent-oriented paradigm – what's in an agent?

The static problem faced with current spatial information systems is common in almost every computer system developed, where complete knowledge about the problem system is assumed. This makes the computer system hard to scale up when facing a change in the problem domain. For a system that deals with the real world the complete knowledge assumption can rarely be satisfied.

The agent-oriented paradigm aims at supplying a flexible and intelligent system, with reasoning and adaptive characteristics that deal with problem where complete knowledge about the system is not possible. Conceptually an agent-based system is an intentional system (McCarthy, 1979, McCarthy, 1995-1999, Wooldridge and Jennings, 1995, Müller, 1996, Shoham, 1997). The design of the system changes from a *task-driven* approach, where each step needs to be known exactly, to a *goal-driven* one with only incomplete knowledge (Georgeff *et al*, 1999). Such an approach has been defined as loose frames. The exact procedure of execution is left to the system, rather then the user. Correspondingly, the use of the system can change from direct manipulation to a task delegation which is described in (Negroponte, 1997).

The basic thoughts and their realisation in the present agent architectures allow for the possibility of designing and building an *intelligent*, *dynamic* and *flexible* system with the computing agent as the basic building block. Agents will adapt their behaviour internally.

2.0 SIMILARITIES BETWEEN THE AGENT IDEA AND THE EXPECTATION OF A GENERIC SPATIAL INFORMATION SYSTEM

In order to create a new paradigm the concepts and the problems raised in the application domain should match (Couclelis, 1998). The cohesion between the agent-based system metaphor and the expectation of SIS problem domain should high.

2.1 Agent-oriented paradigm in software engineering

2.1.1 A computing agent and an agent-based system

What is an agent and agent-based system? Müller (1996) provides a black box model of agents. In this model, agents or agent-based systems are:

> *…autonomous or semi-autonomous hardware or software systems that perform tasks in complex, dynamically changing environments…. Internally, it is described by a function f which takes perception and received messages as input and generates output in terms of performing actions and sending messages. The mapping f itself is not directly controlled by an external authority* (Müller, 1996).

Internally, a computing agent is a computation component with ascribed *mental qualities*, such as *belief, desire, goal, intention* and *commitment*. The computing agent makes decisions on deliberation, planning and execution based on the symbolic manipulation of these *mental qualities* in order to commit its obligation for the realisation of the final task.

From an external view of an agent-based system, it has *sensors* and *perceptors* connecting with the outside world, *brain* like reasoning ability to do planning and deliberation, and *effectors* executing the plans and performing actions in order to support its goal. The task of an agent is fulfilled based on the recognition of the requirement from its external environment, usually the user but also possibly other agents, knowledge about its world and the resources at hand. The brain like reasoning ability is the spirit of a computing agent.

It is worth emphasising that:

- The construction of solution *f* is internal. The controlling of the internal construction of function *f* is through reasoning, i.e. manipulation of the *mental states.* It is not performed by an external executive, or at least not totally.
- In some cases, the processing work simply can not be totally controlled by the outside executive because of incomplete knowledge about the exact procedures for the solution. In this case, the interaction between individual agents are particular important. It is based on their co-ordination, cooperation and negotiation that goals are reached and the common task performed.

The individual computing agent, as the basic building block of an agent-based system, has its own autonomy over its own behaviour. There are different types of agent, *deliberative*, *reactive* and *interactive*, with different reasoning mechanisms (Müller, 1996). Usually, an agent-based system has large amounts of intelligent agents and all those types mentioned above may exist in one application.

2.2.2 The properties of an agent and agent-based system

The ascribed mental qualities - *belief, desire, intention, goal and commitment* are the basic attributes of an agent - the computational component. There are properties expected from the internal consideration of these attributes in order to have a competent, reliable and useful agent. These properties include *rationality, persistence of the mental states, internal consistence of the mental qualities* and to some extent *introspective abilities,* i.e. the agent can be conscious of its *mental states* (McCarthy, 1979, McCarthy, 1995-1999, Shoham, 1997).

From an external view of the behaviour of an agent or agent-based system, the most emphasised abilities include the *autonomy, proactivity, reactivity* and *social* abilities (Wooldridge and Jennings, 1995). Autonomy means the agent can initiate an action instead of passively waiting to be manipulated by an outside executor. Proactivity states that performance of an agent is in a goal-driven manner. Reactivity emphasises that as the environment changes this also effects the agent's behaviour as well as its internal goal. Social property implies that an agent must have the abilities of social behaviour, communication and negotiation with other agents. They then cooperate and coordinate in order to achieve a set of tasks.

There are other properties mentioned by researchers, to some extent outcomes of the previous characteristics, such as *adaptability*. Others may be more particular to those specific application domains, such as *mobility*. It has also been suggested that an agent should have *good faith* and *benevolence* (McCarthy, 1979, Shoham, 1997).

2.2.3 Advantages of an agent based system

The key issues of an agent and agent based system are the *intentional system view* and the *permission of incomplete knowledge* about the problem domain. The basic concept gives a promising description for building an intelligent and dynamic system. The intelligence is expressed in both the reasoning and adaptive abilities of the system, and is therefore dynamic. The final state of the system after execution is not totally determined previously, but depends on the collective behaviour of the system.

Although not all properties of an agent-based system are fully realised, for example, the introspective knowledge ability specified in (McCarthy, 1995-1999), the existing agent architectures do supply the following advantages:

The advantage from a user's point of view

- Intelligence, the system can reason, perform tasks in a goal driven way and respond to changes in the environment, although different agent architecture may have different emphasis on the deliberative, reactive and interactive aspects of intelligent behaviour (Wooldridge and Jennings, 1995, Müller, 1996). The use of the system can be in a task delegation manner in stead of direct manipulation in an extent

The advantage from a designer's point of view

- Encapsulation of both *state* and *behaviour* (Jennings and Wooldridge, 1998), the agent approach is good for the distributed problem solution, i.e. for designing and building of distributed systems, with distributed data, control, expertise and resources;
- Complex modelling and simulation (Jennings and Wooldridge, 1998, Georgeff and Rao, 1998), an agent-based system can solve the complex nonlinear process-modelling requirement where only incomplete knowledge of the domain is available.

With the relative autonomy of individual agents, an agent-based architecture can react to a changing environment. New knowledge — new features or new spatial data analysis functions — can also be easily dealt with by adding a new appropriate agent.

2.2 The Spatial Information System—an intentional system

2.2.1 The dynamic nature of spatial representation and spatial reasoning

The fundamental components of a SIS, spatial representation and spatial reasoning, are dynamic in nature and arise from the dynamics of the:

- real world
- cognition process, and
- encoding

Dynamic from the real world

The world is in constant flux. The *concepts and their relationships* in those space-related research domains evolve with the development of the world. New features are added, whilst old features disappear. The relationship of spatial features, such as neighbourhood and topology, also change.

Dynamic from the cognition process

First, the dynamics from the cognition of the real world give rise to *different concepts* in different domains. Different space-related research domains have their interests in different parts or regions of the world, such as those of a geoscientist or a radiologist in the medical domain; or different aspects of the same part of the world, such as those of a geologist, a hydrologist and a climatologist, a decision maker and a telecommunication network manager.

Except for the information about these concepts themselves, i.e. their *states*, *properties* and *relationships* with other concepts, the knowledge about the circumstance of their existence also need to be considered in information representation and manipulation. The geometric representations are not only the simple graphics, they have their explicitly represented real world meaning and this needs to be known by the system through the representation of knowledge about the conceptual model of a domain—the meta knowledge.

Second, concepts and their relationships in the real world are unavoidably incomplete because the observation and measurement of the world have restrictions from both objective conditions and subjective purposes.

Restriction from subjective purpose: Only the features of interest are represented and used for reasoning. For example, the domain scientist will selectively measure and manipulate only those features that in their view are related to the particular problem in their domain.

Restriction from objective conditions: Different levels of knowledge and details of information will be obtained. The accessibility of an individual to the environment is restricted to different levels of detail due to a number of factors – measuring devices, the available knowledge that can be accessed and time and money constraints. They influence directly which system can be observed and in which levels of details, and what kinds of sampling and measurement methods can be applied, both in terms of *sampling distributions* and *data support*.

The differences, either from the cognition of different features or from the abstractions of the same feature in different situations with different levels of detail, means a *different conceptual model*--object or field, and different *data model*, vector or raster, are suitable and applicable in different application environments. *Different spatial analysis functions* can be expected for knowledge acquisition from the data, which is based on the represented features, their natures, levels of details and relationships.

Spatial representation needs to be defined by, not only the meta-data about the context of the represented features, but also by the data quality inherent from the research purpose and methods for the data acquisition. The quality issue includes both the scale effect in the conceptualisation, generalisation and sampling design process and the possible errors from measurement and pre-processing of data

Dynamic from encoding

The same conceptual model and data analysis method can be implemented differently in different computer systems:

- *The encoding of spatial features in different abstraction levels*: the same concept can be represented as an abstracted point, polygon, or polyhedron with different level of details.
- *The encoding of spatial features in different resolution*: can be encoded in either vector format or raster format. In the raster format, the spatial resolution of a feature can be in different cell sizes. In the vector format, it can have various shortest distances between two neighboured nodes on the polyline or the polygon.
- *The encoding of different methods for the same aspect of knowledge acquisition*: for example, the selection of different interpolation methods and different 3D graphic rendering algorithms in different systems.
- *The encoding of different methods for different aspects of knowledge acquisition*: such as distance searching, overlay or correlation analysis.

- *Different implementation of the same model*: the same conceptual model implemented in a different database management system with different data structures and formats.

All these dynamic aspects influence on final spatial representation and spatial reasoning components in a SIS. These dynamics bring the *non-deterministic nature* to spatial information in SIS, both in terms of the context and quality of spatial representation and applicability of the spatial reasoning functions, thus the adaptation of spatial models of a real application. The *non-deterministic* nature of spatial information in SIS is typically the case, not the exception. The dynamic nature of the SIS domain indicates that the design and modelling of such a system needs a dynamic structure. The intentional system view of agent oriented software design is the only paradigm at present that can give some notion of the *dynamic* expected through the encapsulation of both *state* and *behaviour* (Jennings and Wooldridge, 1998).

2.2.2 Legitimacy, coherency and usefulness of the intentional view for a spatial information system

2.2.2.1. Legitimate, coherent and useful issue of an intentional view

An agent paradigm is related to the intentional system idea from philosopher, Dennett (Müller, 1996). An intentional view of the problem domain is the necessary condition for the adoption of an agent. But, coherency is still not a sufficient condition for selection in the design of a system. Shoham states:

> *It is perfectly coherent to treat a light switch as a (very cooperative) agent…. However, while this is a coherent view, it does not buy us anything, since we essentially understand the mechanism sufficiently to have a simpler, mechanistic description of its behaviour* (Shoham, 1997)

It is important to emphasise the condition that whether such an intentional view for a system design is useful to a problem. Otherwise a conventional software design approach will be more efficient and appropriate. The most useful situations of ascribing *agenthood* are the areas where our knowledge about the system is incomplete. A dynamic and adaptive approach to the problem solution is usually a forced option. As MaCarthy states in his pioneer work:

> *Ascription of mental qualities is most straightforward for machines of known structure such as thermostates and computer operating systems, but is most* ***useful when applied to entities whose structure is very incompletely known.*** (McCarthy, 1979)

2.2.2.2. Intentional view from considering the problem domain itself

A SIS is a model of the real world, with spatial representation and reasoning functions for the features of particular space related research domains. As the digital represented world or partial world is captured from different aspects intelligently, this representation evolves with the changing of the real world, our accumulated knowledge of it and the implementations in the digital environment. Theoretically it should be considered as a coherent intentional as well as a complex one.

The expanding and evolving of the SIS world

SIS as a whole is a complex, open and dynamic system. The evolution of the digital world of spatial information is unpredictable because:

- Various application domains exist and new application domains are being explored.
- Data for old features need to be updated and data for new features need to be added.
- Spatial data analysis functions are increasing, new exploratory data analysis methods are being designed and new laws, theories and models are generalised and implemented.
- New SIS are designed and implemented in different programming environments.

An intentional view is useful for complex process modelling where there is only limited knowledge. The process simulation approach is also sometimes needed for properly handling the data in order to produce more accurate, real time, automatic or semi-automatic feature reconstruction, such as pattern detection and image classification (Curran, *et al*, 1998).

2.2.2.3. Intentional view from considering the use of the system

The internal intelligence of the system will be needed to aid the user. The correct use of the system depends on the system being able to recognise the goal and requirement of the user properly and plan and execute in a rational way based on a consideration of the resources at hand. In the traditional task-driven designed system, the use of the system requires large amount of user's direct manipulation of those functions. The user needs to have more complete knowledge on the domain science, the quality issue of the represented data, the nature of the computer implementation of those spatial data analysis methods used in domain and where those relevant analysis functions should be applied. This makes the use of SIS often a difficult task. Although there may be a common spatial representation for each domain, without internal intelligence supporting and guiding the user to select approaches and techniques, the chance of misusing the system will be greatly increased, especially for the general users.

Intentional view for reasoning about data quality, expected information and knowledge from the user and applicability of the relevant spatial data analysis functions

As mentioned in the introduction, an active and constant interest in the SIScience domain is the issue of data quality. Besides the obvious errors of imperfect equipment in data acquisition and errors caused by people in the pre-processing stage, the issue of *data quality inherent* in the conceptualisation, abstraction and generalisation of representation and *approximate* functions as the model for manipulation and reasoning is gaining attention. It is difficult to integrate or solve in current SIS because of the static nature and error intolerance of the system. Often some complex error model for exploring some issue is built, but it can not be said that the quality issue is being treated as a fundamental spatial phenomenon. It is unrealistic to ask users to appreciate and understand all aspects affecting the quality of their data, especially if they are just the general users of those data.

Different spatial data analysis functions help acquire different aspects of knowledge from the data—*state description*, *relation finding* or *process modelling*. Except the theme the data is representing, i.e. the feature itself, the spatial, temporal restriction and level of details of the data also need to be explicitly reasoned on in order to select and perform a proper spatial data analysis (Goodchild, 1998). When using the spatial representation and spatial reasoning functions, the data must be put in a context (Burrough and Frank, 1995) as well as permit an adaptive attitude towards spatial data. A proper data manipulation is based on the relations already captured and the possible ones that can be built from the spatial representations and levels of detail of the information. Sometimes, the transformation between different data formats is also needed in order to use the manipulation functions. In facing such an issue the agent-approach with intelligent reasoning and planning abilities will be useful.

Intentional view in selection of a particular function from a group of methods for the same knowledge acquisition aspect

In a real application, not all functions can or need to be executed. Function selection should be based on a consideration of the data at hand as well as the requirement from users, for example, the accuracy requirement on the result, the time that can be spent on doing the analysis and the available resources the machine can use. The solution from an intentional system view for this task, i.e. reasoning and performing the task according to the preference of the user and the internal knowledge about the difference between the various functions, will liberate the user from having to know all functions and direct the system at each step of the analysis.

Theoretically, the dynamic nature of SIS, coming from real world processes, cognitive processes and the encoding processes, determine that only the intentional view is suitable and useful for such a system. The system requires reasoning and adaptive execution, from the selection of a proper analysis function, to switching a simple model to a more complex model of relationships for different features with accumulated data and to the simulation of real world processes.

A task driven approach may be appropriate for a particular application, but obviously is unsuitable for the design of a generic SIS with various users and many kinds of goals in mind. The challenge for the designer is to create an intentional structure that is intelligent, open and flexible.

2.2.3 Distributed nature of spatial domains

Jennings and Woodridge state that a practical prerequisite for the adoption of an agent is that the domain should inherently have distributed data, control, expertise, or resources (Jennings and Wooldrige, 1998).

First, the features in the natural world are distributed and have different behaviour rules. Different applications from different domains have different features. Secondly, present spatial information systems are distributed in the digital virtual world. The legacy components need to be considered and interact with old or new computation components (Jennings and Wooldridges, 1998). Present spatial information systems have a distributed characteristic, expressed in both data and data analysis functions. Data are highly distributed and with different levels of details. Actually, an agent-based approaches to integrate SIS are already a research trend, such as the work of Purvis and colleagues (Purvis *et al*, 1999a, Purvis *et al*, 1999b, Cranefield and Purvis, 2000).

The main issue here perhaps should be put on how to build a *coherent conceptual model* of the SIS domain in order to facilitate the integration of distributed data and computing functions but the consideration of if the SIS has the distributed character.

2.2.4 Repetitive, pattern and diversity in the use of a spatial information system

According to Maes (1997), other practical prerequisites for the adoption of agent are, firstly, that there exists a large amount of "repetitive behaviours" that can be modelled. Second, different users should have different repetitive behaviours for different requirements. Jennings and Wooldridge (1998) expressed a similar idea. They state that it is a necessary condition for adopting agents that the domain can be naturally decomposed into a society of autonomous cooperating components.

2.2.4.1 The pattern issue

The fundamental purpose of space related research domains are the accumulation of our understanding of natural, social and artificial fields. The most basic patterns in space-related research aspects may be categorised as the *state*, *relationship* and *process* as previously mentioned. The patterns in those space related research domains evolve from a *descriptive analysis*, what is where and what are the properties, to the *normative analysis*, such as the common attributes behind a concept; from the *empirical modelling* to the more *complex modelling and simulation studies* of the relations and behaviours of those features in a system (Haggett and Chorley, 1967).

The structural approach for representation

The geometric shapes, point, line, polygon, and polyhedron are employed to describe the relevant concepts in a domain, in terms of both the source data and the result from the data manipulation. Graphics are the basic description of a spatial feature, which includes its *position* and *shape*.

The functional approach for reasoning

Spatial data analysis functions are built from topological, spatial, temporal and attributive relationship between the features. For example

- *The topological relations*: exterior, on and interior
- *The spatial relations*: local, focal and zonal operations, buffering and distance searching
- *The temporal relations*: before, on and after
- *The attributive relations*: the relationships between the attributes, such as Boolean operations, correlation analysis, multivariate regression model and neural-network modelling

Process modelling and simulation

The models are built from the common laws and theories from statistics, physics, economics or social sciences. Such as the Gravity model, the diffusion model, cellular automata models. Spatial data is used to construct a partial representation of the world from a particular point of view. Repetitive modifications or updating of the representations are needed for a more accurate approximation of the world or sub-world based on the old model, knowledge base, new modelling techniques as well as the new data at hand. For example, the world may be modelled using correlation analysis, multivariate linear regression or neural network modelling. From the knowledge of *heterogeneity* and *autocorrelation* of spatial features and spatial data, it is expected that modelling methodologies can explicitly capture these aspects, and then be extended to models based on cellular automata for some processes.

2.2.4.2 The diversity issue

In order to understand the diversity issue, it is necessary to understand the meaning of *users* here in a more general sense. It can be a general individual who queries about a particular feature stored in the system for his or her purpose just like the use of a conventional map. It also can be groups of researchers with common interest, the experts in a particular area, such as a radiologist, a navigation robot or a decision-maker. The diversity comes from different parts and aspects of the world that are considered. Different domains have different concepts and relationships. Different methods for the same description and different relations between features may exist in different instantiated systems. Adaptation of the system to different space related research domains and situations are the real meaning of a generic SIS.

3.0 EXISTING WORK INVOLVED AGENT IN THE DOMAIN OF SPATIAL DATA HANDLING

The use of intelligent agent can be found in several spatial data handling application areas. There are three basic trends. The first trend is the area of spatial navigation of a robot, route planning (Ferrand, 1995a) and the automatic map generalisation (Ferrand 1995a, Baeijs, et al 1996 and Lamy *et al*, 1998). The second trend relates to the modelling and simulation study for the complex process in the natural world. For example, the spatial decision support area (Papadias and Egenhofer, 1995, Ferrand, 1995a, Ferrand, 1995b), and the individual based modelling and simulation study (Gimblett, *et al*, 1997, Bennett *et al*, 1995, Kohler *et al*, 1995 and Slothower, *et al*, 1995). In this trend, although the agents are internally the reactive ones, their task is fulfilled involving large amount of interactive and collaborative works among themselves and with the user. In this sense, they are preferred to be called as the interactive ones here. The third trend of using intelligent agent is in the integration study (Purvis *et al*, 1999a, Purvis *et al*, 1999b, Cranefield and Purvis, 2000). Their works concentrates on an agent based infrastructure for a distributed environmental information system. The works of Rodrigues et al (Rodridge *et al*, 1995a, Rodridge *et al*, 1995b, Rodridge *et al*, 1997, Grueau, *et al*, 1999, Grueau, *et al*, 2000) talked about various aspects of using the intelligent agents.

3.1 Agent in spatial navigation, route planning and map building

The original work on the reactive agent is in the spatial navigation, route planning and map generalisation application area. The robot, or called mobile agent navigates in the space, either the real or the virtual space. Some relevant works can be referenced from (Wooldridge and Jennings, 1995, Müller, 1996), such as the works of Rodney Brook, which are among those pioneer works in the reactive agent study. In his works, robots can explore in a room, plan a route and build the maps (Müller, 1996). Other works involves the reactive agent are in the application of interactive contouring for image segmentation, such as the work of (Crawford-Hines and Anderson, 1997, Wang, *et al*, 1998), and the automatic map generalisation in the work of (Baeijs, *et al* 1996 and Lamy *et al*, 1998).

3.2 Agent in complex process modelling and simulation

The works of Papadias and Egenhofer (Papadias and Egenhofer, 1995) and the work of Ferrand (Ferrand, 1995a, Ferrand, 1995b) gives the example of using agents in the spatial decision support application, the decentralised decision support for spatial planning and spatial accessing. In the work of Papadias and Egenhofer (Papadias and Egenhofer, 1995) for the spatial decision, each of the actors (the agents who have their particular views for making the spatial decision) has the qualitative specification, the *constraints* for the spatial decision. Conflicts may exist among these constraints. The actors who give these constraints collaborate until a final common goal, i.e. the efficient query is reached through the "*query optimizer*" based on the interaction and negotiation of these actors. The goal is not pre-definable in a sense that it is possible that the value from the *unified model* for the decision can be in a range with different priorities corresponded rather than just one choice. The factors which will effect the final goal comes from at least two aspects in the example used in their paper, the different interpretations of the same qualitative specification and the different weights assigned to the constraints from these specifications.

The interaction and negotiation issue can be more complex in some cases because of the more complex relations among the features controlled by the different actors. Such as those in the work of Ferrand (1995a, 1995b) and the work of (Rodridges *et al* 1997, Grueau, *et al*, 1999, Grueau, *et al*, 2000). The works of Rodridges, Grueau and colleagues are similar to those of Ferrand (1995b). The agent organisation is a much complex one than that is in the work of (Papadias and Egenhofer, 1995). In the project reported by Ferrand, both the pure reactive agents and the interactive agents are used in the application of decision support for spatial positioning of a new road. The global optimisation problem is changed into the hierarchical structured local optimisations and their compromising. In his work, six phases are planed for the decision support. In the first phase, the reactive agents are employed to supply several plans for the new road. Each of the reactive agents is just like the individual robot navigating the real world environment. The reactive agent has the basic cognitive abilities, such as the starting point, the direction leading to ending point, and the morphological constraints like curve and slope. In the second, third and fourth phases, these plans are evaluated by the environment experts from different aspects with different criterions and changing weights of the criterions for the less environmental damage. Sensitivity analysis is performed and least risky solution is also obtained respectively for the low financial risk and cost. The compromised solutions will be reached involving the multi-actors in "different powers and voting positions" (Ferrand, 1995b) in the social and political levels in phase five and six. The simulation of the negotiation of the multi-actors is also considered in their project.

The individual based process modelling by using agent can be found in the works of (Bennett *et al* 1995, Gimblett, *et al*, 1997, Kohler *et al*, 1995 and Slothower, *et al* 1995). Each of the individuals, the individual recreator, animal or other spatial features in their relevant application domain interacts with each other. The basic thought behind these applications is the emergent behaviour and pattern idea. Although the pattern and behaviour of the whole system is more complex, the rules which govern the behaviour of the individual inside the system is much simpler (Slothower, et al, 1995). From the simulation of the behaviour of the individual, the convergent pattern and behaviour rules for the population or the represented system is expected to be able to emerge in the self-organised form. Although the individual features are the reactive agent, the pattern expected is through the interactive manner, with the real spatial and temporal dimension of the features as the constraints for their collaborations. So the work are put here instead of the above section.

3.3 Agent in the integration of SIS study

The third trend in using the intelligent agent is in the study of SIS integration. Such as the works of Purvis et al (Purvis *et al*, 1999a, Purvis *et al*, 1999b, Cranefield and Purvis, 2000) for an agent based infrastructure of a distributed environmental information system. Their work emphasised on the distributed spatial data management and accessing. Information processing and knowledge acquisitions are basically at the stage of spatial querying and traditional SIS overlay type of operation.

4.0 DESIGN AN AGENT ORIENTED SPATAIL INFORMATION SYSTEM

The dynamics and flexibility of an agent-based design are based on realising of the properties of an agent, i.e. the autonomous, proactive, reactive and social abilities. The dynamic behaviour of the system needs, more importantly, to be in an intelligent way. The intelligence is made possible based on *the world model* and *the user model* of an agent (Negroponte, 1997), i.e. having the knowledge of its work domain and its users. The world model includes the meta-knowledge of its domain, the knowledge of the domain itself - the features, their structure and functional connection, as well as the knowledge of the digital implementations. The design of the system is from the consideration of the workflow in a real spatial data analysis application, from the recognition of data and the user requirement, to the selection of data analysis function and the execution to the final presentation of the result.

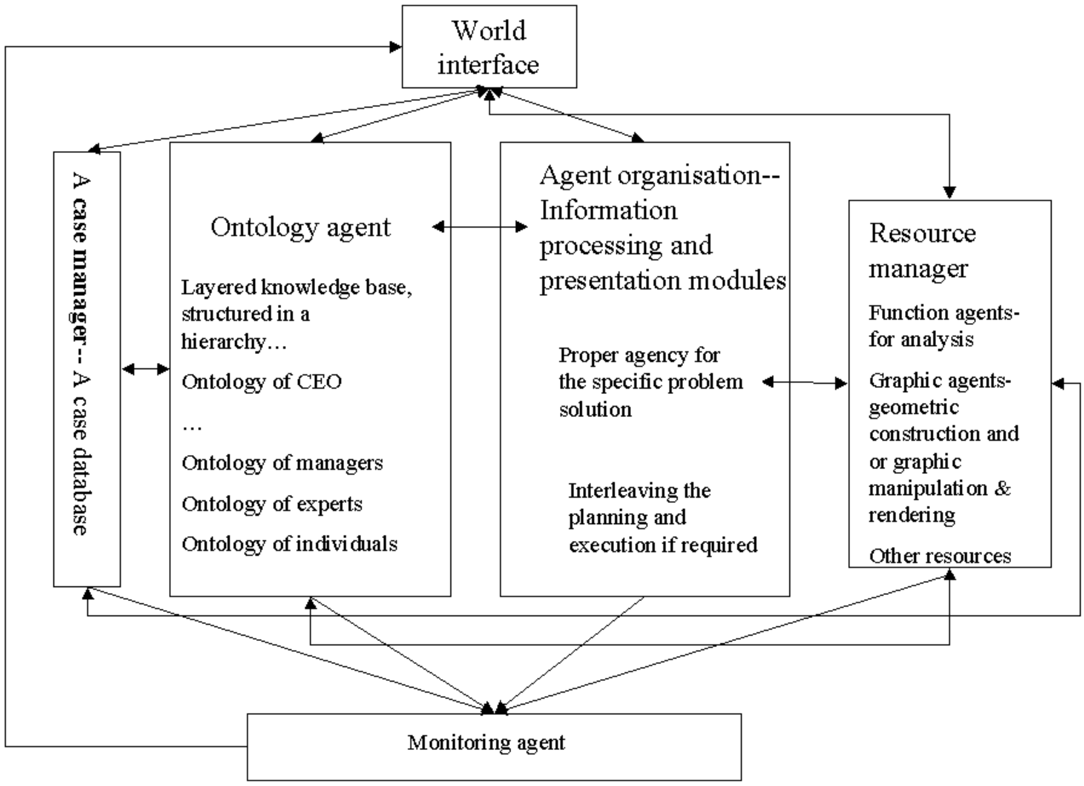

Figure 1. An agent based system SIS architecture

Layered approach of agent architecture in Muller's work (1996) is considered based on the situation of a SIS domain--includes behaviour based layer, local planning layer and cooperative layer. There are also the layered knowledge bases for the world model of an agent. The member agents have their relevant ontologies stored in a hierarchy. Agents with different types of intelligence use different reasoning mechanisms. The communication of agents is realised through the models built from Speech-act Theory of Searle. The basic components of the system include interface component, reasoning and planning component, ontology component, resource management component, case management component and process monitoring components.

4.1. Interface component

Interface is between the agent world and the users. The main functions of it are to extract the user's requirement and match it to the task of a proper agency. It is used for seeking help from a user, the super-agent, or other agents if needed. The interface is also for presenting analysis results.

4.2. The reasoning and planning component

Reasoning about exact steps for information processing, graphic presentation and manipulation. Agent organisation is composed of agents with different type of intelligence: declarative agent, interactive agent and reactive agent. These different types of agents have different inference capabilities. The main function of planing and executing module are, for example, reasoning and selecting methods for data analysis and methods for the presentation of the result from the analysis. The reasoning component begins its work from the user input data. It recognises the domain and the theme of the features from the data first, then consults its ontology and makes sure the user's domain and requirement and matches the beliefs of a relevant agent organisation. From top to bottom, with the aid of the ontology of the agent organisation, it comes to the proper agency. The job of planning and execution is done based on its reasoning, with or without the user's intervention.

4.3. Ontology component

The ontology component stores and manages the knowledge base. There are three-level ontologies, the second level will be the main concern:

- *Common knowledge*: translating the requirement of the user's into the terms understandable by the agent system
- *Domain knowledge*: the conceptual data model in the domain science, in our case the spatial domain in general
- *Knowledge on computing level*: dealing with the different implementation of the same conceptual model. It includes the data format transformation and interpreting the programs in different programming languages

The domain knowledge about the SIS is the main concern in the design consideration. At society level, the knowledge includes the knowledge about different domains. That is, for example, which part and aspect the application is cared about, the earth or the human body. In the organisational level, the knowledge is about the main study trends in that domain. At the agency level, the knowledge about the different data manipulation methods for a particular analysis aspect is supplied. These methods can be chosen for performing the particular task assigned by the users. Although there are some technician type of agents which can be called directly for fulfilling a task. It is possible that the large amount of individual agent in a hierarchical structure may be called, they interact with each other for finishing the job, such as for the spatial decision support application. It is also possible that a pure reactive agent will be employed. The agent learns how to do the job from the user.

4.4. Resources management component

The main function of the component is the management of the more specialised agents, such as graphic agents and functional agents. Graphic manager agent handles the management of the geometric shape reconstruction, graphic rendering and manipulation, e.g. the 3d reconstruction algorithms and 3D graphic rendering techniques. Functional manager agent deals with the management of function solutions and specialised spatial data analysis algorithm, e.g. the clustering analysis. Data format transformation algorithms will also be included in this resource management module in future. Those specialised agents will be treated as speaking agents. They advertise their abilities to the manager. The adding of a new technique implies the adding of a new agent in a proper position.

4.5. Case management module

The case database is the component to store and manage the application cases. The information stored here will be used to update the relevant knowledge in the ontology module.

4.6. Process monitor component

The main function, expected from this component, is the control of the workflow of data processing in an application. It is expected to be possible to execute, stop and check the data processing at the user's steps in order to make the working of an agent-based system more understandable

5.0 CONCLUSIONS

Understanding SIS in the level of epistemology is a fundamental issue. The understanding on the higher abstract level of the problem domain is a prerequisite for the success of the new design paradigm as the intelligent SIS is certainly not a simple sum of those different systems, functions and data. Thus the task is challenging, significant and attractive.

The approach provided here is to joining the present computer systems for spatial representation and spatial reasoning in a coherent way, includes not only those traditional SIS operations, but also the more complex modelling and simulation functions from the artificial intelligent research.

It has been argued the task of design of a new generation SIS need an agent approach not just because it is new and has advantages, but from the consideration of dynamic, complex and uncertain nature of SIS itself. A SIS is the application system that has been or will be implemented further as the aid for the solution of research problems in those space-related research domains, especially the problems that are not properly solved by the present SIS. The system design is based on an agent framework in the belief of giving the system the intelligence, dynamic and openness that an agent-based approach can provide. It is argued that the expectation of a generic SIS and the idea behind the agent are coherent. The agent metaphor for software engineering is appropriate for the SIS problem domain. Not only because the SIS domain is complex, but also because it is possible to decompose it into an automation society, i.e. the encapsulation of spatial representation and reasoning methods.

It is contended that the approach is not only theoretically advantageous but also practically feasible, because of the claimed properties of present agent architectures and more properties outlined by the agent theorist which will be realised in the future.

ACKNOWLEDGEMENTS

This study is sponsored by Foundation of Research, Science and Technology in the form of GRIF industrial fellowship. This research is being conducted in cooperation with Compudigm International Ltd. The generous support of Compudigm International Ltd is acknowledged. Also special thanks to Dr Stephen Cranefield, University of Otago for his invaluable assistance in the work related to the computing agent.

REFERENCES

Anselin, L. (1998) Exploratory spatial data analysis in a geocomputation environment, in P.A.Longley, S.M. Brooks, *et al* (eds) *Geocomputation: A Primer*, pp77-94, John Wiley & Sons Ltd

Baeijs, C., Demazeau, Y. and Alvares, L. (1996) SIGMA: Application of multi-agent systems to cartographic generalization, W.van de Velde and John W. Perram (eds.), *Agents breaking away*, Proceedings of 7th European Workshop on Modelling Autonomous Agents in a Multi-Agent World, MAAMAW '96, Eindhoven, Netherlands, January 22-25, 1996, v.1038, Springe

Bennett, D.A., Armstrong, M.P. and Wade, G.A. (1995) Agent mediated consensus-building for environmental problems: a generic algorithm approach, http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/sf_papers/bennett_david/my_paper.html

Burrough, P. (1998) Dynamic modelling and geocomputation, in P.A.Longley, S.M. Brooks, *et al* (eds) *Geocomputation: A Primer*, pp165-191, John Wiley & Sons Ltd

Burrough, P.A and Frank, A.U (1995) Concept and paradigms in spatial information: are current geographical information systems truly generic? *International Journal of Geographical Information Systems*, 9(2), pp101-116

Couclelis, H. (1998) Geocomputation in context, in P.A.Longley, S.M. Brooks, *et al* (eds) *Geocomputation: A Primer*, pp17-29, John Wiley & Sons Ltd

Cranefield, S. and Purvis, M. (2000) *Integrating Environmental Information: Incorporating Metadata in a Distributed Information Systems Architecture*, The information science discussion paper series, University of Otago, No 2000/02

Crawford-Hines, S. and Anderson, C.W. (1997) Neural nets in boundary tracing tasks, in Proceedings of the IEEE Workshop on Neural Networks and Signal Processing, pp207-215, September, 1997, http://www.cs.colostate.edu/~sgcraw/NNSP97

Curran, P.J., Milton, E.J., Atkinson, P.M. and Foody, G.M. (1998) Remote sensing: from data to understanding, P.A.Longley, S.M. Brooks, *et al.* (eds) *Geocomputation: A Primer*, pp33-59, John Wiley & Sons Ltd

Egenhofer, M.J., Glasgow, J., *et al*, (1999) Progress in computational methods for representing geographical concepts, *International Journal of Geographical Information System*, 13(8), pp775-796, Reading

Ferrand, N. (1995a) Multi-reactive-agents paradigm for spatial modelling, *Contributions to the European Science Foundation SISDATA Program*, *Spatial Models and SIS*, *Stockholm: ESF-SISDATA*, June 1995: London: Taylor & Francis

Ferrand, N. (1995b) Modelling and supporting multi-actor spatial planning using multi-agents systems, http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/sf_papers/ferrand_nils/santefe.html

Georgeff, M., Pell, B., *et al*. (1999) The belief-desire-intention model of agency. In J.P. Müller, M. Singh, and A. Rao (eds) *Intelligent Agents V*, Lecture Notes in Artificial Intelligent, v.1365, Springer-Verlag, March 1999

Gimblett, R., Durnota, B. and Itami, B. (1996) Spatially-explicit autonomous agents for modelling recreation use in complex wilderness landscapes, *Complex international*, 1996(3) http://www.csu.edu.au/ci/vol03/gimetal3/gimetal3.html

Goodchild, M.F. (1998) Different data sources and diverse data structures: metadata and other solutions, in P.A.Longley, S.M. Brooks, *et al.* (eds) *Geocomputation: A Primer*, pp61-73, John Wiley & Sons Ltd

Goodchild, M.F., Egenhofer, M.J., *et al* (1999) Introduction to the Varenius project, *International Journal of Geographic Information Science*, 13(8), pp731-745, Readings

Grueau, C., Muge, F et al (1999) A simulation framework for environmental decision making in surface mining and quarrying projects, In APCOM'99 –Computer Application in the Minerals Industries 28th International Symposium, Colorado School of Mines, USA, October 1999, http://www.dh.lnec.pt/asrodrig/

Grueau, C. Rodrigues, A. and Muge, F. (2000) A multi-agent approach for the management of quarrying environmental impacts, *International Conference on Environmental Modelling and Simulation-ICEMS 2000*, San Diego, California, USA, January 2000, http://www.dh.lnec.pt/ghi/asrodrig/

Haggett, P. and Chorley, R.J. (1967) Models, paradigms and the new geography, in Chorley, R.J and Haggett P. (eds) Models in geography, London: Methuen

Jennings, N.R and Wooldridge, M. (1998) Applications of agent technology, in N.R. Jennings and M. Wooldridge (eds) *Agent technology: foundations, applications, and Markets*, Springer-Verlag, March 1998

Kohler, T.A., West, C.R.van (1995) Agent-based modelling of prehistoric settlement systems in the Northern American Southwest, http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/sf_papers/kohler_tim/kohler.html

Lamy, S. Ruas, A. *et al* (1999) The application of agents in automated map generalisation, The19th International Cartographic Conference in Ottawa, 20th, August 1999, http://agent.ign.fr/public/ica/paper

Maes, P. (1997) Agents that reduce work and information overload, in J.M. Bradshaw (ed) *Software agent*, pp145-164, AAAI press/The MIT press, California: Menlo Park, Massachusetts: Cambridge, UK: London

Mark, D.M., Freksa, C. et al (1999) Cognitive models of geographical space, *International Journal of Geographic Information Science*, 13(8), pp747-774, Readings

McCarthy, J. (1979) *Ascribing Mental Qualities to Machines*, accessible from: http://www-formal.stanford.edu/jmc/, Reading

McCarthy, J. (1995-1999) *Making Robots Conscious of Their Mental States*, accessible from http://www-formal.stanford.edu/jmc/, Reading

Müller, J. (1996) *The Design of Intelligent Agents, A Layered Approach*, Springer-Verlag

Negroponte, N. (1997) Agents: from direct manipulation to delegation in J.M. Bradshaw (eds) *Software agent*, pp57-66, AAAI press/The MIT press, California: Menlo Park, Massachusetts: Cambridge, UK: London

Openshaw, S. (1996) Trend and perspective in spatial analysis and SIS, Paper presented at the SIS Data Conference, Greece, 22 May 1996, Presentation accessible from http://www.ccg.leeds.ac.uk/staff/s.openshaw/athens97/index.html

Openshaw, S. (1997) Conventional, neural, and genetic spatial interaction models, Paper presented at Vienna, April 1997, presentation accessible from http://www.ccg.leeds.ac.uk/staff/s.openshaw/vienna97/index.html

Openshaw, S. (1997) Neurocomputing in Geography, Why Bother? Leeds, 1997, Presentation accessible from http://www.ccg.leeds.ac.uk/staff/s.openshaw/leeds97/index.html

Openshaw, S. and Turton, I. (1998) Geographic Research using lifestyle databases, Paper presented at the IBG/RGS conference, 7 January 1998, presentation accessible from http://www.ccg.leeds.ac.uk/staff/s.openshaw/ibg98/index.html

Openshaw, S. (1998) Building automated geographical analysis and explanation machines, in P.A.Longley, S.M. Brooks, *et al* (eds) *Geocomputation: A Primer*, pp95-115, John Wiley & Sons Ltd

Purvis, M., Cranefield, S. and Nowostawski, M. (1999a) A Distributed Architecture for Environmental Information Systems, The information science discussion paper series, University of Otago, No. 99/06

Purvis, M. Cranefield, S. et al (1999b) *The NZDIS Project: an Agent-based Distributed Information Systems Architecture*, The Information Science Discussion Paper Series, University of Otago, No 99/17

Rodrigues, A. and Raper, J. (1995) Implementing intelligent agents for spatial information, *Proceedings of the First Joint European Conference and Exhibition of Geographical Information*, The Hague, The Netherlands, 27-31 March, 1995, http://www.dh.lnec.pt/ghi/asrodrig/

Rodrigues, A. and Raper, J. (1999) Defining spatial agents, In J. Raper and A.Camara (eds) Spatial Multimedia and Virtual Reality, Research Monographs Series, Taylor & Francis, London, UK, pp 111-129, 1999, http://www.dh.lnec.pt/ghi/asrodrig/

Rodrigues, A., Grueau,C. *et al* (1997) Environmental planning using spatial agents, *Proceedings SIS Research in the UK 1997 (SISRUK'97)*, School of geography, University of Leeds, UK, 9-11 April, 1997, http://www.dh.lnec.pt/ghi/asrodrig/

Sheppard, E., Couclelis, H. *et al* (1999) Geographies of the information society, *International Journal of Geographic Information Science*, 13(8), pp797-823, Reading

Shoham, Y. (1997) An overview of agent-oriented programming, in J.M. Bradshaw (ed) *Software Agents*, pp271-290, AAAI press/MIT press, California: Menlo Park, Massachusetts: Cambridge, UK: London

Slothower, R. L., Schwarz, P.A. and Johnston, K.M. (1995) Some guidelines for implementing spatially explicit, individual-based ecological models within location-based raster SIS, http://www.ncSIS.ucsb.edu/conf/SANTA_FE_CD-ROM/sf_papers/slothower_roger/sf23.html

Wang, W., Wee, W.G, and Wang, X (1998) Volume segmentation of the visible human CT data set, in *Proceedings of the Second Visible Human Project Conference Proceedings*, October 1-2, 1998, Maryland USA http://www.nlm.nih.gov/research/visible/vhpconf98/AUTHORS/WANG/WANG.HTM

Wooldridge, M. and Jennings, N.R. (1995) Intelligent agents: theory and practice, *Knowledge Engineering Review*, 10(2), accessible from: http://www.elec.qmw.ac.uk/dai/people/mikew/pubs/