Supporting Mobile Robot's Tasks through Qualitative Spatial Reasoning

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Keywords: Qualitative spatial reasoning, ontological reasoning, cognitive robotics, knowledge-based systems applications

Abstract: In this paper, we present an application of qualitative spatial reasoning technologies for supporting mobile robot tasks. While focusing on detection of interaction ability, 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 uses Prolog and complex-event processing implements our approach. We illustrate the results with a mobile robot scenario in a restaurant.

1 INTRODUCTION

The focus of the research area *cognitive robotics* lies on the usage of general logical representation and reasoning methods as well as finding appropriate tools for manipulating and controlling robots in dynamic and incompletely known worlds (Levesque and Lakemeyer, 2007). Within this field, qualitative spatial reasoning enables the representation and reasoning about spatial configurations like *The cup is on the counter* or *The robot is near the guest*. Specifically the abstraction that is provided via qualitative representations facilitate effective and concise representations about the quantitative environment of robots. This supports robot's tasks like the ability to interact with the environment. From a cognitive point of view, human perception of the environment also uses qualitative concepts, notions, relations, and recall interrelationships preferably in a qualitative manor.

Qualitative spatial reasoning can be used to explicitly represent spatial interrelations of regions and/or objects. The practical use of this kind of reasoning and representation methods, especially for autonomous mobile robots in an appropriate domain, is an ongoing research topic, notably if all spatial dimensions (i.e. topology, orientation, and distance) are to be considered (Renz and Nebel, 2007). Typically used spatial calculi tend to focus on one dimension (e.g. Region Connection Calculus (RCC) (Randell et al., 1992) on topology and Cardinal Direction Calculus (CDC) (Goyal, 2000; Skiadopoulos and Koubarakis, 2004) on orientation). Thus, the combination of qualitative spatial calculi of different dimensions is necessary.

Ontologies can be used for representing the knowledge of the robot about objects and the environment. This allows domain knowledge (like objects and environment details) and application knowledge (i.e. activities, like serving a meal to a guest in a restaurant scenario) to be made explicit to the robot. However, the combination and enhancement of ontological reasoning with qualitative spatial reasoning is a difficult task. Recent publications show that the combination of these two reasoning and representation methods is coupled with losing the ability to reason about spatial knowledge and revealing inconsistencies or to forfeit the decidability of ontological reasoning (Katz and Grau, 2005; Hogenboom et al., 2010a; Hogenboom et al., 2010b).

Hence, in this paper, we present a case study in which we perform a combination of two qualitative spatial calculi, i.e. Region Connection Calculus and Cardinal Direction Calculus, with ontological representations in a mobile robot scenario. We start with the introduction of a concrete scenario in a restaurant environment, from which we extract technological requirements that are needed by a robot fulfilling specific tasks (Section 2). Then, we continue to provide a brief overview of applied representation techniques, RCC, CDC, and ontological reasoning (Section 3). In Section 4, we present our integrated approach that is evaluated by an implemented system using Prolog (Jan Wielemaker et al., 2012), complex event processing (Anicic et al., 2010), and the Web Ontology Language OWL (Antoniou and Harmelen, 2003) (see Section 5). We close with a discussion (Section 6) and a summary in Section 7.

2 APPLICATION AREA AND REQUIREMENTS

A versatile environment for demonstrating various knowledge representation and reasoning techniques for service robot tasks is the restaurant environment. In this particular domain, it is required to represent domain-specific objects, concepts, and rooms appropriately. Objects may be in use by guests or the robot for certain reasons and can have (spatial and temporal) impacts on the environment. They might also have hierarchical, temporal or spatial relations to each other. Terminological knowledge is needed to distinguish dishes, drinks, meals etc. and their uses from one another as well as to differentiate between areas which may contain food products and seating areas. In our experiments, we investigate a fictional restaurant layout as presented in Figure 1.

The concrete use cases considered in this paper are typical waiter's tasks like serving a beverage or clearing a table. One specific task for example reads as follows: "a robot shall take a cup from a counter and carry it to a guest sitting at a table. The cup shall be positioned in front of the guest and the robot shall go back to the counter".

In the following, some of the requirements are listed that have to be fulfilled for processing the above mentioned and likewise scenarios:

- The robot shall infer, if an own position is practical for placing a cup on the counter, i.e. to infer whether the actual position is practical to interact with a target object or not (*interaction ability*).

- 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 looks like (*global path-finding*).

We focus on interaction ability and derive the following technical requirements from the domain-specific requirements, in this paper:

Knowledge representation: Representation of domain and state knowledge with integration of qualitative spatial calculi.

Consistency: Identifying inconsistencies in the knowledge base and providing facts of a certain situation, especially of spatial relationships.

Computation of spatial relationships: Inferring unknown spatial relationships from known facts.

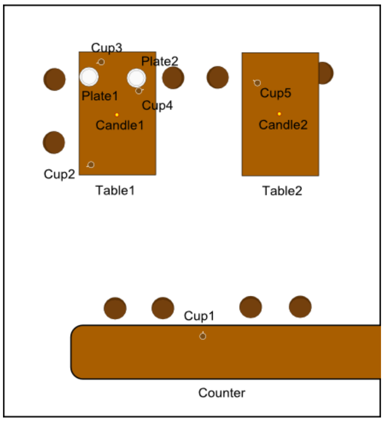

Figure 1: Detailed view of a fictional restaurant environment equipped with counter, tables, cups, etc.

3 BACKGROUND

The basic techniques we combine in our approach are qualitative spatial reasoning introduced in Section 3.1 and ontological reasoning introduced in Section 3.2.

3.1 QUALITATIVE SPATIAL REASONING

Spatial calculi allow to represent relations between objects with finite sets of binary relations. Algorithms can be applied to those representations to derive new knowledge and check if a provided knowledge base is consistent. RCC enables reasoning about topological properties of (abstract) 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).

The basic inference mechanism when using qualitative spatial calculi is based on the 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 relations 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 look up precomputed (or manually resolved) results of all possible compositions (see (Li and Ying, 2003)).

For consistency computation, we map regions and relations to a constraint net. A path-consistency algorithms used for solving constraint satisfaction problems (Tsang, 1993) provides inference services like identifying inconsistency (i.e. if no relation can be computed between two regions) or restricting relations between regions to the only possible ones.

3.2 ONTOLOGICAL REASONING

Ontological languages like OWL make it possible to represent knowledge about objects, activities, relations etc. of a domain. Due to the formal representation such ontologies provide, they are exchangeable and, more importantly, can be used for inference services. Description Logic reasoners (DL reasoner) provide means for inference services like classification or instance checking (McGuinness, 2003). Capabilities for representation involve the separation of instances (representing individual objects) and concepts (as set of instances), taxonomic relations between concepts, and properties as an additional type of relation among concepts. A TBox contains all concepts whereas an ABox contains all instances.

However, the combination of OWL and qualitative calculi is not straight forward. While some theoretical foundations for translating RCC-8 to OWL exist (see (Grütter and Scharrenbach, 2009; Katz and Grau, 2005; Hogenboom et al., 2010a)) as well as some implementations that include RCC-8 in a DL reasoner (see (Stocker and Sirin, 2009)), we would like to use both RCC-8 and CDC (for topology *and* orientation) in a most enclosed fashion. Thus, this paper provides an approach for integrating OWL, RCC-8, and CDC.

4 CONCEPTUAL APPROACH

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

4.1 Ontological Reasoning

To represent the domain knowledge, we use a TBox with classes occurring in the environment (like *cup*, *plate*, *table*, *room* etc.). An ABox is used to represent instances of concrete individual objects (like *table*1, *counter*1 etc. (see Figure 1)). As object properties of OWL follow the same semantics as binary relations, they can be used for representing qualitative relations of the calculi. Thus, in the ABox an *ObjectPropertyAssertion* establishes a property (relation) between two individuals. A fact like "*The cup is on the table, protrudes the table edge or touches the edge or is completely on the table*" will be expressed as *(Cup1, PO, TPP, NTPP, Table1)*, or the fact "*The table is north of the counter and east of the chair*" may be noted as *(Table1 N Counter1, Table1 E Chair1)* (see Listing 1).

Listing 1: RCC-8 and CDC relations as properties of instances

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ObjectPropertyAssertion(:PO :Cup1 :Table1)
ObjectPropertyAssertion(:TPP :Cup1 :Table1)
ObjectPropertyAssertion(:NTPP :Cup1 :Table1)
ObjectPropertyAssertion(:N :Table1 :Counter1)
ObjectPropertyAssertion(:E :Table1 :Chair1)
```

For computing the consistency of the provided facts as well as the computation of all spatial relationships between objects in the environment, we use the introduced calculi RCC-8 and CDC. We utilize the machine readability as basic property of OWL to automatically access ABox instances of the ontology. Once we extracted the object instances and their relations from the ABox we import them into a constraint system which uses the composition tables of the calculi to achieve the mentioned inference tasks. The constraint system uses the path-consistency algorithm for making implicit spatial relations between domain objects (instances) explicit. Newly found relations may afterwards be imported into the ABox. Thus, we combine the ontology with a qualitative spatial constraint system instead of including spatial calculi in a DL reasoner directly (this approach is similar to Pellet-Spatial, see also (Bhatt et al., 2009)), however, with two calculi.

4.2 Interaction Ability

To detect the robot's interaction ability, i.e. whether the robot is able to interact with a given object at a specific time or not, following subtasks need to be performed:

1. The robot has to identify, if its tools, which will be used for interaction, are in the direction of the target object.
2. The robot has to check, if the target object can be manipulated from the robot's position and the orientation of its tools.
3. The robot has to check, if the distance between itself and the target object is appropriate for interaction.
4. The robot has to ensure that no hindering object is in-between it and the target object.

Using the CDC one can find cardinal points but not the orientation. To be able to represent and examine the orientation of different agents and/or objects to one another, we introduce a further instance that may be inserted into the fact base representing the orientation of the robot or any other object. One example would be, if the orientation of the robot is north, the direction would be represented by *(Orientation N Robot)* whereas *Orientation* would be the artificially added instance of the fact base. This allows not only to fulfill the first but also the second subtask: If the robot's orientation is equal to the inverse orientation of the target object, one can assume that the needed orientation for the interaction of the robot with the target object is achieved.

To fulfill the third subtask, the computation of distance between the robot and the target object, quantitative spatial relations, which are not provided by RCC-8 or CDC, are needed. However, for using these calculi a mapping from quantitative acquired positions to qualitative relations will always be done beforehand. Otherwise, some of the RCC-8 relations can not be applied between objects. For clarification, if two objects are near to one another, a computation step is needed that applies either the relation *EC* or *DC* between these objects, dependent of the actual quantitative distance. This implies that the spatial configuration of real world objects with RCC-8 relations inherently contains distance information. If regions touch (*EC*), overlap (*PO*), or are contained in the region of the robot (*NTPP*, *TPP*), the robot and a target object are typically near enough to interact.

Considering obstacles as well, the previously computed orientation and the inherent distance (CDC and RCC-8 relations) can be used. Seen from the topological angle, an object can only be between two other objects, if the corresponding region of the object is connected with the other two regions. Thus, using RCC-8 one considers the robot's region, the target object's region, and the region of a potentially obstacle *O*. If *O*'s region is related to the other two regions with the relation *PO*, *NTPP*, or *TPP* one can assume that *O* is really an obstacle. With CDC an object *O* might be an obstacle if, considered from the target object, it is in the same direction like the robot is and, considered from the robot, *O* is in the same direction as the target object. For example, if the robot is east of the target object *(Robot E Target)* (thus, also holds *(Target W Robot)*), then an object that is also east of the target and west of the robot might be in-between, thus, might be an obstacle. However, such inference might not be correct, because the calculi only considers two dimensions or the robot might find a plan for grasping the target although an object is in-between. In summary, it is possible to evaluate the interaction ability with spatial qualitative relations, although it might be uncertain.

5 EVALUATION OF THE APPROACH

For the evaluation of our conceptual approach, an architecture was implemented that combines the needed inference technologies. As underlying system serves the Event Transaction Logic Inference System (ETALIS) (Darko Anicic, Paul Fodor, 2011), that implements a complex event processing (CEP) framework on the basis of Prolog. Event processing enables the processing of continuous data streams, which in our case are created through the sensors of a robot. The use of Prolog allows not only the generation of complex events from simple events (like it is possible with traditional CEP systems) but also to make strong logically rooted conclusions and inferences about the events, their context, or other formulated predicates. In comparison to other CEP-systems, which are implemented with procedural or object-oriented languages, ETALIS is more flexible and has partially better performance results (Anicic et al., 2010). Starting with ETALIS, we combine it with the PROLOG-OWL interface THEA2 (Vangelis Vassiliadis, Chris Mungall, 2012), and DL reasoners (like Pellet (Clark and Parsia, LLC, 2011), Racer (Racer Systems GmbH Co. KG, 2011), or HermiT (Boris Motik, Rob Shearer, Birte Glimm, Giorgos Stoilos, and Ian Horrocks, 2011)) to our system called *ETALIS-Spatial*.

The knowledge representation of our system is realized with an OWL2 knowledge base. Objects and spatial relations are defined as described in Section 3. THEA2 enables access to the ABox for extracting and including spatial relations and all instances for participating objects.

Processing with ETALIS-Spatial starts from sensor data, which is assumed to be already mapped from quantitative values to qualitative values. The input consists of identified objects and their direct spatial relations. This preprocessing could also be done in principal by the Prolog engine. Typical examples for input data (*primitive events*) are *assertobject(Plate1)* for an recognized object, *assertRelation(Plate1, Plate2, DC)* for establishing a spatial relation, *robotMoved*, for a finalized movement of the robot. A *robotMoved* event triggers the new computation of spatial relations between the robot and other objects. Such input is continuously streamed into the system. After asserting a bunch of new data the system starts a consistency test of the knowledge base and furthermore infers new relations if possible (marked e.g. as *foundRelation(Plate2, Cup4, EC)*). Complex events represent the output of this computation, e.g. *interactable(Plate2)* for indicating that the system detected an object with which the robot can interact. These complex events can be used like primitive events for further computations.

The system was tested with a scenario depicted in Figure 1. In it, the system computes the interaction ability of the robot with *Plate2* from different positions resulting out of two different paths (see figure 2). If the robot approaches *Plate2* from south-east (solid path), it computes that an interaction with *Plate2* is not possible because *Cup4* is an obstacle. If the robot approaches *Plate2* from north (dotted path), it computes that an interaction with *Plate2* is possible because no other object hinders the interaction.

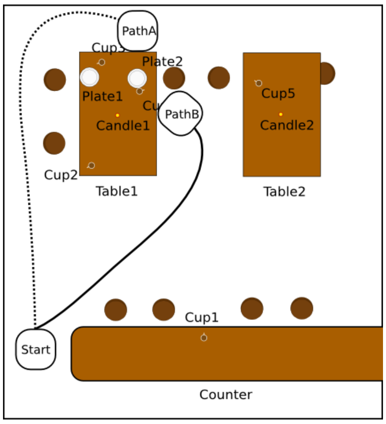

Figure 2: Path of the robot; dotted path A, solid path B

In summary, the evaluation shows an implementation of our conceptual approach presented in Section 4. The qualitative spatial relations can be represented in an ontology as properties. The knowledge can be extracted from the ontology for processing in a separate spatial Prolog-based reasoner. This reasoner computes all spatial relations and detects interaction ability between the objects. By using complex event processing, a continuous stream of data could be processed.

6 Discussion

Our work shows that typical robot tasks can be supported by applying qualitative spatial reasoning. We applied RCC-8 and CDC to cover topology and orientation aspects of spatial reasoning. Relations of these calculi could be integrated in an OWL-based ontology for maintaining the needed knowledge centrally. Computing new spatial relations and consistency checks were performed by a Prolog system based on composition tables provided by the calculi in combination with path-consistency algorithms.

A first implementation used 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 for cover more facets of the tasks. Further or other qualitative calculi which handle other aspects can be integrated into the system by modeling their composition tables and relations in Prolog.

7 CONCLUSIONS

This paper demonstrates the application of the qualitative 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.

ACKNOWLEDGMENTS

This work is supported by the RACE project, grant agreement no. 287752, funded by the EC Seventh Framework Program theme FP7-ICT-2011-7.

REFERENCES

Anicic, D., Fodor, P., Rudolph, S., Stühmer, R., Stojanovic, N., and Studer, R. (2010). A Rule-Based Language for Complex Event Processing and Reasoning. In Hitzler, P. and Lukasiewicz, T., editors, *Web Reasoning and Rule Systems*, volume 6333 of *Lecture Notes in Computer Science*, pages 42–57. Springer Berlin / Heidelberg.

Antoniou, G. and Harmelen, F. V. (2003). Web Ontology Language: OWL. In *Handbook on Ontologies in Information Systems*, pages 67–92. Springer.

Bhatt, M., Dylla, F., and Hois, J. (2009). Spatio-terminological inference for the design of ambient environments. In *COSIT*, pages 371–391.

Boris Motik, Rob Shearer, Birte Glimm, Giorgos Stoilos, and Ian Horrocks (2011). Hermit OWL Reasoner.

http://hermit-reasoner.com/. Date: March, 6th 2012.

Clark and Parsia, LLC (2011). Pellet: OWL 2 Reasoner for Java. http://clarkparsia.com/pellet. Date: March, 1st 2012.

Darko Anicic, Paul Fodor (2011). etalis - Event-driven Transaction Logic Inference System. http://code.google.com/p/etalis/. Date: February, 25th 2012.

Goyal, R. K. (2000). *Similarity assessment for cardinal directions between extended spatial objects*. PhD thesis, The University of Maine. AAI9972143.

Grütter, R. and Scharrenbach, T. (2009). A qualitative approach to vague spatio-thematic query processing. In *Terra Cognita (Terra2009)*.

Hogenboom, F., Borgman, B., Frasincar, F., and Kaymak, U. (2010a). Spatial knowledge representation on the semantic web. In *Semantic Computing (ICSC), 2010 IEEE Fourth International Conference on*, pages 252 –259.

Hogenboom, F., Frasincar, F., and Kaymak, U. (2010b). A review of approaches for representing rcc8 in owl. In *Proceedings of the 2010 ACM Symposium on Applied Computing*, SAC '10, pages 1444–1445, New York, NY, USA. ACM.

Jan Wielemaker et al. (2012). SWI-Prolog - a comprehensive Free Software Prolog environment. http://www.swi-prolog.org/. Stand: 8. März 2012.

Katz, Y. and Grau, B. C. (2005). Representing qualitative spatial information in owl-dl. In *Proceedings of the OWL: Experiences and Directions Workshop. Galway*.

Levesque, H. and Lakemeyer, G. (2007). Cognitive Robotics. In van Harmelen, F., Lifschitz, V., and Porter, B., editors, *Handbook of Knowledge Representation*. Elsevier.

Li, S. and Ying, M. (2003). Region connection calculus: Its models and composition table. *Artificial Intelligence*, 145(1Ű2):121 – 146.

McGuinness, D. L. (2003). Configuration. In Baader, F., Calvanese, D., McGuinness, D. L., Nardi, D., and Patel-Schneider, P. F., editors, *Description Logic Handbook*, pages 397–413. Cambridge University Press.

Racer Systems GmbH Co. KG (2011). RacerPro, der OWL Reasoner und Inference Server für das Semantic Web. http://www.racer-systems.com/. Stand: 8. März 2012.

Randell, D. A., Cui, Z., and Cohn, A. G. (1992). A spatial logic based on regions and connection. In *PROCEEDINGS 3RD INTERNATIONAL CONFERENCE ON KNOWLEDGE REPRESENTATION AND REASONING*.

Renz, J. and Nebel, B. (2007). Qualitative spatial reasoning using constraint calculi. In Aiello, M., Pratt-Hartmann, I., and van Benthem, J., editors, *Handbook of Spatial Logics*, pages 161–215. Springer.

Skiadopoulos, S. and Koubarakis, M. (2004). Composing cardinal direction relations. *Artif. Intell.*, 152:143–171.

Stocker, M. and Sirin, E. (2009). Pelletspatial: A hybrid rcc-8 and rdf/owl reasoning and query engine.

Tsang, E. (1993). *Foundations of Constraint Satisfaction*. Academic Press, London, San Diego, New York.

Vangelis Vassiliadis, Chris Mungall (2012). A toolbox for Qualitative Spatial Reasoning in applications. http://www.semanticweb.gr/thea/index.html. Date: March, 10th 2012.