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Commonsense Spatial Reasoning: an Informational Perspective from Pervasive Computing

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Abstract: Pervasive Computing systems are characterized by possibly mobile components distributed in the environment and are devoted to collect, process and manage information in order to support users in different kind of activities. High-level correlation of information in such context can be defined, exploiting a formal model arising from the spatial disposition of information sources, as a form of commonsense spatial reasoning. With respect to this model, a Hybrid Logic to formalize commonsense spatial reasoning in these context has been defined. Here, on the basis of relevant analogies among Pervasive Computing and human practice in handling spatial knowledge, we suggest to provide the term "commonsense" with a positive meaning, showing that our logical framework captures some features of non-mathematical reasoning when spatially qualified information is concerned. The focus on such features and the analogies mentioned above suggest to qualify our approach to (commonsense) spatial reasoning as an informational approach.

Keywords: Knowledge Representation, Spatial Cognition, Computational Models, Commonsense Reasoning

1 Correlation of Information in Pervasive Computing.

Thanks to the improvement and growing availability of information acquisition and delivery technology (sensors, personal devices, wi-fi, and so on) computational power can be embedded almost in every object populating the environment. This brought a growing attention of computer scientists on pervasive and ubiquitous systems: as shown e.g. in Zambonelli and Parunak(2002) these systems are characterized by different, possibly mobile, components distributed in the environment and are devoted to collect, process and manage information in order to support users in different kind of activities (ranging from monitoring and control of specific areas to management of personal data, and so on).

A particularly strong relationship holds among those systems and the spatial environment they habit since acquisition, delivery and processing of information are sensitive to the *location* in which they are performed. A model of the spatial environment in which the system habit is required both at a global and at a local level in order to correlate information coming from distributed sources, to coordinate devices according to their spatial disposition, and to provide *context-aware services*.

Context can be defined by a set of different and heterogeneous information concerning the *presence/absence* of devices, relevant *properties* of the devices and their functionalities, information about the users and the *environment*.

Once that specific devices and technological tools, provided the capability to acquire meaningful information about both localization of devices and relevant features of the environment (e.g. temperature of a room, the detection of an anomalous situation in traffic monitoring), a challenging problem concerns the exploitation of this kind of information. In fact, devices localization and context dependent information should be integrated with domain theories specifying knowledge about what can be done, that is, how this information can be correlated according to the system's goal. From a Knowledge Representation point of view (for an introduction to Knowledge Representation principles see Brachman et al.(1991)), high-level correlation of the information required in Pervasive systems can be viewed as a form spatial reasoning (see e.g. Randell and Cohn(1989)) by defining a formal model of the system's environment.

In Bandini et al.(2005a), we presented a logical framework for *commonsense spatial reasoning* to model high level correlation in Pervasive Computing, where the term "commonsense" was used mainly because the underlying relational spatial model was not quantitative, but neither a mathematical qualitative one (such as algebraic topology). Here, on the basis of relevant analogies among Pervasive Computing and human practice in handling spatial knowledge, we suggest to provide the term "commonsense" with a positive meaning, showing that our logical framework captures some features of non-mathematical reasoning when spatially qualified information are concerned. The focus on such features and the analogies mentioned above suggest to qualify our approach to (commonsense) spatial reasoning as an *informational* approach. These two claims will be argued in the last section, while our logical framework will be briefly recalled in the next one.

2 A Hybrid Logic for Commonsense Spatial Reasoning in Pervasive Computing

The literature about space modeling, supporting computational frameworks to be adopted in order to develop reasoning capabilities, is wide and distributed in several areas of Artificial Intelligence. Within a rough classification two main classes of approaches can be distinguished: a first "quantitative" approach tends to justify spatial inference with mathematical models such as euclidean geometry, trigonometry, differential equations systems and so on (for an overview of these approach see Davis(1990)); in the "qualitative" second one, different topological approaches can be considered, ranging from point set and algebraic topology (e.g. the RCC calculus presented in Randell et al.(1992) and modal logics with mereotopological semantics, an example of which can be gound in Aiello and Benthem(2002)), to topological route maps (see Kuipers(2000), and Leisler and Zilbershatz(1989)). As far as pervasive systems are concerned, there is little interest in applying reasoning to obtain a deeper knowledge of the spatial environment for what concerns its topological or morphological aspects, because those aspects are partly known by design and partly calculable by means of technological tools (e.g. the instant position of mobile devices by a GPS). Spatial information is often available (whether possibly incomplete), but it needs to be integrated with domain theories to carry out specific tasks. For example, in the correlation of alarms for traffic control, the core theory for carrying out the traffic flow management consists in the theory about the formation of traffic anomalies Bandini et al.(2002); of course, this theory must exploit a model of the spatial environment in which the system is installed.

Within the qualitative approach to spatial reasoning, spatial disposition of information sources distributed in the environment (e.g. close circuit cameras, smart home or complex industrial plant sensor networks) can be mapped into a set of relations among interesting places (i.e. a topology) and high-level reasoning beyond low-level sensors' capabilities can be carried out by reasoning about properties holding at different places.

2.1 Basic Concepts: Places and Conceptual Spatial Relations

Suppose to have a sensor platform installed in a building in order to monitor a significant portion of it as depicted in *Figure 1*. Sensors distributed in the environment return values that can be interpreted in order to provide local descriptions, possibly generating alerts or alarms, of what is happening in the range of each sensor (e.g. "fire","broken-glass").

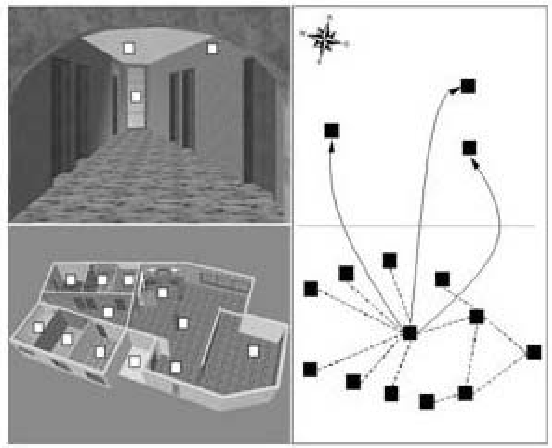

Figure 1: A sketch of monitored apartment and a relative topology. The nodes represent the interesting places (rooms and sensors), while proximity and containment relations are represented by dashed and unbroken lines respectively.

Different types of sensors are located into separated rooms: in the corridor, for example, there can be a camera, a smoke/fire detector and a broken-glass sensor. Sensors and rooms are related together by means of orientation relations, such as "*to be north of*"; rooms are linked together by means of proximity relations; and, finally, rooms and sensors are linked together by means of containment relations.

Regardless of a mathematical model of space, focusing on the relevant entities of the environment, such as sensors and rooms, and on their reciprocal relations it is possible to define a relational structure which represents a commonsense model of the space identified by the monitored area. From this perspective, meaningful correlation can be viewed as a form of commonsense spatial reasoning over the topology emerging from the spatial disposition of the different information sources.

From a conceptual point of view, such a commonsense model of space is defined as a finite topology whose nodes are identified by interesting places and whose relations are conceptual spatial relations (CSR) arising from an abstraction of the spatial disposition of these places. A place is a conceptual entity completely identified by an aggregation of attributes/properties of different kind; examples are the type of place (e.g. a place can be a sensor or a room), its internal status properties (e.g. "*is_faulty*"), its functional role (e.g. a kitchen or a living room), and so on.

Once a topological model has been defined, properties holding at different places can be correlated together to provide a more comprehensive understanding of the environment (e.g. neither a broken glass nor a person detected by the camera are per se a proof of intrusion, but those two facts considered together may lead to infer that a stranger is entered into the house passing through the window and walking in the corridor).

2.2 Commonsense Spatial Models: a relational approach

From a formal perspective a general Commonsense Spatial Model can be defined as follows:

Definition 1. *A Commonsense Spatial Model* $CSM = \langle P, R_S \rangle$ *is a relational structure, where* $P = \{w_1, \ldots, w_n\}$ *is a finite set of places and* $R_S = \{R_1, \ldots, R_n\}$ *is a finite non-empty set of binary conceptual spatial relations labeled by a set of labels* $L \subseteq N$*, and where, for each* $i \in L$*,* $R_i \subseteq P \times P$.

A place w can be any entity identifiable by a set of properties that inhabits the environment; the idea behind this choice is that information is what makes an entity interesting in the spatial environment. As for the set R_S, although from a conceptual point of view it can be any arbitrary set of binary CSRs, some classes of relations are particularly significant for a wide set of reasoning domains and play a special role in the definition of a Commonsense Model of Space. On the basis of both theoretical and pragmatic observations, three main classes of relations can be identified according to a set of shared formal properties (for a deeper discussion about the choice of these classes of relations see Bandini et al.(2005b)): the class of *proximity* relations (e.g. a place can be adjacent to another place), the class of *containment* relations (e.g. a place can contain another one or be contained in it) and the class of *orientation* relations (e.g. a place can be north of another one). Proximity relations are *symmetric* and *irreflexive*; containment relations are *transitive*, *antisymmetric* and *reflexive*; orientation relations require some more explanations. The idea is that orienting into space primarily consists in assuming reference points and then ordering the other places with respect to them. Therefore, an orientation relation consists of a *strict partial order* on the set of places with respect to a chosen *reference point*, which is the top element of the order; a usual choice is to take Cardinal Points as the top elements of the common orientation relations, but other reference points can be chosen as well. A CSM that has relations only of those three types and at least one for each one is called a Standard CSM (the formal definition of SCSMs can be found in Bandini et al.(2005a)).

2.3 Reasoning into Space: a Hybrid Logic Approach

Now, the passage from the model to logic is straightforward: since every CSM is a relational structure, it can be naturally viewed as part of the semantic specification for a multi modal hybrid language. A clear and detailed presentation of Hybrid Logic which contains also an introduction to common Modal Logic can be found in Blackburn(2000); here, recall just that a Kripkean semantics for a multi-modal logic consists in a relational structure (that can be called *frame*) plus an *evaluation* that states in which worlds (i.e. nodes of the frame) propositional symbols are true.

Hybrid Logic adds to the modal perspective features that are particularly useful with respect to our approach to commonsense spatial reasoning. In fact, Hybrid languages are modal languages that allow to refer to specific states of the model and to express (in the language itself) sentences about satisfiability of formulas, that is to assert that a certain formula is satisfiable at a certain world (i.e. at a certain place in our framework). So, it is possible to reason about what is going on at a particular place and to reason about place equality (i.e. reasoning tasks that are not provided by basic modal logic). Formally, this is achieved by adding to the language a specific set of propositional symbols NOM, called “nominals”, disjoint from the set of usual propositional symbols $PROP$, and introducing a set of “satisfaction operators” $@_i$. A nominal differs from a common propositional symbol because it is evaluated to be true at a single state of the model, which is called its *denotation*. Then semantics is given as usual for modal logic, and introducing the following truth condition statements for the set of satisfaction operators:

$$W,w \vDash @_i\varphi \quad \textit{if and only if} \;\; W,w' \vDash \varphi$$

and the place w' is the denotation of i, i.e. $V(i) = w'$.

Now, every CSM, being a relational structure, can be taken as a *frame* (and, thus, classes of CSMs such as the SCSMs identify classes of frames), in which the states of the model are places and the CSM relations specify the meaning of the spatial modal operators that can be chosen (thus, from now on we will use *places* to refer to *worlds*). A Hybrid Commonsense Spatial Model is thus given by a CSM and an evaluation that allows to recursively interpret formulas of an hybrid language specifying which propositional variables are true in which place and which is the denotation of the nominals introduced. Now we just need to introduce a suitable hybrid language to speak about the CSM, and this can be achieved, for example, by means of the following Basic Standard Commonsense Spatial Language.

Definition 1. ***Basic Standard Commonsense Spatial Language*** *($SCMS^{basic}$). L^b is a Hybrid Language containing the modal operators $\Diamond_N$, $\Diamond_E$, $\Diamond_S$, $\Diamond_W$, $\Diamond_{IN}$, $\Diamond_{NI}$ and $\Diamond_P$, and where $\{east, west, north, south\} \subseteq NOM$.*

The formal semantics for the $SCMS^{basic}$ language is defined accordingly to the definition of Standard CSMs, and can be found in **Error! Reference source not found.**. The intuitive meaning of $\Diamond_N$ is "possibly north of" ($\Diamond_N\ \varphi$ means that there is some place north of the current one in which φ is true) and $\Diamond_P$ stands for "possibly proximal to"; $\Diamond_{IN}\ \varphi$ means that there exist a place contained in the current one, in which φ is true, and its inverse, $\Diamond_{NI}$, is satisfied, conversely, when φ is true in a place that contains the current one.

In **Error! Reference source not found.** we gave a complete axiomatization for this language and exploiting some peculiarities of Hybrid Logic (like frame definability) we showed that there is a complete tableau-based calculus (for every SCSM, indeed) that endows reasoning over CSMs. Moreover, that axiomatization includes the formal definition of many cross-properties (inter-definabilities and logical interdependencies among different modal operators) that provide the CSM with still more structure. Some examples of deductions with tableaux are given, while other intuitive examples of the exploitation of this logic for information correlation can be found in **Error! Reference source not found.**.

3 Beyond Pervasive Computing: an Informational Approach to Commonsense Spatial Reasoning.

The form of spatial reasoning addressed with this Hybrid Logic approach, had been called "commonsense" essentially for the basic notion which the logical model of space is built upon, that is the notion of interesting "place". "Place" is a common notion since, as a matter of fact, it is more related to the *information* that makes it significant to different reasoning tasks than to its characterization in terms of abstract mathematical notions, which are not directly experienced in the everyday practice. Thus, from the formal point of view, the notion of place has been taken as primitive and has not been reduced to other mathematical constructions (such as set of points, open of points, vectors, and so on), neither has been defined by means of an algebra (as for the notion of spatial region in algebraic topology), neither has been characterized by means of a definite set of axioms (like in the RCC first order formalization).

Nevertheless there are significant analogies between spatial reasoning in pervasive computing and some forms of spatial reasoning in human everyday experience that suggest to give a richer meaning to the term "commonsense"; these analogies are basically related to the *acquisition*, the *organization*, and the *exploitation* of spatial information.

3.1 Pervasive Computing and Commonsense Spatial Knowledge

Let us start taking back some considerations about the pervasive computing from the way in which spatial information is acquired, organized and exploited in pervasive systems, that will be necessary to the proposed investigation.

First of all, pervasive systems are open and are strongly related to the environment principally for the role of the systems' sensors. Spatial information is usually gained from different sources: (1) some information are known by design, when a system has been designed for a particular environment (e.g. the map of a smart environment or the distribution of situated sensors), (2) some are acquired by means of sensors and low-level processing (e.g. when the position of a device is obtained from the processing of the data collected by a GPS sensor, and then projected on a map), and (3) some other are inferred relating data collected to suitable models.

In an analogous way, as for the practice of reasoning with spatial information, it is often the case that (1) some high level knowledge - eventually partial - about the spatial environment is already available; (2) new information is gathered by means of perception, elaborated by different cognitive processes and then related to a high level representation of the spatial environment (e.g. I recognize to be in a room, and I refer this information to the representation of the environment in which the room is proximal to the corridor); (3) inferential capabilities are exploited to infer new knowledge by correlating the information acquired with respect to the spatial representation; part of these capabilities concern the inference of spatial knowledge on the basis of known general properties of the spatial model (infer that a building is into a neighborhood knowing that it is into a street which is into that neighborhood).

In Pervasive Computing, since spatial information is gathered by means sensors, low-level processing techniques and high-level inference, different interpretative models are often involved. For example, in order to provide a context aware service, the location in terms of coordinates (e.g. "I am at <33є35'*N*,101є51'*W*>") must be mapped into a model of the environment richer from a semantical point of view (e.g. "I am at *Finsbury Park*"). In this sense, as for space and environment, it is not necessary, not common, and arguably not computationally convenient to provide a unique spatial model able to describe all the environmental features in the most exhaustive way. Aiming to balance expressivity and computational complexity, it is more reasonable to focus on the *integration* of different interpretative models, providing a composite framework for the acquisition, processing and organization of the information, enough flexible to merge together available information. Relying on such a composite framework the idea behind the Commonsense Spatial Logic introduced in the previous section is to exploit logic for high-level reasoning, grounding this reasoning on a spatial model which takes into account the global goals of the system.

In analogy to what happens in pervasive computing, different sources of information are involved and different cognitive processes deals with spatial information: memory, perception, communication, low-level cognitive processes and high-level reasoning interact when orientation in space is concerned, when there is the need to interact with the environment, or when it is significant to investigate what is true according in the environment according to some knowledge.

The fact that spatial knowledge and information are obtained by different sources and by integrating different interpretative levels, along with the above general considerations, influences as a matter of fact the way in which the key elements of our commonsense spatial knowledge are characterized. In particular:

1. commonsense spatial knowledge is often not exhaustive with respect to the spatial properties of the entities living in the environment; does not exist a list of sufficient and necessary properties which places must have in order to be part of the model. Many properties may be known or may not without preventing a place from being considered a "place"; a place may be considered a meaningful entity of the spatial environment also when its extension, its shape, its measures are not known. Some very rough information may be sufficient in order to take into account a place in the commonsense spatial model (e.g. knowing that there is a cinema

adjacent to the university is sufficient to assume the existence of two places distinguished by these two properties and a spatial relation holding between them).

2. Commonsense knowledge about the environment is often selective and incomplete; only a selection of the spatial entities is identified and memorized. This selection almost depends on the relevance of the information about the selected entities rather then on the application of an abstract mathematical principle of space division (e.g. a principle such as “if A is a spatial entity, its complement is a spatial entity of the model as well” does not hold when places are taken as primitive spatial entities).

3. Commonsense spatial reasoning often does not rely on a mathematical model of space and exploits *ambiguous* notions like “place”, instead of definite notions like “spatial region” or “region of points” and so on. Actually, many applications of commonsense spatial reasoning involves terms that have a meaning and a clear spatial reference, but to which it is not always possible to associate a definite extended spatial region. Recalling an example discussed in **Error! Reference source not found.**, consider terms as “Mont Everest”, or “Milan”: to these terms it is not possible to associate a definite spatial region (following the authors, not because these terms denote vague regions, but because they denote vaguely), but it is possible to associate to these terms some meaningful reference, that is, some places. With these terms it is possible to formulate common spatial expressions and among those places different spatial relations can be considered (the refuge is on the Everest, the Everest is north of India, and so on).

These remarks about commonsense spatial knowledge match with the basic assumptions on which this approach to commonsense spatial reasoning has been introduced in the Pervasive Computing domain. Focusing on the notion of available knowledge and assuming as primitive the notion of place, this logical framework addresses reasoning about spatial qualified information at a high level of abstraction and has been designed to be integrated with other tools and models for the acquisition and elaboration of spatial information. Moreover, with respect to the choice of Hybrid Logic for the formalization of this form of spatial reasoning, let us observe that this logic provide some features very interesting with respect to commonsense spatial reasoning; in fact, Hybrid Logic allows the local perspective over reasoning typical of modal logic (that is reasoning from a current place), while enabling also a global perspective (exploiting satisfaction operators) still preserving a good computational behavior as discussed in **Error! Reference source not found.**; finally, nominals allows to reason about specific places (whose name is known) in the environment and about place equality.

3.2 An Informational Approach to Commonsense Spatial Reasoning

These considerations tend to claim that there are some conceptual and, in part, philosophical reasons to consider this framework as an attempt to formalize commonsense spatial reasoning, and that the scarce use of mathematics in the model definition is not the only pointer to the term “commonsense”. In particular, we argue that this approach can be considered as an informational approach to commonsense spatial reasoning, essentially for the role that information plays in defining the notion of “place”. As mentioned above, a place is considered a place not only with respect to the extension in space that it is supposed to occupy (indeed it is problematic that it is always possible to associate a definite spatial region to a place), but also for other extra-spatial cognitive aspects of the environment. Observe that a conceptual spatial relation is grounded on physical space but not “founded” on it: no necessary relationship among CSMs and any objective physical representation of space needs to be assumed as primitive.

Now it becomes quite clear why we defined "informational" this approach to commonsense spatial representation, that is for the weight that the (available) *information* about space have, not only in the characterization of the places, but also in determining their existence as part of the spatial representation, where this is contextualized in other reasoning practices (in pervasive computing we started from alarm correlation as one of these practices).

4 Concluding Remarks

The relational commonsense model of space proposed and the logic based on it, born in a context in which information plays a crucial role, that is, in a Computer Science application framework for Pervasive Computing domain. The very goal of the Commonsense Spatial Hybrid Logic introduced was indeed to enable high-level correlation of information. Nevertheless, this focus on the role of information characterizes a specific approach to commonsense spatial reasoning that goes beyond the above mentioned application field.

In this sense this work should be put in relation with the attention on the notion of information that is emerging as a well defined philosophical trend at least in the past decade (e.g. see Floridi(2003)). In particular, an interesting future development of this research concerns a deeper inquiry on the relationship among the notion of "available information" and ontological and epistemological issues related to spatial representation. Such an inquiry should take into account also those dynamic aspects involved in the formation of a commonsense spatial model which have been only sketched so far from a conceptual point of view, and which have not been considered yet from the formal perspective.

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