

# Sensor Web Deployment Using Informed Virtual Geographic Environments

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**Abstract**—In this paper, we propose a knowledge-based approach to support Sensor Web (SW) deployments in Informed Virtual Geographic Environments (IVGE) using multi-agent geo-simulation techniques. Sensor webs can be thought of as distributed network systems composed of hundreds of nodes deployed in geographic environments for in-situ sensing and data acquisition purposes. The deployment of sensor webs is by nature a spatial problem since nodes are highly constrained by the geographic characteristics of their environment. Therefore, there is a need for an efficient modelling paradigm to address the issue of SW deployment while taking into consideration the constraints of the geographic space and knowledge it provides to support their autonomous decision making capabilities. The proposed approach builds on top of our previous works on Informed Virtual Geographic Environments. It also relies on well-established theories on spatially reasoning agents and on qualitative reasoning about geo-simulation results. The applicability of our approach is illustrated using a scenario of a sensor web deployment for weather monitoring purposes.

**Keywords**—*Informed Virtual Geographic Environments; Sensor Web; Geographic Deployment; Multi-Agent Geo-Simulation.*

## I. INTRODUCTION

Sensor Webs (SW) are distributed network systems composed of hundreds of such sensor nodes [1] [2]. New capabilities such as micro-sensing and in-situ sensing as well as the wireless connection of these nodes open new possibilities for applications in various domains such as military, environment and disaster relief [3] [4]. The low per-node cost and the shrinking size of microprocessors in addition to the enhancement of their computation capacities, while decreasing their energy consumption, will allow dense distribution of these wireless networks of sensors and actuators [2]. SW can be thought of as a macro-instrument concept that allows for the spatio-temporal understanding of phenomena which take place in geographic environments through the coordinated efforts of a large number of sensing nodes of different types [2]. However, once SW are designed, the deployment of such complex systems is a real challenge because of the complexity and the large-scale of the geographic environment [4]. Sensor web deployment is by nature a spatial problem since nodes are highly constrained by the geographic characteristics of the environment. Even if it is practical to evaluate research

on the real hardware platform, it may not be practical to experiment in an appropriate environment. An example of this are sensor webs which operate on glaciers, remote wildlife habitats, volcanos, and other environments where in-situ sensing techniques are required and with which it is expensive or dangerous to experiment. Therefore, there is a need for an efficient modelling paradigm to address the issue of sensor webs deployment using actors representing sensor nodes evolving in and interacting with a representation of their geographic environment.

In order to address the above mentioned challenges, we propose a knowledge-based multi-agent geo-simulation approach to support the simulation of SW deployments in informed VGEs. A critical step towards the simulation of SW deployment is the creation of appropriate representations of the geographic space and of the sensors evolving in it, in order to efficiently support the sensors' spatio-temporal reasoning capabilities (Figure 1). Moreover, a VGE should provide sensor agents with knowledge about the virtual environment in which they evolve and with which they interact. A number of challenges arise when creating knowledge about the environment, among which we mention: 1) to represent knowledge using a standard formalism; 2) to provide agents with tools and mechanisms to allow them acquire knowledge about the environment; and 3) to infer and to predict based on premises and facts that characterise the geographic environment in order to support spatial agents' decision-making. This approach builds on our previous works on Informed Virtual Geographic Environments [5] [6] [7], on spatially reasoning agents [5] and on qualitative reasoning about geo-simulation results [8].

The rest of the paper is organised as follows. Section II presents related works on agent-based simulation tools for Sensor Web. Section III presents our approach and details its underlying components. Section IV illustrates our framework through a SW deployment scenario for weather monitoring purposes. Section V discusses the results and concludes with our future works.

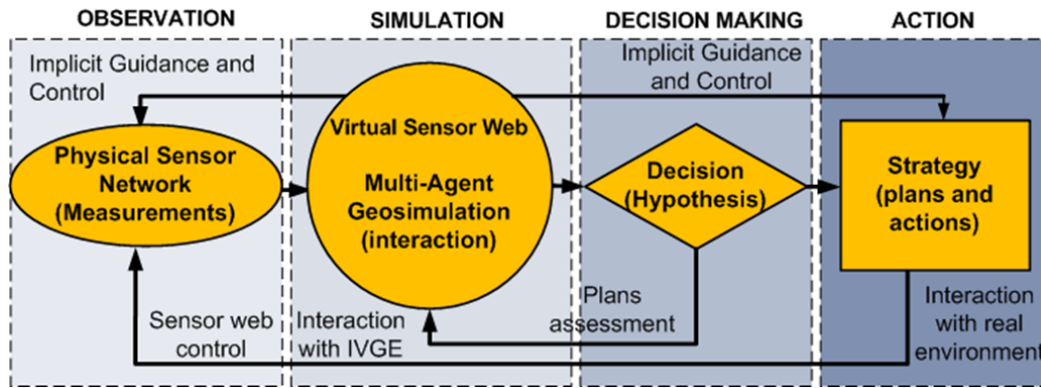


Figure 1. Sensor Web Multi-Agent Geo-Simulation Layered Approach: Observation; Simulation; Decision-Making; Action.

## II. RELATED WORK

According to our literature review, architectures for the management of sensor webs involving the Multi-Agent Geo-simulation paradigm do not exist. However, a few research projects have attempted to integrate the agent paradigm into sensor web architectures such as IrisNet [9], Abacus [10], Biswas and Phoha’s architecture [11], and SWAP [12].

Most of these architectures identify the need for distributed data collection and processing, and propose layered architectures to achieve this. In Abacus different agents in the processing layer detect and report alert conditions to a higher layer interacting with users [10]. IrisNet uses agents such as Sensor Agents (SA) and Sensor Organisers (SO) to collect and analyze data from sensors to answer specific classes of queries [9]. Biswas and Phoha’s approach uses agents in the service layer to analyze data from sensors and transfer it to the application layer [11]. All these approaches deal with data collection by providing a distributed infrastructure for publishing, discovering and accessing sensor resources. They also address the challenge of data fusion, to some extent, and aim to provide end-users with the information they need. These approaches share a common objective through the use of the agent-paradigm which is the distribution of tasks. However, these applications do not take complete advantage of the multi-agent systems approach. Indeed, they use reactive agents which are efficient for alerting purposes, but are neither able to perform situated behaviors nor autonomous decision-making. On the one hand, situated behaviors include performing spatial reasoning and taking advantage of the virtual environment’s description where sensor agents are located. On the other hand, autonomous decision-making includes managing sensor nodes in order to efficiently cover the area of interest while taking into account their limited capabilities as well as local spatial characteristics. We think that, in order to achieve intelligent and autonomous deployment of sensor webs, it is

essential to use a multi-agent geo-simulation approach in which agents are endowed with advanced capabilities such as perception, navigation, memory, and knowledge management. The knowledge management process includes the following tasks: (1) to represent knowledge about geographic environments using standard formalisms; (2) to allow spatial agents to acquire knowledge about the environment; (3) to allow agents to reason and to make decisions while taking into account knowledge about geographic environments.

As the above-mentioned architectures do not address the more challenging sensor web management issues, we propose the knowledge-based multi-agent geo-simulation model for the deployment of sensor webs in informed virtual geographic environments.

## III. A KNOWLEDGE-BASED MAGS APPROACH

The proposed approach (depicted in Figure 2) relies on the Multi-Agent Geo-Simulation paradigm in order to simulate the behaviour of a SW in a dynamic, complex, and large-scale virtual geographic environment. Sensors are

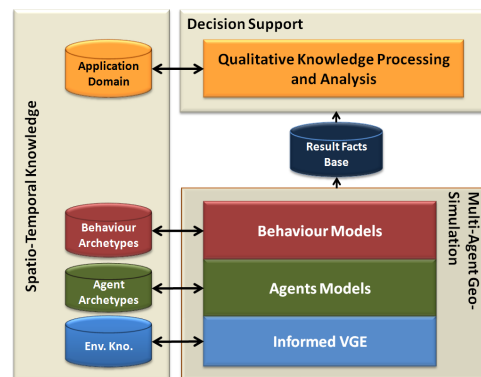


Figure 2. The proposed knowledge-based multi-agent geo-simulation model .

modeled as intelligent agents embedded in a virtual space where dynamic phenomena can occur. Sensor agents have reasoning capabilities allowing them to reason about the virtual space and to react to its dynamic phenomena. Spatio-Temporal knowledge is used for two main purposes. First, it is used during the geo-simulation to support agents reasoning capabilities. Second, it is used to analyze the results of the geo-simulation and to offer decision support to users. Finally, the results of the geo-simulation (which are inserted as facts in the Result Facts Base) are analyzed in order to offer decision support. In the following, we present these components.

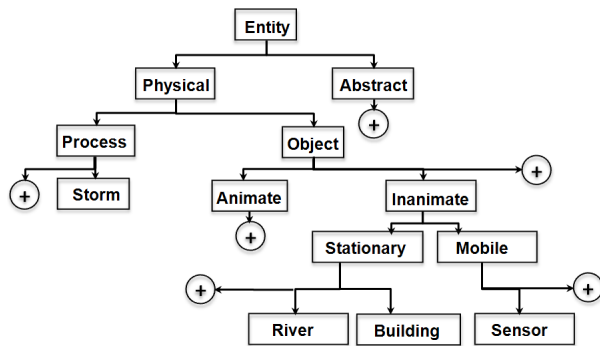


Figure 3. An example of the semantic type hierarchy of agent archetypes.

#### A. Multi-Agent Geo-Simulation

The idea behind the agent-based simulation approach is to move the most intensive processing out of the Physical Sensor Web (PSW) into a parallel Virtual Sensor Web (VSW) operating on a base station or a remote server. The objective is to reproduce, in a realistic manner, the real world in a virtual environment. Indeed, in this virtual environment, which imposes no limits on data processing, energy consumption and communication capabilities, it is possible to create a system for the deployment of the physical sensor web. In order to faithfully mimic the physical sensor web deployed in the area of interest, we need to simulate, in a realistic way, the physical sensor nodes as well as the geographic environment where they are located. Physical sensor web are represented in the virtual environment using software agents. An agent is a program with domain knowledge, goals and actions. An agent can observe and sense its environment as well as affect it. Agents' capabilities may include (quasi-) autonomy, perception, reasoning, assessing, understanding, learning, goal processing, and goal-directed knowledge processing. The reproduction of the geographic environment in which physical sensor nodes are deployed is based on reliable data obtained from Geographic Information Systems (GIS). The concept of Multi-Agent Geo-Simulation (MAGS) evolves from such type of simulations involving

software spatial agents immersed in a virtual geographic environment.

#### B. Spatio-Temporal Knowledge

As we mentioned so far, spatio-temporal knowledge is used in our approach 1) to support agents decision making during the geo-simulation and 2) to analyze the results of the geo-simulation in order to offer decision support. In the following we respectively present the representation formalism and the categories of spatio-temporal knowledge used in the proposed approach.

1) *Representation formalism:* We use Conceptual Graphs (CGS) to represent spatio-temporal knowledge and to support spatio-temporal reasoning. CGs were introduced by Sowa [13] as a system of logic based on Peirce's existential graphs and semantic networks of artificial intelligence. They provide extensible means to capture and represent the semantic of real-world knowledge and have been implemented in a variety of projects for information retrieval, database design, expert systems, qualitative simulations, and natural language processing. However, their application to dynamic geographic spaces modeling and analyzing is an innovative issue. More details about CGs and their theoretical foundations can be found in [13], among others.

Syntactically, a conceptual graph is a network of concept nodes linked by relation nodes. Concept nodes are represented by the notation [Concept Type: Concept Instance] and relation nodes by (Relationship-Name). The formalism can be represented in either graphical or character-based notations. In the graphical notation, concepts are represented by rectangles, relations by circles and the links between concepts and relation nodes by arrows. The character-based notation (or linear form) is more compact than the graphical one and uses square brackets instead of boxes and parentheses instead of circles. Some examples are presented in the following sub-section.

2) *Knowledge Categories:* We distinguish three levels of spatio-temporal knowledge: 1) Knowledge about the environment, 2) Knowledge about actors and their behaviours and 3) knowledge about the application domain (Figure 2)

- **Knowledge about the environment:** We define the notion of knowledge about the environment (Environment Knowledge (EK) for short) as a specification of a conceptualization of the environment characteristics. Hence, EK is a description of the spatial concepts (geographic features) and relationships (topologic, semantic) that may exist in a geographic environment. In multi-agent geo-simulation, EK is a specification used for enabling knowledge exploitation for spatial agents. Practically, EK is an agreement to use spatial concepts (i.e., ask queries and make assertions), spatial

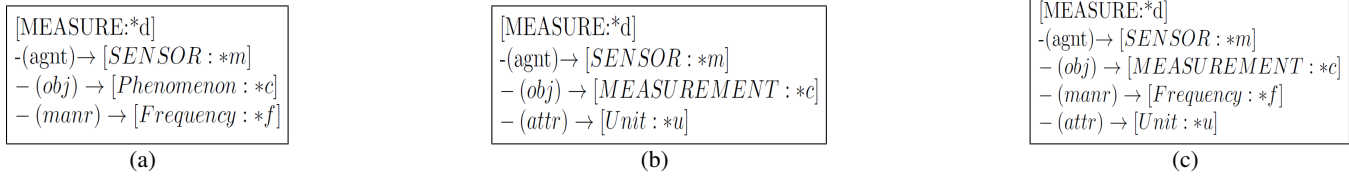


Figure 4. Specification of rules using the Prolog+CG syntax.

relationships (i.e., describe actions and behaviors), in a way that is consistent so we can share knowledge with and among spatial agents. Our aim is to improve the perception-decision-action loop on which relies most of the existing agents' models.

- **Knowledge about Actors and Behaviours**

**Archetypes:** Dealing with the specification of agents' attributes and associated spatial behaviors may be complex and time and effort consuming. Agents' characterization aims to specify: the agent archetype, its super-types and sub-types according to the semantic type hierarchy; and the behavior archetype that an agent archetype is allowed to perform within the informed VGE. Figure 3 shows an example of a semantic type hierarchy of agent archetypes. Entity is an abstract node and Storm, River, Building and Sensor are instance nodes (leaves) of this agent archetype lattice. A key characteristic of agent archetype is inheritance. Agents belonging to one or several agent archetypes inherit the characteristics associates with these agent archetypes.

For example, let us consider two agent archetypes *Temp-sensor* and *Press-sensor* respectively sensing temperature and pressure. The *Temp-sensor* is characterised by a measurement frequency *f*. On the other hand, *Press-sensor* is characterised by a one meter circular sensing field. Consider now *TP-sensor* a multi-functional sensor which inherits from *Temp-sensor* and *Press-sensor*. Thanks to the inheritance property provided by agent archetypes, this agent performs measurements at a frequency *f* within a circular sensing area of one meter. Since our research addresses the simulation of spatial behaviors, it has been influenced by some basic tenets of active theory [14]. In particular, our approach to manage environment knowledge rests on the commitments in active theory that: (1) activities are directed toward objects, zones, or actors; (2) activities are hierarchically structure; and (3) activities capture some context-dependence of the meaning of information. Theoretically, the common philosophy between our knowledge-based approach and activity theory is a view of the geographic environment from the perspective of an agent interacting with it [18]. Practically, the most important borrowings from activity theory are the

idea that [15]: (1) the semantic of behaviors and objects are inseparable; and (2) behaviors, objects, as well as agents are hierarchically structured. Let us define the following behavior archetypes that we associate with the Sensor agent archetype as follows: (a) "an agent \**m* which is a sensor measures an object \**c* which is a phenomenon with a frequency \**f*" (See Figure 4(a)); (2) "an agent \**m* which is a sensor measures an object \**c* which is a measurement of unit \**u*" (See Figure 4(b)). Since the above description is equal or more specific than the antecedent of the following behaviour, it can be inferred, by deduction, as shown in Figure 4(c).

- **Knowledge about the Application Domain:** The above mentioned levels of knowledge are used during the geo-simulation to support agents in their decision making. In contrast, knowledge about the application domain is mainly used to qualitatively analyze the results of the geo-simulation and is thus more linked to decision support. In the context of SW deployment, nodes are aimed to collect measurements about phenomena of interest which vary according to the application domain (military, environmental surveillance, etc.). Knowledge about the application domain defines phenomena of interest in a particular application domain. In our approach, we use the concept of spatio-temporal situations [19] to model and reason about phenomena of interest. A spatio-temporal situation represents a state, an event or a process situated in space and time and involving various objects of the world. Examples of spatio-temporal situations can be a sensor which brake down for a certain period of time at a certain spatial area (state), the start of rain in certain spatial area (punctual event) or a durative heavy rain in a given area (process). A spatio-temporal situation has a semantic type (rain, network breakdown, etc.), a start and end times and is located in space. Knowledge about the application domain defines spatio-temporal situations of interest according to their temporal (state, punctual event or durative process) and semantic characteristics. For example, the semantic punctual event "Start of rain" can be defined as the fact of water level exceeding a given threshold. Relationships between spatio-temporal situations (temporal and spatial) are also specified in the application domain knowledge, which enables defining

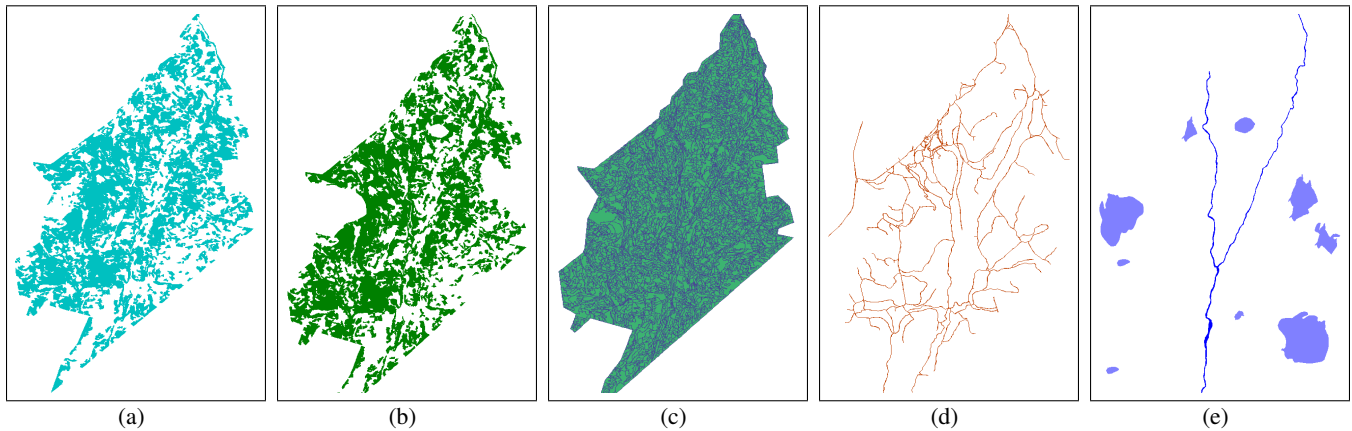


Figure 5. Various geometric and semantic layers related to the Montmorency experimental forest, St.Lawrence Region, Quebec, Canada: (a) and (b) two types of vegetation characterizing the land cover; (c) water resources including rivers and lakes; and (d) road network

complex phenomena. For example, a situation of storm can be defined as a situation of heavy rain followed by / accompanied with a situation of strong wind.

### C. Decision support

The decision support component analyzes the result of the geo-simulation using application domain knowledge in order to identify situations of interest to the user. This data analysis process is implemented using the approach proposed in [19]. Details of this approach are beyond the scope of this paper. We only illustrate the principle using the simple example showed in Figure 6. In this example, the situation of interest

there is a flood situation if the water-level exceeds 0,15 meter. Otherwise, there is no flood situation. The decision support component uses this knowledge in order to analyze the facts collected by agents during the simulation (Result Facts Base). Particularly, the two facts illustrated in Fig. 3 are respectively interpreted as the start of flood in (Area A, t= 14:35) and the end of flood in (Area A, 22:12) (punctual events). Finally, start and end flood situations are used to identify the flood situation itself as a process located in Area A during the time interval [14:35, 22:12]. Obviously, detection of real complex situations requires taking into consideration other aspects (measurement errors, conflict of measurements between several sensors, etc.) that are beyond the scope of this paper.

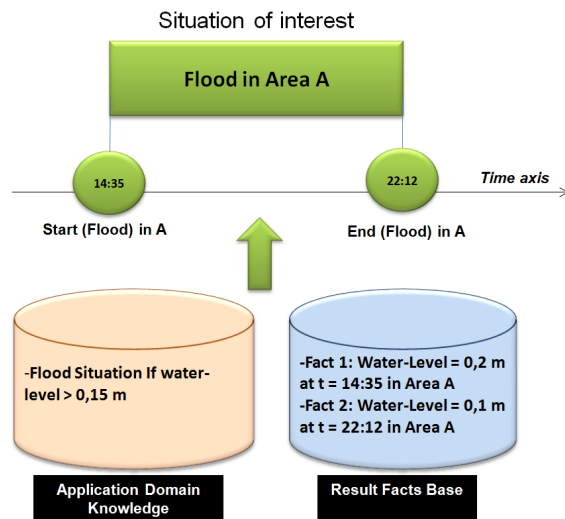


Figure 6. An example of a simulation result analysis and processing

is Flood. The application domain knowledge specifies that

## IV. EXPERIMENTAL RESULTS

In order to illustrate our knowledge-based multi-agent geo-simulation framework, we propose to simulate a sensor web deployed in an IVGE representing the experimental forest of Montmorency (Quebec, Canada) for weather monitoring purposes (Fig. 4 and Fig. 5). This scenario shows how agents adapt their spatial behaviors with respect to knowledge they acquire from the IVGE using our environment knowledge management along with their perception capabilities. The objective of the simulated sensor web is to identify and monitor a simulated storm evolving in the IVGE. In order to reason about knowledge, we used a platform to deal with CGs manipulation called Amine [20]. Amine platform provides a pattern-matching and rule based programming paradigm embedded in Prolog+CG language which is basically an object-oriented and conceptual graphs-based extension of Prolog language.

A few agent archetypes representing different kinds of

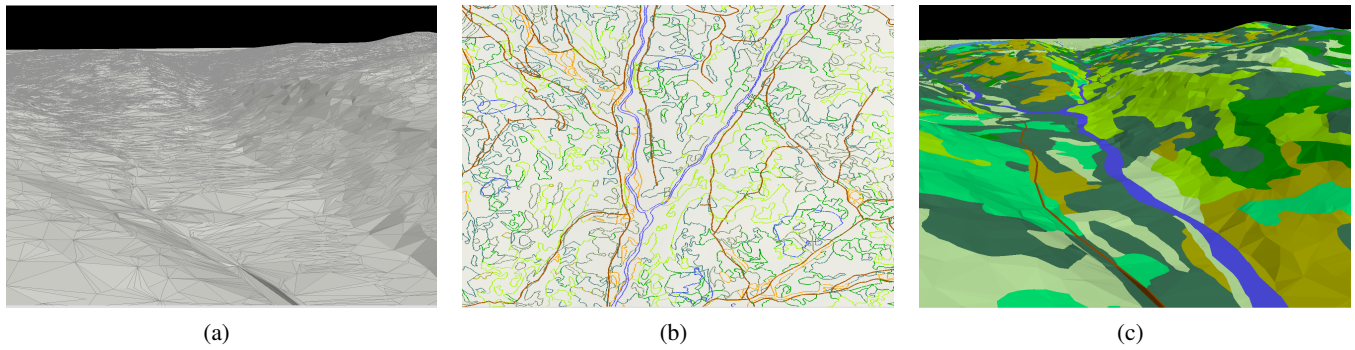


Figure 7. IVGE representing the Montmorency experimental forest; (a) the 2.5D triangulated elevation map; (b) the semantic maps; and (c) the 3D unified map

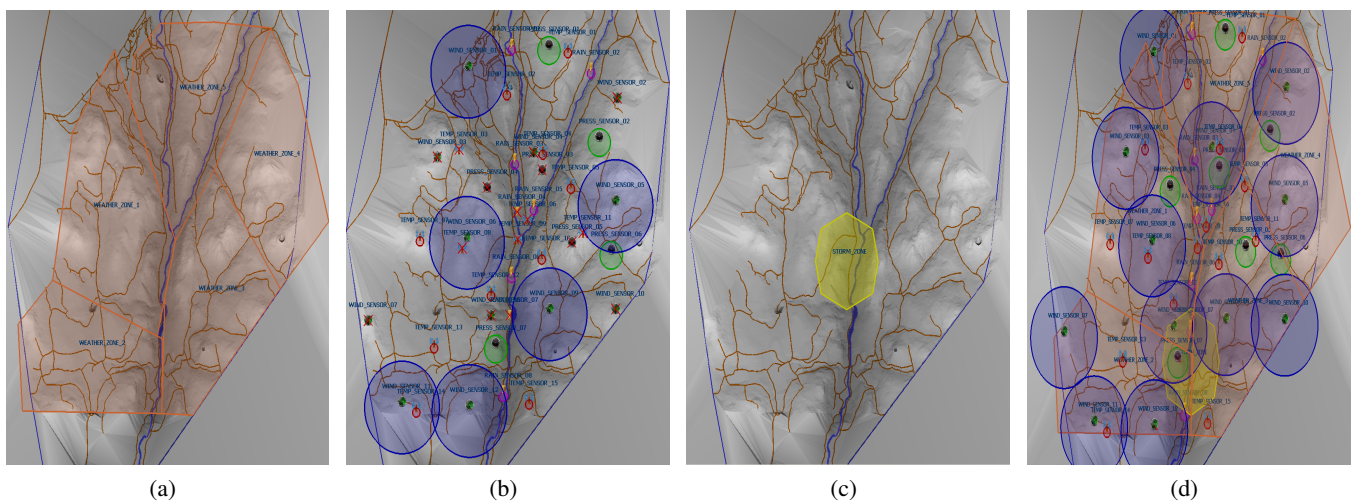


Figure 8. Simulation results: (a) WeatherZone agents covering the monitored geographic area; (b) the simulated sensors autonomously reaching their deployment position in the IVGE. The blue circle corresponds to the perception field for active sensors; and (c)

sensors are involved in this scenario. These sensors are first randomly deployed in the IVGE. Then, each sensor computes a path in order to reach its deployment position while taking into account the geographic environment characteristics. When sensors reach their final destinations, some of them stay active while other switch to idle in order to preserve the overall energy of the sensor web. Active sensors make measurements at a frequency  $f$  in order to monitor weather conditions. Active and idle sensors as well as the measurement frequency are specified in the simulation scenario created by the MAGS's user.

The simulated storm appears after a time frame  $t$  from the beginning of the simulation. If an active sensor perceives the storm agent, it directly accesses to its properties and extracts the information that it monitors depending on its kind of sensor, i.e. temperature, pressure, wind speed and direction, or humidity. If a difference above a certain threshold  $\Delta$  is

observed, the sensor proceeds as follows: (1) it accelerates its measurements frequency, (2) it adds a new fact that keeps track of the event with its timestamp in the Result Facts Base; and (3) it sends a message to weak up idle all sensors of the same kind which are situated in a certain estimated distance. As the simulation time goes by and the storm agent evolves in the IVGE, most of initially idle sensors become active to sense the observed phenomenon. When the storm agent is out of the perception field of the sensor, this latter senses a new difference between the past and the current measurement. It notifies the Result Facts Base by adding a new fact that keeps track of the new event with its timestamp; Idle and active sensors switch states in order to preserve their energy. In order to model the simulation described above, let us first consider the two agent archetypes ZONE and SENSOR. In contrast with the ZONE agent archetype, which represents a geographic area, the SENSOR agent archetype is associated with individual sensors

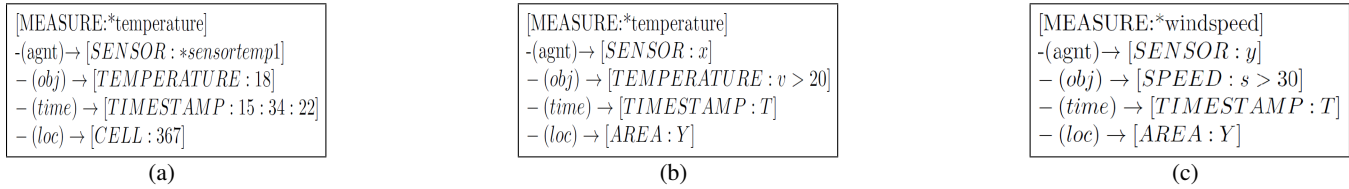


Figure 9. Behaviour archetypes expressed using the linear notation of Conceptual Graphs (CGs).

deployed in the informed virtual geographic environment. Let us consider the two agent sub-types *WEATHERZONE* and *STORMZONE*. Agents of type *WEATHERZONE* are stationary and represent meteorological conditions within the geographic area they cover. 5 instances of *WEATHERZONE* are created in order to approximately cover the monitored area (Fig. 6). In addition to their geometric characteristics, these agents encompass attributes which characterize the meteorological conditions such as temperature = 18 °C, pressure = 1010 hPa, humidity = 30. When a sensor detects a difference above the threshold, it adds a fact in the Results Facts Base using the CGs formalism. Consider the following example involving the *sensortemp1* adding a fact describing an observed difference of temperature measurement of value 18 at cell 367 at 15h : 34 : 22 (See Figure 9(a)).

Let us now define the following sub-types of *SENSOR* archetype: *TEMPSENSOR* for temperature measurement, *PRESSENSOR* for atmospheric pressure measurement, *WINDSENSOR* for wind speed and orientation measurement, and *HUMISENSOR* for humidity measurement (Figure 8). In this scenario, the situation of interest is the storm. Let us suppose that we need to describe the evolution of the storm during the geo-simulation for decision support purposes. Knowledge about the application domain allows specifying how the presence of a storm phenomenon can be detected in a certain area.

For simplification, let us consider the following (Prolog+CG) rule specifying that a storm is detected at time T in area A if there are (in the results facts base) facts describing that temperature exceeds 20 °C and wind speed exceeds 30km/h at the same time T and the same area A (See Figure 9(b) and Figure 9(c)). A storm detection event is triggered as soon as the conjunction of these two facts exists within the result facts base. The analysis of the simulation results conceptualize this event using the knowledge associated with the situation description shown in Figure 9.

## V. CONCLUSION AND PERSPECTIVES

Our environment knowledge management approach is original at various aspects. First, a multi-agent geo-simulation model which integrates an informed virtual geographic environment populated with spatial agents capable

of acquiring and reasoning about environment knowledge does not exist. Second, a formal representation of knowledge about the environment using CGs which leverages a semantically-enriched description of the virtual geographic environment has not yet been proposed. Third, providing agent with the capability to reason about a contextualized description of their virtual environment and phenomenon occurring within it during the simulation is also an innovation that characterizes our approach. We are currently working on the automated assessment of different simulation scenarios for sensor web deployment using our qualitative knowledge processing and analysis module. Indeed, users usually need to analyze and compare various scenarios in order to make informed decisions. This task may be complex and effort and time consuming. However, since our framework already supports the analysis of the multi-agent simulation results, it is easy to extend it to automatically assess scenarios.

## ACKNOWLEDGEMENT

This research was supported in part by the Grant in Aid provided by the University of Minnesota. The author would like to thank the reviewers for their valuable comments.

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