Commonsense Spatial Reasoning for Context–Aware Pervasive Systems

Stefania Bandini, Alessandro Mosca, and Matteo Palmonari

Department of Computer Science, Systems and Communication (DISCo),
University of Milan - Bicocca
{bandini, alessandro.mosca, matteo.palmonari}@disco.unimib.it

Abstract. A major issue in Pervasive Computing in order to design and implement context–aware applications is to correlate information provided by distributed devices to furnish a more comprehensive view of the context they habit. Such a correlation activity requires considering a spatial model of this environment, even if the kind of information processed is not only of spatial nature. This paper focuses on the notions of place and conceptual spatial relation to present a commonsense formal model of space supporting reasoning about meaningful correlation. The model consists of a relational structure that can be viewed as the semantic specification for a hybrid logic language, whose formulas represent contextual information and whose satisfiability procedures enhance reasoning, allowing the local perspective typical of many approach to context–awareness.

1 Introduction

Ubiquitous computing can be viewed as a paradigm concerned with a new way of conceiving the interaction among humans (users) and computational devices. Mobile devices, sensors and integrated environments depict a scenario in which users will interact with embedded devices, dynamically connected with each other and almost disappearing in the environment.

Thanks to the improvement and growing availability of information acquisition and delivery technologies (sensors, personal devices, wi-fi, and so on) computational power can be embedded almost in every object populating the environment. Nevertheless, technological evolution is not combined with an equally rapid evolution of the conceptualization necessary to understand and govern the new situation [1]. The term *context–aware* has been introduced to represent new challenges and possibilities, but it is usually interpreted in technological terms, mainly, of physical localization and available resources (e.g. network connectivity).

Context can be defined by a set of different and heterogeneous information concerning the *device properties* (configuration, settings, status, and so on), the *presence of other devices*, their features, their position and function in the environment, and other *abstract and physical information about the environment* itself (predefined or acquired). Perceiving, representing and manipulating contextual information is necessary to perform high-level tasks that devices need to carry out in order to behave as much autonomously as possible according to the basic idea of pervasive computing paradigm.

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Sensors and devices are located in the environment and computation performed locally by them makes use of information that is related to space and physical environment in different ways: location and other spatial information are, thus, a primary aspect of every model of context, at least as far as a pervasive computing scenario is considered.

Different technological tools, specific devices and techniques, provide the capability to acquire meaningful information about both localization of devices in an environment and relevant features of the environment itself (sensors). Many problems are still open, ranging from basic technical issues (e.g. localization technologies) to protocols and software level issues (e.g. self-configuration of wireless devices), and to high level conceptual considerations (e.g. models of contexts). In fact, a first issue in context–awareness concerns the dynamic "perception" of context (such as localization, communication, collection of data from the environment, and so on); nevertheless, once those information have been acquired, a further challenging problem concern the exploitation of this information.

This exploitation primarily concerns representational issues, according to a formal model of the spatial environment, and the definition of suitable inferential capabilities. In fact, devices localization and context dependent information provided by those devices should be integrated with domain theories specifying knowledge about what can be done with the available information, that is, how this information can be processed according to the system's goal. In particular, from a logical point of view, this processing is a *meaningful correlation* of information provided by devices (that can be a result of local interpretation of raw data, as shown in [2]). A meaningful correlation of heterogeneous data collected from different networked sources consists in exploiting relations among data in order to provide a more comprehensive and informative view on the set of significant properties characterizing the environment.

This correlation task can be achieved by endowing the devices with the suitable inferential power; nevertheless, a preliminary step in order to enable such inferential capabilities is to define a model of context allowing to integrate an explicit representation of the environment with information provided by devices (including their position). According to [3], in order to be enough descriptive, modeling of context information needs to be general, semantically rich and formal.

From this perspective, meaningful correlation can be viewed as a form of commonsense spatial reasoning, where reasoning is grounded on the topology emerging from spatial disposition of the different information sources. Commonsense spatial reasoning presents some specific capabilities, that is, not only to reason about properties of space, but also to exploit spatial information in order to support activities related to various other types of task.

The aim of this paper is to present a logical approach to correlation of information coming from networked devices distributed in the environment: the topological model arising from the devices network can be viewed as a relational structure and, thus, as semantics specification for a hybrid modal language, and reasoning tasks are carried out by means of domain dependent axioms.

In the following section the commonsense spatial concepts of *place* and *conceptual spatial relation* are introduced as the basis of Commonsense Spatial Models, while the formal model is described in Section III. In Section IV it is shown how the defined model can be exploited as kripkean-like semantics for a specific logical language, that is a Multi-Modal Hybrid Language. Concluding remarks end the paper.

2 Basic Concepts: Places and Conceptual Spatial Relations

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 such as Automated Vision, Robotics, Knowledge Representation, and so on. Within a rough classification two main classes of approaches can be distinguished: a first one tends to justify commonsense spatial inference with mathematical models such as Euclidean geometry, trigonometry, differential equations systems and so on [4]; in the second one different topological approaches can be considered, ranging from point set and algebraic topology, with the choice of different kinds of primitive entities and relationships (e.g. RCC calculus [5], modal logics [6]), to topological route maps (see [7, 8], and [9]).

Within the second conceptual framework, correlation as commonsense spatial reasoning can be supported by defining a formal model of space that exploits the basic notions of place and conceptual spatial relation. 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.

Suppose to have a sensor platform installed in a building in order to monitor a significant portion of it (and, eventually, to take suitable control actions). 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. Architectural issues are out of the scope of this paper, but in [2] the advantages of distinguishing the detection, local interpretation and correlation levels have been widely discussed, and a four-leveled architecture, which had been fruitfully exploited in the traffic monitoring domain [10], has been presented.

An example of such an environment, e.g. an apartment, is given in Figure 1. Here, 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 at north of*"; rooms are linked together by means of proximity relations; and, finally, rooms and sensors are linked together by means of containment relations. In the example proximity between rooms has been defined taking into account "direct access", but the proximity relation can be interpreted differently as well (e.g. as the relation between adjoining rooms). Here sensors and rooms and their reciprocal relations define a commonsense model of space of the monitored area.

A commonsense model of space supporting reasoning about the environment emerges therefore as a topology whose nodes are identified by interesting *places* and

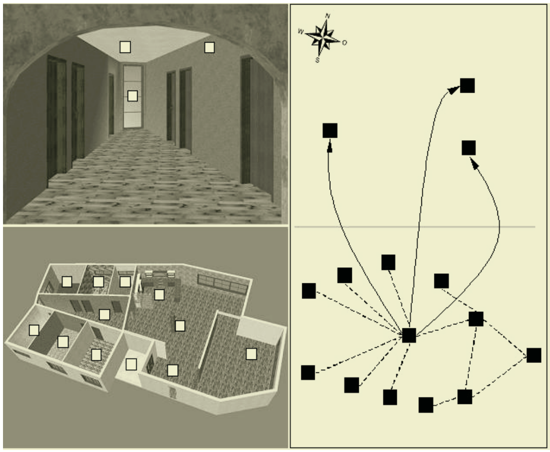

Fig. 1. The emergence of a commonsense spatial model in the context of a monitored apartment. On the left a 3D model of the apartment and a cross-section of its corridor are presented. In the right side, the generation of the corresponding spatial model is represented: the nodes are the interesting places (rooms and sensors), while proximity and containment relations are represented by dashed and unbroken lines respectively. Orientation relations can be guessed but have been omitted for sake of clarity

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.

Observe that a CSR is grounded on physical space but not "founded" on it: no necessary relationship among CSRs and any objective physical representation of space needs to be assumed as primitive. Nevertheless, theoretical considerations about the epistemological relevance of this notion of "emergent topology" based on these two basic concepts concerns controversial philosophical issues, which would deserve a deeper analysis that goes beyond the aims of this paper.

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). Observe that a fundamental characteristic of a commonsense model of space is finiteness, that is, the number of places is always limited; this issue is significant for computability and tractability but is also sound with the fact that, when considering a specific situation, any reasoner necessarily selects a limited portion of the context. As it will be stressed out in the conclusions, this work does not deal with dynamical aspects of the environment yet: the interesting places may change in time; nonetheless, this problem is related to the places selection process and concerns how the model forms and changes, but it does not hinder the model finiteness.

3 CSM, A Model for Commonsense Spatial Reasoning

From a representational perspective the conceptual framework introduced naturally recalls the definition of a relational structure, whose nodes are places and relations are CSRs. A relational structure is a non-empty set on which a number of relations have been defined; they are widespread in mathematics, computer science and linguistics. In particular, according to the epistemological framework specified in the previous section, only finite structures are considered and this is a fundamental characteristic with respect to the computational tractability problem as mentioned in the previous section. A general commonsense spatial model is thus defined as follows:

Definition 1. *A commonsense spatial model $CSM = \langle P, R_\sigma \rangle$ is a relational structure, where $P = \{p_1, ..., p_i\}$ is a finite set of places, and $R_\sigma = \{R_1, ..., R_n\}$ is a finite non-empty set of binary conceptual spatial relations, labeled by means of a set of labels N.*

Finiteness and cardinality of P (the domain must contain at least two places) are minimal requirements to have a well-founded commonsense model of space according to the observation reported at the end of the previous section. An *edge labeled multigraph*(a graph with admitted multiple edges between nodes as in [11]), whose nodes and labeled edges are respectively places and CSRs, is a powerful instance of a CSM.

A place can be anything that satisfies the informal definition of the previous section. As for R_σ, although R_σ can be any arbitrary set of binary CSRs, some classes of relations significant for a wide reasoning domain will be characterized in the following paragraphs. As far as a commonsense model of space is concerned, it is not possible (nor useful) to identify a minimal set of primitives relations (as for RCC). In fact, this approach is not aimed at providing a mathematical model of space, but rather to define the basic elements for the specification of axioms defining relevant properties of specific environments.

Nevertheless, there are some significant classes of relations that provide a model enough powerful but still general. In particular, a place can be "oriented by" the presence of an other (distinct) place, a place can be "contained in" or can be "proximal to" an other place. Although many different relations can fit here, according to different application domains, it seems natural to identify in *Orientation*, *Containment*, and *Proximity*, the archetypes of any form of commonsense spatial arrangement among entities.

Orientation. First of all, we need some relations to ensure *orientation* in space: assuming reference points is a rudimentary but fundamental way to start orienting into space. Assuming points of reference consists in ordering entities with respect to these particular points. Since many different sources of orientation can be found (stars, magnetic fields, a subjective set of mnemonic sites, and so on), a further step is to choose *good* reference entities and this can be achieved by means of the traditional four *cardinal points*: North, East, South, West. The latter suggests the definition of a set of orientation relations R_N, R_E, R_S, and R_W among places (observe that, from a formal perspective, only two of these relation symbols need to be taken as primitive).

Thus, two relations $R_N \subseteq P \times P$ and $R_E \subseteq P \times P$ are introduced and interpreted in the following way. Let p and q be two places, the relation $R_N(p,q)$ holds *iff* p is *at north of* q ($R_E(p,q)$ is defined analogously). Orientation relations are both *strict partial orders* on the set of places that is, they are *irreflexive*, *asymmetric* and *transitive* relations; the order is "partial" because two places might be incomparable. Moreover, both relations have a *superior* and an *inferior* that coincide respectively with North and South, and with East and West. The relations R_S and R_W are defined as the inverse respectively of R_N and R_E. Other non-primitive relations such as *at north-east of* (R_{NE}), *at north-west of* (R_{NO}), and so on, can be defined by means of usual set theoretic operators from the previous ones, e.g. $R_{NE} = R_N \cap R_E$.

It is important to observe that, for what concerns orientation, the notion of order among entities is more fundamental than the contingent choice of particular reference points in order to enable that ordering. The choice of cardinal points seems quite intuitive, but, if different perspectives are needed, reference points can be easily changed or added preserving the basic structure (a lattice with superior and inferior) and the relations' properties (irreflexivity, asymmetry, transitivity). For instance, higher/lower relations can be represented by orientation relations with suitable entities as superior and inferior of the lattice.

Containment. Since places are arbitrary entities, possibly with different shapes, dimensions and nature (e.g. a room and a printer can both be places), a physical inclusion relation $R_{IN} \subseteq P \times P$ is needed in order to relate different types of places: an object may be in a room that may be in a building (where the object, the room and the building are interesting place of the same topology). The relation $R_{IN}(p,q)$ is interpreted as stating that the place q is *contained* in the place p; R_{IN} is a typical mereological relation: it is a partial order, and, more precisely, a *reflexive*, *antisymmetric* and *transitive* relation. Here, the stronger antisymmetry (i.e. $\forall p,q(R_{IN}(p,q) \wedge R_{IN}(q,p) \rightarrow p = q)$) holds because this can be exploited to infer identity between two places for which is said that one is in another and vice versa.

Proximity. Another basic relation useful to characterize space concerns the possibility of accessing one place from another (in both physical and metaphorical sense). Two places are said to be proximal if it is possible to go from one to the other without passing through another place: a *proximity* relation $R_P \subseteq P \times P$ is then introduced, whose meaning is that the place q is directly reachable from place p. This relation can be modeled as an adjacency relation since is *irreflexive* and *symmetric*. However, different criteria of reachability can be adopted to define an adjacency proximity relation. In a network of radio transmitter/receiver devices proximity is a very different notion from the one adopted in crowding dynamic analysis or in molecular morphogenesis.

Therefore, according to the above observations about orientation, containment, and proximity relations, it is possible to define an *elementary* Conceptual Spatial Model CSM_e as a CSM where, at least $\{North, South, East, West\} \in P$ (the upper and lower bounds of the orientation relations), and $R_\sigma = \{R_N, R_E, R_{IN}, R_P\}$.

4 Reasoning into Space: A Hybrid Logic Approach

Since the commonsense spatial model just introduced is a relational structure, it can be naturally viewed as the semantic specification for a modal logical language. According to a well known modal logic tradition, which relates to Kripke "possible worlds" semantics, classes of relational structures (such as CSMs) can be considered as "frames", structures whose relations define the meaning of specific sets of modal operators.

Therefore, modal languages turn out to be very useful as far as reasoning about relational structures is concerned, and have been exploited for temporal and spatial logics, for logic of necessity and possibility and many others (see [12]). Nevertheless, recent studies in Modal Logic lead to further improve its expressiveness and power according to issues coming mainly from research in the Knowledge Representation area. One of the most notable results has been the development of Hybrid Logic. Hybrid languages are modal languages that allow 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). In other words, its syntactic side is a formidable tool 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).

The definition of a hybrid logic for commonsense spatial reasoning according to the presented CSM requires the assumption of a specific *sort* of atomic formulas (i.e. "nominals") to refer to the interesting selected places. As usual, each place-nominal is true at exactly one place of the CSM and the introduction of the so-called "satisfaction operators" $@_i$ provides the capabilities of reasoning globally on the universe of places. Given a model $W = \langle CSM, V \rangle$, where CSM is the frame and V is an hybrid valuation, the true condition for a formula $@_i\phi$ (where ϕ can be any arbitrary formula), is given as follows:

$$W, w \models @_i\phi \text{ if and only if } W, w' \models \phi,$$

where the place w' is the denotation of i, i.e. $V(i) = w'$. A complete set of symbols for modal operators is then given according to the classification of the basics conceptual spatial relations introduced above. Thus, with respect to the CSM_e, the operators $\Diamond_N$, $\Diamond_E$, $\Diamond_S$, $\Diamond_W$, $\Diamond_{IN}$, and $\Diamond_P$ are introduced; their groundedness in the CSM is guaranteed by the fact that their accessibility relations are defined, respectively, by the CSM's relations R_N, R_E, R_{IN}, and R_P (the semantics of $\Diamond_S$, $\Diamond_W$ is defined over the inverse of the R_N and R_E relations).

According to the aims of the modeled correlation task, a domain dependent set of properties can be chosen and represented in the formal language by means of a suitable set of symbols for propositional letters (e.g. the information "there is a man", coming from a local data processing, can be represented with a proposition "is_man", true or false at some place of the model).

The combination of the multimodal and hybrid expressiveness provides a powerful logical reasoning tool to shift perspective on a specific place by means of a $@_i$ operator, which allows checking properties holding over there; for instance, with respect to Figure 1, when a system devoted to intrusion detection need to query if "a glass is broken" at the place corresponding to the broken-glass sensor, the satisfiability of the formula $@_{window\_sensor} broken\_glass$ must be checked. Moreover, exploiting this operator, it is possible to define local and internal access methods to explore the spatial model according to the other defined operators - e.g. checking the satisfiability of the formula $@_{kitchen}\Diamond_W\Diamond_{IN} smoke$ formally represents the verification, for the system, that “in” some room “at west of” the kitchen some “smoke” has been detected.

Hybrid Modal logic is particularly useful to model reasoning about correlation in pervasive computing environments and, especially, when correlation is exploited for context–awareness, thanks to the double perspective over reasoning that this logic introduces, that is, both local and global.

In modal logic, in fact, reasoning and deduction start always from a given point of the model, i.e. from what is taken as the “current world”. In terms of the interpretation of worlds as places, this means that reasoning is performed by a local perspective, and precisely, from the place in the environment taken as the current one. Since, according to the presented model, devices are places, each device can reason about context from its local perspective but exploiting a shared model of the environment. Taken a device, checking the satisfiability of the formula $\Diamond_P\,(sensor \wedge broken\_glass)$ from this current place means to query if a broken glass has been detected by a sensor adjacent to the current one (an adjacent place on which $sensor$ and $broken\_glass$ are true). On the other hand, hybrid modal logic, still preserving the same local attitude to reasoning of classic modal logic, allows global queries such as $@_{window\_sensor} broken\_glass$. This, in fact means, that whatever is the device on which reasoning is performed, the query regard a specific place/device, that is, the $window\_sensor$.

This double approach to knowledge representation and reasoning typical of hybrid logic (which has been well described in [13]) allows correlation to be modeled as performed both by a central processing unit that reason globally and by single devices locally: this is consistent with different technological approaches to context–awareness, from more centered–based approaches such as blackboard approaches, to approaches stressing more the autonomy of devices, such as multi-agent based approaches.

5 Concluding Remarks

In this paper we presented a commonsense spatial model of space supporting correlation of information coming from distributed sources, which does not assume a strong mathematical ontology, but focuses on the commonsense concepts of place and spatial conceptual relation.

We have shown that the proposed model can suitably provide a formal semantics for a hybrid modal language, whereas the axiomatization and the definition of a complete calculus is object of current work. It is easy to observe that a CSM is not a closed model, in the sense that, although some basic conceptual spatial relations have been formally characterized, the definition of new arbitrary relations is left open, still preserving the basic model definition (def. 1). A similar modal approach to correlation as commonsense spatial reasoning has been already applied to design and implement the Alarm Correlation Module of SAMOT, a monitoring and control system mainly devoted to traffic anomalies detection (as shown in [14]). In this system the representation of space is mono-dimensional, but correlation is performed along both space and time dimensions.

Actually, there are many domains in which time dimension is crucial and a very interesting problem for further formal and theoretical work is how to consider time and dynamism integrated with CSM. On one hand, in fact, considering the dynamical evolution of a system, correlation may need to relate facts true at different places at different time (properties holding over a place change in time). On the other hand, in domains characterized by the presence of wireless technologies, interesting places, properties holding over them and the relations' extension may change, since new interesting places can be discovered (e.g a mobile object is identified as a place) and known places can move.

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