Commonsense Spatial Reasoning about Heterogeneous Events in Urban Computing

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Abstract. In this paper we discuss the adoption of a formal approach to correlation of heterogeneous information based on qualitative spatial reasoning to contribute to some relevant aspects that stream reasoning need to face in Urban Computing. The approach is based on the adoption of Commonsense Spatial Hybrid Logics to reason about events and infer higher-level scenarios of interest. This paper therefore extends previous work of the authors in the context of pervasive computing systems in order to take into account an urban-scale application context. In order to discuss the advantages of the approach a real-world application devoted to control and monitor different phenomena occurring in urban environments is described. Finally, some issues related to the exploitation of the approach in Semantic Web frameworks are discussed.

1 Introduction

The large availability of sensing technologies, connectivity, mature data analysis algorithms and ubiquitous access to information opened the door to a new application scenario that has been recently referred to as Urban Computing [1]. Control and monitoring systems on an urban scale consist of distributed components that collect, process, and manage heterogeneous information to take suitable control actions or deliver information to users [2, 3].

In this scenario, a great deal of the available information concern specific parts of the environment and has a temporal reference. The continuous nature of the information management process tightly connects the problem of interpreting and reason about this kind of information to the problem of analysing and reasoning about data streams [3].

Modern applications in Urban Computing require not only monitoring of specific phenomena e.g. traffic, but an integrated monitoring of the heterogeneous information produced by different information acquisition devices and different subsystem (e.g. concerning traffic, pollution, occurrence of special events, and so on) in order to govern complex urban phenomena, interpret and infer critical situation, and possibly take on suitable control actions. In particular, there is an increasing need of relating computation to the spatial context in which it takes place, and models managing spatially related information are necessary to correlate local information, to coordinate devices and to supply context aware services.

In this paper we discuss the adoption of a formal approach to correlation of heterogeneous information based on qualitative spatial reasoning to contribute to some of the crucial aspects that stream reasoning need to face in Urban Computing. The approach is based on previous work where these techniques have been applied to home-scale pervasive computing applications [4] and to monitor anomalous traffic patterns on highway sections [5]; in this paper we show how the approach can be extended to take into account an urban-scale application.

In Section 2 we discuss the application context, which consists of a real-world platform for monitoring and control of an urban area; the platform integrates domain-specific subsystems and different kind of information and knowledge sources. Section 3 introduces a four-layered conceptual architecture for information management, on which the above mentioned platform and other similar monitoring and control systems [5] are based, and discusses how this architecture relates to stream reasoning. The core of the architecture is the distinction between a local interpretation level, producing atomic events as outputs, and a global correlation level for merging such events to infer higher-level scenarios. Due to the events' spatial and temporal references, information correlation can be interpreted as a form of qualitative spatio-temporal reasoning; in this paper, we focus on spatial correlation, assuming to reason about the state of affairs known to be true in a fixed temporal window. Commonsense Spatial Hybrid Logics (CSHLs) [4] are exploited to codify interesting scenarios to be inferred, and are introduced in Section 4. Section 5 show the application of Commonsense Spatial Hybrid Logics to reason on events at an urban scale. After the related works (Section 6), we end the paper (Section 7) with a discussion about the advantages of the formal approach proposed w.r.t. modeling capabilities and the issues that need to be addressed to bridge the gap between CSHL-based reasoning techniques and Semantic Web languages to represent events.

2 The Urban Context of the Supercentro Project

Supercentro is an ongoing project carried out by Project Automation S.p.A. for the development of a platform integrating different subsystems producing and storing information about phenomena related to mobility (or relevant to it) in the City of Milan. The aim of the platform is to support qualified operators in monitoring such phenomena in order to take suitable actions, to diffuse relevant information to citizens and to eventually select retroactive actions autonomously.

At the bottom level, data are collected by a number of technologies and devices including traffic and environmental sensors (monitoring air pollution, noise and other weather reports), traffic violation detectors, closed circuits televisions (CCTV), and so on. A calendar containing extraordinary or periodic events occupying part of the road network (e.g. roadworks, demonstrations, local markets, and so on) provides another information source. The information collected are processed and interpreted at the local level by a number of softwares and algorithms that take raw data as input and produce aggregate information, represented as events, that are stored in a repository; as an example, data about traffic flows are aggregated with statistical techniques to associate a qualitative measure of traffic both to road sections where sensors are not available and to wider areas. Information can then be diffused through multiple channels, among which mobile services providing context aware functionalities: messages about traffic congestions should be filtered on the basis of the agent location and proactive suggestions need to be delivered on the basis of the overall context. Other control actions that need to be taken on the basis of the context concern the management of traffic regulators, Variable Message Panels (VMP), CCTV, and so on.

An event correlation manager is needed in the Supercentro platform in order to make sense of the great amount of events populating the repository at any time, providing human and software agents with meaningful high level information about the environment they are and move in. The event manager needs to consider (i) the urban spatial environment, and (ii) a high degree of heterogeneity of the events to be correlated. Consider that some of these correlations need to produce information which can be referred to the spatial environment in a global perspective (e.g. heavy traffic affects all the trade fare area and its neighborhood); however, it would be also useful to model correlations on a local perspective (e.g. heavy traffic occurs on all the areas that are reachable from the current location x) because these correlations should provide information to be delivered to users' mobile devices, or, in the future, could be even performed by the mobile devices themselves.

3 Streams, Events and Commonsense Spatial Reasoning

The approach described in this paper is based on a four-layered conceptual architecture for information processing in control and monitoring systems. The general characteristic of the architecture and the covered domains have been discussed in [2]; the architecture has been also applied in former projects in real world control and monitoring systems [5]. The four layers the architecture is composed of are the following:

- the **acquisition level** - sensors and devices, eventually different and heterogeneous, acquire data from the environment or from other devices; outputs of this phase are raw data (e.g. video streams caught by a camera);
- the **local interpretation level** - data acquired by sensors are locally processed and interpreted, returning information about a specific parameter or about a particular portions of the environment; outputs of this phase are information interpreted according to a given model (e.g. an event representing that a queue is formed on a road section is detected by video image processing algorithms [5]).
- the **correlation level** - information coming from local interpretations, and possibly from different sources, is correlated, i.e. is managed and filtered according to a more global[1] view of the whole situation; outputs of this phase are products of

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[1] Notice that local interpretations might be centralized, but exploit local models proper of particular types of information; conversely, the correlation level can be centralized or decentralized

information correlation (e.g. a global event such as the reduction of a queue along the spatial dimension is inferred [5]);
- the **actuation level** - different actions are taken on the basis of the available high-level information (e.g. a traffic regulation plan is activated, a thematic map provides traffic operators with high-level information about the monitored area).

Where much of the processing at the local interpretation level is usually performed by targeted and domain specific efficient algorithms (e.g. neural-networks for the first analysis of camera streams), model and knowledge-driven correlation approaches are effective at the correlation level [6]. Since heterogeneous pieces of information returned by the local interpretations have spatial and temporal references, they can be handled as *events*, that is, properties of places in the spatial environment that have been detected to be true at a given time (e.g. in the Sempione Area traffic is fluid at 10/03/09 h:20.35). The correlation task can be then defined as the task to detect and infer non-atomic high-level events starting from a set of atomic events, on the basis of specific domain dependent rules; these non atomic events, will be called *scenarios*.

The key aspect of the spatial and temporal-based approach to correlation consists in exploiting the spatial and temporal representation as the substratum that allows to correlate otherwise heterogeneous information (e.g. a air pollution detection and a traffic measure detection have in common that they can be interpreted both as events occurring on a portion of space and time). In order to map the above described approach to what has been defined as “stream reasoning”, data in the streams we focus on consist of events as representational units, which are usually outputs of preliminary processing. From our perspective stream reasoning is interpreted as a knowledge based event correlation problem.

In this paper we focus on space for two main reasons. On the one hand, the extension of a spatial modal logic in order to a logic considering also the temporal dimension is quite intuitive because of the well known axiomatizations of temporal modal logics and of some spatio-temporal modal logics [7]. However, the main problems are related to complexity and decidability, since qualitative spatio-temporal reasoning easily lead to undecidability, even when rather simple and decidable spatial logics (with only one primitive modal operator) are integrated with decidable temporal logics [7].

We therefore focus on spatial-based correlation of events assuming to reason about what is known within an observation window, considering this window as time unit. Different possible representations and interpretations of temporal event sequences are represented on the left side of Figure 1; our approach assumes the regular and discrete interval-based interpretation of regular timestamp-based event sequences, according to the model adopted in [8].

The approach to information correlation as spatial reasoning consists therefore in defining: (i) a spatial model representing the environment; (ii) a logic that allows to talk and reason about events referenced w.r.t. the adopted spatial model; (iii) the domain correlation axioms. In particular, as for the models, we defined the class of Commonsense Spatial Models (CSMs), and as for the logic, we defined a family of Hybrid Commonsense Spatial Logics (HCSLs), whose semantic is given by CSMs as underlying

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but is based on correlations taking into account heterogeneous pieces of information and/or information coming from different sources [6].

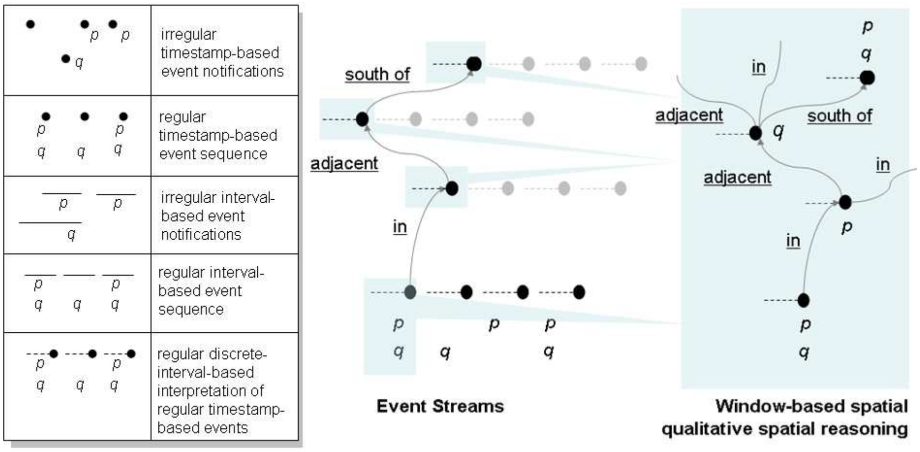

Fig. 1: A sketch of the mapping between streams and a spatial reasoning-based approach to event correlation

relational structures [4]. The HCSLs are based on the adoption of graph-based models, where points are places in the space and a number of classes of commonsense spatial relations are formally defined. Figure 1 (on the right side) shows the relationship between event streams and the window-based commonsense spatial reasoning approach to event correlation discussed here.

4 Commonsense Spatial Reasoning with the $\mathcal{SL}^{\texttt{basic}}$ Hybrid Logic

The CSHLs are based on a class of models for commonsense spatial reasoning based on the notions of "place" and "commonsense spatial relation". We call Commonsense Spatial Models these kinds of graph-like models, which are defined as follows:

Definition 1. *(Commonsense Spatial Model, CMS).*
A Commonsense Spatial Model $CSM = \langle P, R_L \rangle$ is a relational structure, where $P = \{p_1, ..., p_k\}$ is a finite *set of places, and $R_L = \{R_1, ..., R_n\}$ is a finite non-empty set of binary conceptual spatial relations labeled by a set of labels $L \subset \mathbb{N}$, and where, for each $i \in L$, $R_i \subseteq P \times P$.*

A place can be any entity identifiable by a set of properties or information, and relations in the structure are intuitively interpreted as spatial relations between places. Standard Commonsense Spatial Models are a class of models identified by three kinds of spatial relations, namely *proximity*, *containment*, and *orientation*.

All the formal properties of proximity and containment relations, and the main properties of orientation relations are represented in Table 1 (abbreviated respectively as

P,C and O). Two more properties specific to orientation relations are provided later on, in Definition 3. Intuitively, proximity relations represent the possibility of reaching one place from another one (in both a physical and a metaphorical sense), establishing *connections* among spatial entities. Containment relations define location and physical inclusion between places, allowing to define hierarchies among places possibly with different shapes, dimensions and nature (e.g. a room and a printer are both places). Finally, *relative orientation relations* are introduced. Orientation relations are strict partial orders of places w.r.t. some reference points: cardinal points are particular reference points, and a relation such as "north of" defines an order on places such that north is northern than any other place, that is, it is the top element of the order. Properties of orientation relations include therefore the existence and uniqueness of a top element for any orientation relation (axioms EX and UNI top element in Definition 3). This approach allow to define special orders of interest in particular domains, as shown in the next sections (e.g. the Trade Fair of a city). We refer to [4] for a detailed justification of this axiomatization. Standard Commonsense Spatial Models (SCSM) are therefore defined as follows.

	Property	CSR class	HL Definition
(*ref*)	*reflexivity*	P,C	$@_i \Diamond i$
(*irref*)	*irreflexivity*	O	$@_i \neg\Diamond i$
(*sym*)	*symmetry*	P	$@_i \Diamond\Diamond i$
(*asym*)	*asymmetry*	O	$@_i \neg\Diamond\Diamond i$
(*antisym*)	*antisymmetry*	C	$@_i \Box (\Diamond i \to i)$
(*trans*)	*transitivity*	C,O	$\Diamond\Diamond i \to \Diamond i$

Table 1: SCSM properties definability

Definition 2. *(Standard Commonsense Spatial Model, SCSM).*

Let assume that $\{R^p_1, ..., R^p_k\}$ *is a set of* proximity *relations,* $\{R^c_1, ..., R^c_m\}$ *is a set of* containment *relations, and* $\{R^o_1, ..., R^o_n\}$ *is a set of* orientation *relations each one with its* top *element* top_i*. A Standard Commonsense Spatial Model* $SCSM$ *is a* CSM *with* $R = \{R^p_1, ..., R^p_k, R^c_1, ..., R^c_m, R^o_1, ..., R^o_n\}$ *and* $\{top_1, ..., top_n\} \subseteq P$*.*

Modal languages already proved to be very useful to reason about relational structures, and have been exploited for temporal and spatial logics, for logic of necessity and possibility and many others [9]. Hybrid languages extends modal languages (characterized by a set of modal operators $MOD = \{\langle\pi_0\rangle, [\pi_0], ..., \langle\pi_n\rangle, [\pi_n]\}$ and a set of propositional variables $PROP = \{p_0, ..., p_n\}$) by adding: (i) a nonempty set of propositional symbols $NOM = \{i_0, ..., i_n\}$, disjoint from $PROP$, that are called *nominals*, and (ii) a *satisfaction operator* of the form $@_i$ for each nominal $i \in NOM$. Informally, we just recall that a hybrid model is a triple $(W, \{R_\pi | \pi \in MOD\}, V)$ where $(W, \{R_\pi | \pi \in MOD\})$ is a frame[2] and V is a hybrid valuation. Semantics of hybrid

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[2] The notion of frame, defined here as a set of states and a set of binary relations on such states, will be used in the rest of the paper.

formulas is defined as usual for modal logics, but (i) nominals are interpreted to be true at one and only one state of the model (their *denotation*), and (ii) given a model $\mathcal{M}$ and a state w in the model, formulas preceded by satisfaction operators are interpreted as follows:

$$M, w \vDash @_i\varphi \text{ iff } M, w' \vDash \varphi \text{ , where } w' \text{ is the denotation of } i$$

Hybrid logics allow to express in the language itself, by means of nominals and satisfaction operators, sentences about the satisfiability of formulas; formulas preceded by satisfaction operators allow in fact to represent statements about specific states of the model, e.g. states of affairs occurring at certain places in our spatial interpretation of modalities.

A spatial hybrid logic is defined introducing a specific set of modal operators interpreted as spatial operators. The SCSMs then define the class of relational structures that provide the semantics, e.g. the spatial interpretation, of specific spatial operators.

Adjacency among places is represented by the *somewhere near* $\langle\text{P}\rangle$ and *everywhere near* $[\text{P}]$ operators, interpreted over proximity relations; containment among places is represented by the *somewhere inside* $\langle\text{IN}\rangle$ and *everywhere inside* $[\text{IN}]$ operators, and the respective inverse $\langle\text{NI}\rangle$ and $[\text{NI}]$ interpreted over containment relations; orientation in space is represent with cardinal direction operators interpreted over orientation relations; as an example, for North, we have *somewhere north* $\langle\text{N}\rangle$ and *everywhere north* $[\text{N}]$.

Intuitively, a formula such as $\langle\text{P}\rangle alarm$ means that an alarm is occurring somewhere near the place the formula is evaluated at (more literally: there is a place proximal to the current one where the proposition $alarm$ is true). A formula such as $[P]alarm$ means that an alarm is occurring everywhere near the place the formula is evaluated at (in every place proximal to the current one the proposition $alarm$ is true). Nominals can be exploited to refer to specific places: $@_{school}alarm$ means that an alarm is occurring at the school (at the place named $school$ the proposition $alarm$ is true). Formulas can be arbitrarily combined with standard logical operators and modal operators can be nested: a formula such as $@_{school}(alarm \wedge [\text{P}][\text{IN}]\neg smoke)$ means that everywhere inside every place that is close to the school is free of smoke (the proposition $smoke$ is not true).

Formally, we introduce the notion of Standard Commonsense Spatial Logic, defined as follows.

Definition 3. *(Basic Standard Commonsense Spatial Logic, $\mathcal{SL}^{\texttt{basic}}$).*

Language. *$\mathcal{SL}^{\texttt{basic}}$ is a hybrid multimodal language containing the modal operators $\langle N\rangle$, $\langle E\rangle$, $\langle S\rangle$, $\langle W\rangle$, $\langle IN\rangle$, $\langle NI\rangle$ and $\langle P\rangle$, the respective boxes ($[N]$, and so on), and where $\{north, east, south, west\} \in NOM$.*

Semantics. *Formulas of $\mathcal{L}^b$ are interpreted over a $SCSM$: $\langle IN\rangle$, $\langle NI\rangle$ are interpreted over* containment *accessibility relations, $\langle P\rangle$ over a* proximity *relation, and $\langle N\rangle$, $\langle E\rangle$, $\langle S\rangle$, $\langle W\rangle$ over* orientation *relations, whose top elements are respectively the denotation of "north", "east", "south", "west".*

Calculus. *A sound and complete calculus for $SCMS^{basic}$ is given by $H + \Phi^S + X^S$ where:*

- *H is the standard tableau system for Hybrid logic [10]*
- *Φ^S consists of the following combination of pure formulas:*

$$\begin{array}{rl}
\langle P\rangle & \textit{ref, sym} \\
\langle IN\rangle,\ \langle NI\rangle & \textit{ref, antisym, trans} \\
\langle N\rangle,\ \langle E\rangle,\ \langle S\rangle,\ \langle W\rangle & \textit{irref, asym, trans, ex, uni} \\
@_i\Box_{\bigstar}\Diamond_{\bigstar}\top \leftrightarrow \neg\Diamond_{\bigstar}\top & \textit{EX top element} \\
@_i\neg\Diamond_{\bigstar}\top \rightarrow @_j\neg\Diamond_{\bigstar}\top \rightarrow @_i j & \textit{UNI top element} \\
 & \textit{where } \bigstar = (N|E|S|W)
\end{array}$$

- *X^S is given by the following cross-property formulas:*

$$\begin{array}{r}
@_i\,([N]\langle S\rangle i \wedge [S]\langle N\rangle i) \\
@_i\,([E]\langle W\rangle i \wedge [W]\langle E\rangle i) \\
@_i\,([IN]\langle NI\rangle i \wedge [NI]\langle IN\rangle i) \\
@_i\,(\langle NI\rangle\langle P\rangle\langle NI\rangle j \rightarrow \langle P\rangle j) \\
\Diamond_{\bigstar} i \rightarrow [IN]\Diamond_{\bigstar} i \quad \textit{where } \bigstar = (N|E|S|W)
\end{array}$$

Finally, the interpretation of "north" is bound by the formula $@_{north}\neg\langle N\rangle i$, and analogous formulas are introduced for the other top elements.

As for the represented cross-properties, the first three axioms specify that the relations R^S/R^N, R^E/R^E and R^{IN}/R^{NI}, are reciprocally one the inverse of the other one. The fourth axiom represent that if two places are proximal, the places that contain them are proximal as well. The last axiom represent that if a place has a specific orientation with respect to another place, then every place contained in it inherits such an orientation. Observe that each SCSM *is* a frame; therefore, *classes of SCSMs* characterized by specific constraints on their relations identify *classes of frames*. On the basis of the above axiomatization, in [4] we proved that: (i) for every SCSM S there exists a finite frame F^S that corresponds to it and that is definable by a set of pure hybrid formulas Φ, and therefore, (ii) for every SCSM S there exists a tableau based calculus sound and complete with respect to the corresponding class of frames F^S.

We want to stress here at least some peculiarities of the tableau based calculi for Hybrid Logic that will turn out to be very important for commonsense spatial reasoning.

- First, Hybrid Logic's pure formulas, i.e. formulas that do not contain propositional variables, allow defining more properties than normal modal formulas (see Table 1). We will refer to this property of Hybrid Logic as *frame definability*.
- Secondly, Hybrid Logic allows us to fully exploit *frame definability* for reasoning purposes. In fact, consider that the tableau rules given by Blackburn provide a sound and complete calculus for Hybrid Logic in this sense: a formula φ is tableau provable *iff* it is valid, that is, *iff* it is true in every frame. It has been proved that it is sufficient to add a set of pure formulas defining the desired frame to the tableaux to obtain a sound and complete calculus with respect to that frame. We will refer to this property as to *modularity*. As an example of how one can exploit modularity, see the introduction of the $R^{tF_{\succ}}$ relation and of the corresponding $\langle \mathrm{tF}_{\succ}\rangle$ modal operator, in Section 5.

5 Reasoning about Events with the $\mathcal{SL}^{\mathsf{area}}$ Logic in the Supercentro Project

Given the application scenario described in Section 2, here we discuss (i) the extension of SCMSs introduced in order to model the urban spatial environment of interest, (ii) the hybrid logic to talk about these models, and (iii) some formulas defining the interesting scenarios that can be inferred. To show the expressiveness of hybrid commonsense spatial logics for modelling context aware reasoning in this paper we focus on traffic-related aspects of the correlation.

5.1 CSMs for the Urban Context

Different cartographic and spatial representation levels are considerd in the Supercentro project. The first level relevant to event correlation consists of an undirected graph where nodes are intersections and edges are road sections with no driving direction[3]. A second level of representation can be defined on top of this last undirected graph, considering *area-level* entities as specific clusters of roads. An *area* consists of a set of edges and intersections, that is, a set of undirected arcs and nodes of the higher-level cartographic representation. Each edge belongs to one and only one area, while intersections can belong to more than one area.

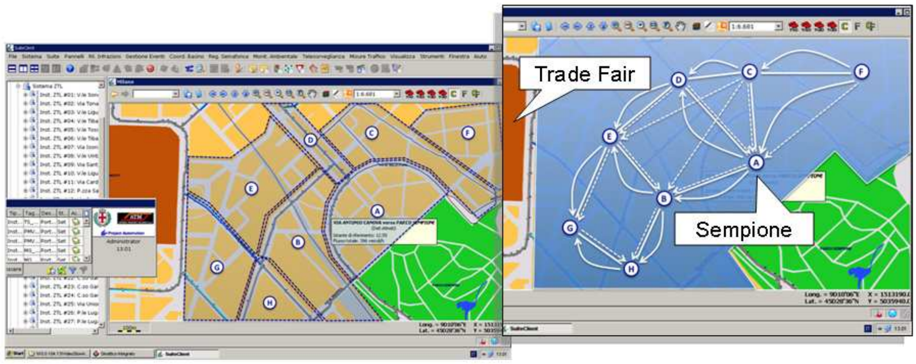

Fig. 2: The figure shows a sketch of the area-level model for the Supercentro project. A segmentation of the cartography into a finite set of interesting areas is showed on the left. The definition of accessibility relations among areas according to the selected spatial conceptual relations is represented on the right; continuous arcs represent proximity relations between areas, dotted arcs represent the "south of" orientation relation, and the continuous arcs with arrow represent the "closer to Trade Fair" orientation relation (only a subset of the relations are represented for the sake of readability).

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[3] Edges of the directed graph are the main entities of the road network while intersections are pure connectors; a square, e.g. in such cartographic models is represented by a set of edges; location is referred to edges.

As for the scenario of the Supercentro project, *areas*, *mobile* and *static agents* are a first set of spatial entities (i.e. places of the CSM) that need to be considered. Mobile and static agents represent mobile and static devices, that is, sensors (e.g. CCTV, traffic violation detectors, and so on) and actuation devices such as information clients and providers (e.g. Virtual Message Panels, PDA-based software agents, control central), and control systems (e.g. traffic regulators).

Since in the following we focus on traffic-related aspects, an important issue that needs to be considered is the connection between areas interpreted as the possibility for drivers to move from an area A to an area B. This new connection relation that must be introduced is not a "proximity relation" of a SCSM essentially because it cannot be considered symmetric. In fact, the possibility to move from an area A to an area B depends on the existence of an intersection belonging to A and B, but also on the Administrative Code (in fact, it can be the case that two areas would be topologically connected, but the Administrative Code prevent drivers from moving from A to B because of, e.g. one ways or forbidden turns). In an urban context, it is possible to define interesting relative orientation relation w.r.t. to significant reference points in the city. As an example, we introduce an order toward the *Trade Fair*, a place of the city of Milan that often attracts many visitors inducing traffic congestions. These relations, together with those of SCSM, will be considered as accessibility relations (in the sense of Modal Logic) of the resulting model.

5.2 Reasoning about Traffic Scenarios

We recall that area-level traffic measures can be estimated on the basis of local interpretation carried out with statistic algorithms (see Section 3). As a consequence, in correspondence to each area-level entity in the model we have an inferred qualitative measure of its traffic density and condition, namely: heavy congestion, congestion, dense, fluid-dense, fluid, very fluid. The system is also able to map location on the area-level spatial representation; these mapping will be exploited to show the capability of our approach to define context-aware scenarios. The hybrid multimodal language for representing event correlation at the area-level for the Supercentro project results from an extension of the $\mathcal{SL}^{\mathtt{basic}}$ language.

Definition 4. *(Supercentro Area-level Commonsense Spatial Logic, $\mathcal{SL}^{area}$).*

Language. *$\mathcal{SL}^{area}$ is a hybrid multimodal language containing the modal operators $\langle N\rangle$, $\langle E\rangle$, $\langle S\rangle$, $\langle W\rangle$, $\langle IN\rangle$, $\langle NI\rangle$, $\langle P\rangle$, $\langle R\rangle$ and $\langle tF_{\succ}\rangle$, the respective boxes ($[N]$, and so on), and where $\{north, east, south, west, tradeFair\} \in NOM$.*

Semantics. *Formulas of $\mathcal{SL}^{area}$ are interpreted over a specialization of the $SCSM$, that is devoted to "area-level" of the Supercentro project. In particular: $\langle IN\rangle$, $\langle NI\rangle$, $\langle P\rangle$, $\langle N\rangle$, $\langle E\rangle$, $\langle S\rangle$, $\langle W\rangle$ are interpreted over the relations introduced in Section 4, $\langle R\rangle$ is interpreted over a reflexive* reachability *relation defined among areas, and $\langle tF_{\succ}\rangle$ is interpreted over the relation $R^{tF_{\succ}}$, that is an orientation relation whose reference point is tradeFair.*

The definition of the formal properties of the reachability relation R through axioms defined on $\langle \mathrm{R}\rangle$ is given by the pure formula defining reflexivity: $@_i\langle \mathrm{R}\rangle i$. Formally this means that the frame capturing the spatial representation needed in this scenario is defined by pure formulas of $\mathcal{SL}^{\mathsf{area}}$. Therefore, Theorem **1** of [4] can be exploited to guarantee the existence of a sound an complete calculus for $\mathcal{SL}^{\mathsf{area}}$ with respect the extension of SCMS defined. Such a calculus is built adding the pure formulas for $\langle \mathrm{R} \rangle$ to the calculus defined for $\mathcal{SL}^{\mathsf{basic}}$ (see Section 4).

In order to represent interesting scenarios in the domain of the Supercentro project, we equipped the $\mathcal{SL}^{\mathsf{area}}$ language with the following set of propositional symbols representing traffic density on the areas: `heavy congestion`, `congestion`, `dense`, `fluid-dense`, `fluid`, `very fluid`. Finally, `highway access` is a propositional symbol that is used to qualify specific peripheral areas of the city, with the obvious meaning. The satisfiability of the formulas, that have to be considered as scenario descriptions depends on: (i) the place of the CSM the formula is evaluated at ; (ii) the contextual information provided by the model, concerning the topological structure and the information referred to each place (e.g. traffic density, ontological qualifications of the areas, and so on). Such information is provided by formulas of type $@_i p$, with p being a propositional variable. In what follows, we present some examples of interesting scenarios, defined by means of $\mathcal{SL}^{\mathsf{area}}$ formulas. An intuitive description of their satisfiability conditions explains the meaning of the formulas and how they can be exploited in deductions. For each formula φ defining a scenario one should think of introducing a formula $\varphi \leftrightarrow$ *ScenarioID*, where *ScenarioID* is a propositional variable naming the scenario. Then deduction can be performed on the names of the scenarios defined. For formal details about deductions based on the tableaux we refer again to [4].

Scenario 1. (*Everywhere Outgoing Fluent*).

$$[\mathrm{R}](\mathtt{fluid} \vee \mathtt{veryFluid})$$

"Every area I can reach from here is characterized by fluid or very fluid traffic".

Scenario 2. (*Somewhere Outgoing Slow*).

$$\langle \mathrm{R} \rangle(\mathtt{heavycongestion} \vee \mathtt{congestion})$$

"Some area I can reach from here is characterized by heavy congestion or congestion".

The satisfiability of the above two formulas is context dependent in the sense that it depends on the place from where the formula satisfiability is checked. As a consequence, if one suppose that the task of verifying the presence of specific scenario is performed by a mobile agent, the outcomes of this task may be different according to the current location of the agent itself.

Scenario 3. (*Somewhere Outgoing Towards Trade Fair Fluent*).

$$(\langle \mathrm{R} \rangle(\mathtt{fluid} \vee \mathtt{veryFluid}) \wedge i) \wedge \langle \mathrm{tF}_{\succ} \rangle i$$

"There exists at least an area that I can reach from here *in the direction of the Trade Fair*, where traffic is *fluid* or *very fluid*".

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[3] Note that this choice strictly depends on the nominals that immediately follow the first satisfaction operators in a formula but also, where there is no satisfaction operator in the head of a formula, on the specific locations the reasoning task takes place.

Scenario 4. (*Somewhere Inside Somewhere Outgoing Towards Trade Fair Fluid*.

$$\langle \mathrm{IN} \rangle ((\langle \mathrm{tF}_{\succ} \rangle i \wedge \texttt{fluid}) \wedge \langle \mathrm{R} \rangle i)$$

“There exists at least an area inside the one I am in, from which I can reach an area *in the direction of the Trade Fair* that is, where traffic is *fluid*”.

The scenario above provides useful information in the case the satisfiability check is performed on a non atomic area of the model. As an example, the following formula stating that the area “Sempione” contains the areas “Sempione Cerchia East” and “Sempione Cerchia West” is a valid in the area-level model of the Supercentro project:

$$@_{sempione} \langle \mathrm{IN} \rangle sempioneCerchiaEast \wedge \langle \mathrm{IN} \rangle sempioneCerchiaWest$$

Therefore, checking the satisfiability of the formula describing Scenario 4 at the Sempione macro-area, may provide useful contextual information about light regulation plans for the Sempione macro-area can be activated to make the traffic flow out better.

Scenario 5. (*Everywhere Outgoing from Trade Fair Slow*).

$$@_{tradeFair} [\mathrm{R}] (\texttt{heavycongestion} \vee \texttt{congestion})$$

“All the areas *reachable* from the *Trade Fair*, are characterized by *heavy congestion* or *congestion*”.

Note that a satisfaction operator in the head of a formula can be introduced, and exploited, as integral part of the definition of a specific scenario (as suggested in the above example), or can be dynamically added to the formula, possibly with different nominals, according to the current location of the mobile agent requiring the outcomes of the reasoning task.

Scenario 6. (*Somewhere at North of Trade Fair Fluent Highway Outgoing*).

$$@_{tradeFair} \langle \mathrm{N} \rangle ((\texttt{fluid} \vee \texttt{veryFluid}) \wedge \langle \mathrm{R} \rangle \texttt{highwayAccess})$$

“There exists at least an area at *north* of the Trade Fair, at which it is the case that the traffic condition is qualified as *fluid* or *very fluid* and from which it is *reachable* an area characterized by the presence of a *highway access* point”.

Due to the semantics of the satisfaction operators, these last formulas provide a “global” perspective on what is going on in term of traffic conditions at the area-level model. The presence of the satisfaction operators, in fact, indicate that the satisfiability of these formulas, regardless of the current location of the mobile agent, starts from the area denoted by the nominal *tradeFair*.

6 Related Work

Here we briefly introduce some pointers to previous papers of the same authors that provide an accurate comparison of our approach to correlation and spatial reasoning with related work. [11] introduces the approach based on commonsense spatial representation and reasoning to model context aware reasoning. This approach has been further described and discussed in [6], together with the underlying knowledge based approach to information correlation (with the related pros and cons) and the comparison with other non knowledge based approaches. Moreover the last paper discusses the choice of qualitative spatial models and qualitative spatial reasoning techniques which are similar to the reasons discussed in [12]. The formal characterization of the Hybrid Commonsense Spatial Logics (HCSLs) is given in [4], together with a calculus and the discussion of deduction examples in a Smart Home context; here the relationship between our approach and other prominent logics for qualitative spatial representation and reasoning is discussed.

We refer to this last work and to [6] also for the comparison with other approaches to qualitative spatial representation and reasoning (QSRR). Basically QSRR focused on topological models, providing first-order, and modal axiomatization of the Region Connection Calculus or topological foundations for modal theories (see [12] and [13] for an overview). These approaches study spatial concepts analyzing possible connections among spatial regions. Our approach provides a lighter analysis of spatial entities taking on a more pragmatical point of view: that is, it focuses on the formalization of many interesting classes of spatial relations and on the possibility of combining them to provide a comprehensive spatial model aimed at supporting the definition of specific domain inferences. Given such a goal, modularity of the logical framework has been pursuit (see Section 7). Spatial graph-like model are indeed quite intuitive and popular in many pragmatical approaches to model spatial inferences [6]. The major originality of the approach proposed is related to the formalization of relative orientation relations, for which a new approach is proposed based on the concept of ordering toward an arbitrary reference point instead of on topological concepts [12].

As for the consideration of spatio-temporal events, an example of spatio-temporal correlation (but where spatial representation is simplified up to the 1D) is presented in [8]; the module correlation of SAMOT, a system for monitoring of traffic over highway sections installed on different highway sections in Italy[5], was based on this model.

7 Discussion: Commonsense Spatial Hybrid Logic and Stream Reasoning in the Semantic Web

The approach to stream reasoning based on event correlation presented in this paper aims at providing a controlled modeling framework to define and reason on event patterns (the scenario). As for modeling capabilities, the approach has a number of advantages.

First, the combination of the modal and the hybrid perspective available in CSHL allows for the representation of global and context aware scenarios (scenarios whose definition with a CSHL formula is satisfiable depending on the place it is evaluated); the last feature is interesting to model correlation tasks for mobile agents.

Second, the approach is flexible enough due to the expressive power of hybrid logics: also within the new scenario described in this paper, we exploited the hybrid logic approach to spatial representation and reasoning, with some slight modifications and extensions of the language introduced in Section 4. In particular, we almost kept containment and direction relations basic properties (with some constraints related to typing) and we modified connection relations.

Third, we took advantage from both the characteristics stressed out in Section 4: frame definability and modularity. In fact, the hybrid language introduced allowed to model quite specific conditions defining the frame of reference (the road network), and this would have not been possible within plain modal logic. On the other hand, we have been able to adapt and modifying single operators still not loosing the logical calculus defined in Section 4 (it is sufficient to replace the rules for binary operators with their generalization for operators of arbitrary arity).

In the past a subset of the possible correlation definable through our logic has been implemented through production rule-based systems, via non formal mappings of a set of significant logic-based correlation axioms to rules. However, this approach is not formal and is domain dependent. The calculus defined here and based on [10] did not receive any actual implementation. A concrete reasoning strategy can be implemented by decoupling spatial inferences based on the axioms characterizing $\mathcal{SL}^{\mathsf{area}}$ according to Definition 4 and the detection of scenarios. Assuming to complete spatial relations in the model according to such axioms, then detection of the scenarios can be performed via model checking, that is, by checking the satisfiability of the formulas defining the scenarios. Model checking for hybrid logics have been investigated by [14] and implemented in a Hybrid Logic Model Checker[4]

Nowadays Semantic Web technologies and languages such as RDF, RDFS and OWL are becoming more and more popular for knowledge, information and data exchange on the Web. In the following we discuss some preliminary ideas on how to bridge the gap between the HCSL as modeling framework and Semantic Web technologies and languages to implement the approach.

As a matter of fact, hybrid logics are logics to talk about graph structures, which are also at the basis of RDF and OWL. Basic hybrid logics (standard modal semantics plus nominals and satisfaction operators) easily map to $\mathcal{SHOIQ}$ constructs. Assume to focus on Abox statements since events are represented as assertions. The more straightforward mapping between Abox statements and CSHL formulas is given by interpreting $\mathcal{SHOIQ}$ nominals as CSHL nominals, concepts as propositional variables, type assertions and role assertions as hybrid pure formulas as depicted in Table 2.

$\mathcal{SHOIQ}$	Hybrid Logic	RDF syntax example	Hybrid Logic Example
$i : C$	$@_i C$	`Sempione rdf:type Fluid`	$@_{sempione} fluid$
$\langle i, j \rangle : R$	$@_i \langle r \rangle j$	`S.C.E. cshl:in Sempione`	$@_{S.C.E.} \langle IN \rangle Sempione$

Table 2: Mapping between Abox statements and CSHLs

Tbox-level formal relationships between hybrid logics and description logics have been also studied in [15]. Given the above considerations about possible mapping be-

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[4] Available at http://www.luigidragone.com/hlmc/

tween CSHLs and Semantic Web-related languages such as the Description Logics, we discuss two main questions related to the application of the approach discussed here to event correlation in a Semantic Web context.

Question 1. *Assuming to represent events as RDF triples or molecules, are the CSHLs enough expressive to reason about such events?* Two main features of OWL-DL (via mapping to $SHOIQ^D$) that are not covered by the CSHLs presented here are cardinality restrictions and an explicit treatment of datatype properties and concrete domains. As for the first issue, extension of modal logics to represent cardinality constraints on accessibility relations are called graded modal logics; graded hybrid logics and tableaux to reason about them are introduced in [16]. The problem of datatype properties and their representation in CSHL are more interesting for stream reasoning. Our spatial interpretation of hybrid logic is based on the assumptions that all the states of the model are places; this is reasonable for physical entities, but is problematic when one wants to represent a scenario like "the Trade Fair area has a noise pollution measure of 28 DB". According to our interpretation (all relations are spatial relations) having a noise pollution should be a spatial relations and even worst 28 DB would be a property holding at some place, and this property would be translated as a concept; moreover, any constraint operator used in such a formula (e.g. "the noise pollution measure in the Trade Fair area is greater than 28 DB") would have no semantics. Extending the CSHL to explicitly consider such kind of properties would be very interesting for stream reasoning. This could be achieved by introducing a bipartition on both the set of nodes and of relations in the relational structure: a first set of nodes represent places, and the other set of nodes consists of values in concrete domains; a first set of accessibility relations represent spatial relations, and another set represent datatype properties.

Question 2. *To what extent it is possible to exploit available Semantic Web technologies to perform event correlation as modeled in CSHLs?* Many of the axioms described in Definition 3 cannot be translated in $SHOIQ^D$ axioms and therefore OWL-DL reasoners are not able to handle them. The more promising strategy is therefore to exploit rules for Semantic Web languages or combining rules and query answering. Suppose to be able to represent all the axioms characterizing $\mathcal{SL}^{\mathsf{area}}$ according to Defition 4, or in alternative, at least an important core of them; then, is it possible to codify the scenarios described in Section 5.2 in SPARQL queries? This question can be also interpreted as follows: given some kind of algorithms that is able to complete the spatial information in the model according to the semantics of the spatial relationships, is it possible to exploit query answering for SPARQL to perform model checking on available information? The answer to this question is "no" in the general case. The formulas that can be straightforwardly translated into SPARQL queries are the formulas built only from propositional variable, nominals, conjunction and diamond operators (e.g. Scenario 4 of Section 5.2). In particular, a script-based strategy to handle conjunction, disjunction and box operators (e.g. $[IN]$) is needed. SPARQL extensions that allow to quantify on variables in the query graph could provide support at least for the treatment of box operators and therefore the detection of scenarios including "everywhere" conditions[5].

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[5] The RDF Gateway 3.0 triple store provides a query engine that seems to be able to treat a SPARQL extension including provide quantification and negation; cf. http://www.intellidimension.com/developers/library/sparql-extensions.aspx

Our current research focus on the above two questions, inquiring extensions of the SCHLs to explicitly treat concrete domains and datatype-like relations, and exploring the combination of rule-based reasoning and script-based SPARQL query answering.

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