

Combining Qualitative Spatial Reasoning and Ontological Reasoning for Supporting Robot Tasks

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Abstract: This paper presents an application of spatial and ontology reasoning technologies for mobile robot tasks. We provide a combination of the spatial reasoning calculi RCC-8 and CDC as well as their integration with OWL-based ontologies. An architecture that combines inference tools like Prolog, description logic reasoners, and complex-event processing implements our approach. We illustrate the results with a mobile robot scenario in a restaurant. In this paper, global path-finding demonstrates the use of qualitative spatial and ontological reasoning.

1 INTRODUCTION

The research field *cognitive robotics* addresses the use of general logical representation and reasoning methods and tools for controlling robots in dynamic and incompletely known worlds (Levesque and Lakemeyer, 2007). Following this direction, qualitative spatial reasoning provides a mean for representing and reasoning about spatial occurrences like *The plate is on the table.* or *The robot is close to the guest.* Especially the abstraction provided by qualitative representations enables effective and short representations about the quantitative world of robots. Such representation support robot's tasks like interaction ability or path finding. Qualitative spatial reasoning enables the explicit representation of spatial interrelations of regions or objects. Its use for autonomous, mobile robots is still a research topic. Especially, if all main spatial dimensions (i.e. topology, orientation, and distance) shall be considered (Renz and Nebel, 2007). Because typical spatial calculi focus on one dimension (e.g. Region Connection Calculus (RCC) (Randell et al., 1992) on topology and Cardinal Direction Calculus (CDC) (Goyal, 2000) on orientation), the combination of qualitative spatial calculi becomes important.

For representing robot's knowledge about objects and the environment, ontologies can be applied. By using this approach, domain knowledge (like objects and environments) and application knowledge (like activities for serving a guest in a restaurant) can be

made explicit to the robot. Enhancing ontological reasoning with qualitative spatial reasoning is a challenging task, because, if combining both, the ability to reason about spatial knowledge and recognize inconsistencies gets lost, or the decidability of ontological reasoning gets lost (Katz and Grau, 2005). Furthermore, the concrete contribution of qualitative and ontological reasoning for robot tasks is not finally clear.

Thus, in this paper, we present a case study about combining two qualitative spatial calculi, i.e. RCC and CDC, with ontological representations in a robot scenario. We start with a concrete scenario dealing with a robot acting in a restaurant environment and extract requirements for the technologies (Section 2). Then, we provide a short overview of applied representation techniques, RCC, CDC, and ontological reasoning (Section 3). Section 4 presents our integrated approach which is evaluated by implementing a system using Prolog, the complex event processing ETALIS (Event Transaction Logic Inference System), and the Web Ontology Language OWL (Antoniou and Harmelen, 2003) (see Section 5). We conclude with a summary in Section 6.

2 USE CASES AND REQUIREMENTS

An interesting environment for illustrating the use of knowledge representation techniques for service

robot tasks is a restaurant environment. In such an environment, domain-specific objects, concepts, and rooms have to be represented. Objects might have hierarchical relations and temporal or spatial relationships to each other. Terminological knowledge about dishes, drinks, meals etc. is needed. Areas which may contain food products may be distinguished from seating areas. For our experiments demonstrated in this paper, we consider an artificial restaurant layout as it is presented in Figure 1.

One requirement that have to be fulfilled for processing such scenarios is that the robot shall identify an ideal path to a table, i.e. using the spatial configuration of the environment the robot shall infer, if a certain place is reachable and how the path to it is (*global path-finding*, see Section 4). Another task would be to compute if the current position of the robot is suitable for placing a cup on the counter, i.e. to infer if the actual position is practical to interact with a target object (*interaction ability*, see (Rost et al., 2012)).

3 BACKGROUND

The basic techniques we combine in our approach are qualitative spatial reasoning and ontological reasoning.

Spatial calculi represent relations between objects with finite sets of binary relations. They can derive new knowledge and check if a provided knowledge base is consistent. RCC enables reasoning about topological properties of regions. Especially RCC-8 provides eight spatial relations *disconnected* (*DC*), *externally connected* (*EC*), *tangential proper part* (*TPP*), *non-tangential proper part* (*NTPP*), *partially overlapping* (*PO*), *equal* (*EQ*), and the inverses TPP_i and $NTPP_i$.

The Cardinal Direction Calculus (CDC) enables reasoning about relative orientation between objects by using the eight cardinal points (N, NE, E, SE, S, SW, W, NW) as well as one further relation for representing direct neighborhood (i.e. bounding box, B).

When using a calculus like RCC-8 or CDC the basic inference mechanism is based on a composition operator \circ . Let D be a set of regions and R_1, R_2, R_3 relations of the qualitative calculus: $R_1 \circ R_2 = \{ (x R_3 z) \mid \exists y \in D : ((x R_1 y) \wedge (y R_2 z)) \}$. Thus, a composition operator computes the relation between two regions x and z on the basis of a further region y which is related to x and z . A composition table for a certain calculus can be used to compute the composition operator (Goyal, 2000).

Through an ontological language like OWL it is possible to represent knowledge about objects, activi-

ties, relations etc. of a domain. By providing a formal representation such ontologies are exchangeable and, more important, they can be used for inference services (e.g. provided by Description Logic Reasoners, (*DL reasoner*)). Means for representation are the separation of instances (representing individual objects) from concepts (as set of instances), taxonomic relations between concepts, and properties as a further type of relation between concepts. A TBox contains all concepts and an ABox all instances.

However, the combination of OWL and qualitative calculi is not straight forward. Especially to combine both, RCC-8 and CDC (for topology *and* orientation) with an ontology is not yet elaborated (at least to our knowledge).

4 CONCEPTUAL APPROACH

For applying qualitative spatial reasoning in a mobile robot environment as presented in Section 2, we developed the following approach.

For getting a representation of the domain knowledge a TBox is used for representing classes occurring in the environment (like *cup*, *plate*, *table*, *room* etc.). ABox instances represent concrete individual objects (like *table1*, *counter1* etc.). Object properties of OWL (*ObjectProperty*) can be used for representing qualitative relations of the calculi. Object properties follow the same semantics as relations do.

For computing the consistency of the provided facts and computing all spatial relationships of all objects in the environment, we use the introduced calculi RCC-8 and CDC. Here, we apply a basic property of OWL-ontologies, i.e. machine readability. By automatically accessing ABox instances of the ontology, we extract the instances and their relations from the ABox and import them into a constraint system which uses the composition table for the mentioned inference tasks. The constraint system uses the path-consistency algorithm for making implicit spatial relations between domain objects (instances) explicit. After doing so, new spatial relations can be imported into the ABox. Thus, we combine the ontology (and a DL reasoner) with a qualitative spatial constraint system instead of including spatial calculi in a DL reasoner directly. Our approach is similar to Pellet-Spatial (Bhatt et al., 2009), however, with two spatial calculi. In summary, using an ontology enables a central point of interchangeable knowledge needed by a robot for fulfilling its tasks, ensuring consistency of the knowledge through its formal representation, and making implicit knowledge (here about spatial occurrences) explicit by inference methods.

Table 1: Spatial configuration of the rooms modeled with RCC-8.

	Wardrobe	Counter	Kitchen	Dining Room	int. Area	Sanitary	Floor	int. Floor	Door1	Door2	Door3	Door4
Wardrobe	EQ	EC	DC	EC	DC	DC	PO	DC	DC	DC	DC	DC
Counter		EQ	EC	DC	DC	DC	PO	DC	PO	DC	DC	DC
Kitchen			EQ	DC	DC	DC	DC	EC	PO	PO	DC	DC
Dining Room				EQ	DC	EC	PO	DC	DC	DC	DC	DC
int. Area					EQ	EC	DC	EC	DC	DC	PO	DC
Sanitary						EQ	PO	DC	DC	DC	DC	DC
Floor							EQ	EC	DC	DC	DC	PO
int. Floor								EQ	DC	PO	PO	PO
Door1									EQ	DC	DC	DC
Door2										EQ	DC	DC
Door3											EQ	DC
Door4												EQ

Qualitative spatial reasoning with RCC and CDC can be used for computing a path from a start to an end point. In the following, we consider global path-finding from a point A to B without taking obstacles into account. Handling obstacles would involve local path-finding algorithms. Typically applied global path-finding algorithms represent the search environment as an undirected, weighted graph (Dijkstra, 1959). For making use of this source, our approach maps qualitative representations of the environment from the ontology into undirected graphs and applies one of these algorithms. If the ontology is not (manually) populated with pre-existing spatial configurations of the rooms in the environment, the population process could be done with a combined SLAM (Simultaneous Localization and Mapping) and image processing approach. The exact procedure of automatic population of spatial configurations is an ongoing research topic.

Following scenario illustrates the mapping of a spatial configuration into a graph for computing a global path. A robot needs to compute a global path for getting from the kitchen to the dining area. From such a scenario, we model the undirected graph by introducing for each room a node and the relations between rooms as edges between nodes. As edges we use RCC-8 relations, especially the relation PO (overlapping) is used when there exists a direct path from a room to another room. Thus, between two nodes in the graph there exist exactly one edge, if between the corresponding rooms or regions a PO relation exists. The weight of the edge models the quantitative distance between the rooms or is equal 1, if not known. Unknown, or uncertain spatial relations between different rooms can be computed with the previously shown reasoning techniques. Figure 1 presents a sketch of the restaurant with rooms and doors. The floor is separated into *Floor* and *internal Floor* (int. Floor). Table 1 represents the spatial configuration modeled with RCC-8 relations. Relations of type PO are bold, the rooms can be directly reached. Each door is represented by an own region. Figure 2 presents the undirected graph for this configuration. Edges have no weights, for simplicity rea-

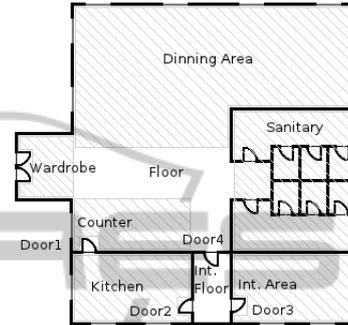


Figure 1: Environment of the restaurant with doors.

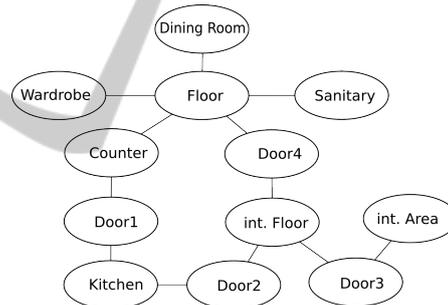


Figure 2: Undirected, unweighted graph for global path-finding.

sons. Such a graph can be used as input for typical path-finding algorithms.

5 EVALUATION OF THE APPROACH

For evaluating our conceptual approach, we implemented an architecture that combines the needed inference technologies. First, we represent the system setup and then discuss some insights we had.

As a basic system, we use ETALIS¹. This system combines complex event processing (CEP) with Prolog. Event processing enables the processing of continuous data streams created through the sensors of a robot. Prolog enables the representation and

¹<http://code.google.com/p/etalis/>

dynamic adaptation of facts of the environment of the robot, an external database is thus not necessary. Compared to other CEP-systems, which are implemented with procedural or object-oriented languages, ETALIS is more flexible and partially with good performance. Our approach combines ETALIS with the PROLOG-OWL interface THEA2 (Vangelis Vassiliadis, Chris Mungall, 2012), and DL reasoners to our system called *ETALIS-Spatial*.

For knowledge representation, we create an OWL knowledge base. Objects and spatial relations are defined as described in Section 3. THEA2 enables the access to the ABox for extracting spatial relations and all instances for participating objects. Furthermore, THEA2 allows direct access to commonly used DL reasoners, like Pellet². ETALIS-Spatial starts with the composition tables and applies a path-consistency algorithm typically used for solving constraint satisfaction problems (Tsang, 1993).

In summary, the evaluation shows an implementation of our conceptual approach presented in Section 4. We applied RCC-8 and CDC to cover topology and orientation aspects of spatial reasoning. The qualitative spatial relations can be represented in an OWL ontology as properties. The OWL-based ontology acts furthermore as a central place for all needed knowledge. The knowledge can be extracted from the ontology for processing in a separate spatial Prolog-based reasoner. Computing new spatial relations and consistency checks are performed by a Prolog system based on composition tables provided by the calculi in combination with path-consistency algorithms. Thereby, we use the implicit inherent information about paths contained in RCC-8 relations for building an undirected unweighted graph that again is used by typical global path-finding algorithms. By using complex event processing, a continuous stream of data could be processed.

Our implementation uses the CEP-framework ETALIS and enhances it to ETALIS-Spatial. We implemented an ontology representing parts of a restaurant. In principle, such an ontology can be enhanced to cover more facets of the tasks or other domain areas. Further or other qualitative calculi which handle other aspects can be integrated into the system by modeling their composition tables and relations in Prolog.

6 CONCLUSIONS

This paper demonstrates the application of the quali-

²<http://clarkparsia.com/pellet/spatial/>

tative spatial calculi RCC-8 and CDC for robot tasks. The approach combines these calculi with ontological reasoning by modeling the relations in OWL but computing spatial inferences with logical programming. Thus, consistency checking and computation of new spatial relations could be performed. An extension of the complex event processing framework ETALIS implements our approach. We demonstrate it's use in a restaurant scenario and could show how qualitative spatial reasoning can support tasks of mobile robots.

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