A SPATIAL ONTOLOGY FOR HUMAN-ROBOT INTERACTION

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Abstract: Robotics quickly evolved in the recent years. This development widened the intervention fields of robots. Robots interact with humans in order to serve them. Improving the quality of this interaction requires to endow robots with spatial representation and/or reasoning system. Many works have been dedicated to this purpose. Most of them take into account metric, symbolic spatial relationships. However, they do not consider fuzzy relations given by linguistic variables in humans language in human-robot interaction. These relations are not understood by robots. Our objective is to combine human representation (symbolic, fuzzy) of space with the robot's one to develop a mixed reasoning. More precisely, we propose an ontology to manage both spatial relations (topological, metric), fuzziness in spatial representation. This ontology allows a hierarchical organization of space which is naturally manageable by humans and easily understandable by robots. Our ontology will be incorporated into a planner by extending the planning language PDDL.

1 INTRODUCTION

Robotics quickly evolved in the last decade and there is an increasing demand for intelligent systems like robots that can help in daily life. This development widened the intervention fields of robots such as a public area where robots interact with humans in order to serve them. To improve the quality of this interaction, robots should behave as much as possible like humans. This requires to endow robots with representations and/or systems of reasoning directly inspired by humans. We focus on human-robot interaction (HRI) based on spatial organization of observed structures, in order to plan robots actions.

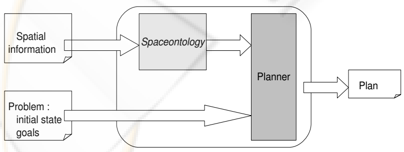

Figure 1: Spatial Planner.

Our goal is to develop a planner allowing to solve problems taking into account spatial information. This planner, called *Spatial Planner* (Fig. 1), consists of two sub-systems. The first sub-system, *SpaceOntology* allows a spatial representation and reasoning model. As input, it takes a set of imprecise and incomplete spatial information. However, as output, it provides a structured knowledge about the environment to explored in planning. The second sub-system, *Planner*, defines the set of actions to be executed by the robot in order to achieve its mission.

In this paper, we focus on *SpaceOntology* that models spatial representation and reasoning for better mediation between humans and robots. This ontology concerns:

- Hierarchical representation of space. The space is structured to be manageable by humans and robots.
- Numerical/Symbolic representation of space. From the human's point of view, the space is generally considered in a symbolic way (in, disjoint, north, close, ...). From the robot's point of view, the space is considered in numerical way (angles, distances, ...).

SpaceOntology gives a description of the environment (hierarchical organization, spatial relations) understandable by both humans and robots.

This paper is organized as follows. In section 2, we place our work with regard to the state of art of the spatial representation and ontologies. In section 3, we present our framework to model spatial representation and reasoning. In section 4, we present *SpaceOntology*. In section 5, we present how we use ontology to develop a mixed reasoning (from human to robot and

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from robot to human). In conclusion, we present our future works.

2 RELATED WORK

2.1 Spatial Relations

The spatial relations have been developed in many domains (image processing (Bloch and Ralescu, 2003), GIS (Casati et al., 1998), ...). They can be divided into topological, directional and distance relations (Kuipers and Levitt, 1988). In this paper, we consider all these relations.

In robotics, quantitative representations of spatial relations are commonly applied. Purely quantitative representations have limitations particularly when imprecise knowledge use spatial relations expressed in linguistic terms, particular in HRI. Imprecision has to be taken into account in such problems. It is often inherent to human language. It may be caused by imprecision about the objects to recognize due to the absence of crisp contours or by the imprecise semantics of some relationships (eg. quite far, ...), or else by a kind of task we would like fulfill in HRI. For example, we may want a robot go towards a person while remaining at security distance of it.

Our objective is to combine all symbolic representation with robotic numeric representation to develop a mixed reasoning.

2.2 Ontologies and Spatial Dimension

Different techniques of spatial representation and reasoning have been proposed. Most are based on constraints, logical and algebraic approaches (Balbiani et al., 1999). However, these approaches can not manage quantitative, qualitative and imprecise knowledge at the same time. In HRI, we need to combine this knowledge. For this reason, we must use an unified framework to cover large classes of problems and potential applications, and able to give rise to instantiation adapted to each particular application. Ontologies (Gruber et al., 1995) appear as an appropriate tool toward this aim.

Spatial ontologies can be found in some fields such as GIS (Casati et al., 1998), Virtual Reality (Dasiopoulou et al., 2005), Robotics (Dominey et al., 2004), ... All these ontologies are focused on the representation of spatial concepts according to the application domains. A major weakness of usual ontological technologies is their inability to represent and to reason with imprecision. An interesting work presented in (Hudelot et al., 2008) overcome this limit.

3 OUR FRAMEWORK

In our work, we set up an ontology to manage both spatial relations, fuzziness in spatial representation. Moreover, our ontology allows an organization of space naturally manageable by human and easily understandable by the robot: *hierarchical representation of space*.

3.1 Hierarchical Organization of Space

Hierarchical organization of space reduces the amount of information considered for coping with a complex, high-detailed world: concepts are grouped into more general ones and these are considered new concepts that can be abstracted again. The result is a hierarchy of abstractions (or specialization) or a hierarchy of concepts that ends when all information is modeled by a single universal concept (or we reach a desired level of specialization). Thus, we consider this hierarchy to describe the considered space.

Our organization is made from the highest abstraction level to lowest (most detailed one) unlike the organization described in (Fernández-Madrigal et al., 2004). The highest level represents the environment with the maximum amount of detail available. The lowest level represents the environment by a single concept. Hierarchical representation of space allows us to represent this space in a structure easily manageable by human and robot. In addition, it provides better performance than flat representation in navigation or path planning.

3.1.1 Spatial Entity

All concepts in spatial representation are called *Spatial Entities*. A spatial entity is localizable in a given space by one of its attributes or by geometric transformation. From a geometric point of view, a spatial entity ε is defined by a rectangle $rect_{\varepsilon}$ corresponding to its axis-aligned bounding rectangles.

From hierarchical organization of space, derives two categories of spatial entities. *Space* represents a global space. This entity is the highest abstraction and the lowest level in the hierarchy organization. *Region* represents any spatial entity belonging to different hierarchical levels (intermediate and final). A region is a sub-space included in the given space. A region is itself considered as a space that can be decomposed into different sub-regions.

3.2 Spatial Relations

A spatial relation requires a reference frame. For example, the relation *bench is in front of coffee machine*.

The semantic of the relation is not the same depending on whether the reference system is the coffee machine itself or an external observer. In order to have an unique meaning and to remove the ambiguity, three concepts have to be specified : the target object, the reference object and the reference system (Hudelot, 2005). In our work, we consider both *Intrinsic* and *Egocentric* reference frame.

3.2.1 Topological Relationships

We consider the ALBR relations defined in **ABLR (Above Below West Right)** (Laborie et al., 2006). This algebra balances between expressiveness and the number of relations (reasoning/complexity). **ABLR** reduces the number of relations while preserving the directionality property of the representation defined in (Allen, 1983). A topological relation is an **ABLR** relation. This relation is a couple $\langle r_X, r_Y \rangle$, where;

$r_X \in \{Left(L), OverlapsLeft(O_L), Contains(C_x), Inside(I_x), OverlapsRightO_R, Right(R)\}$

and

$r_Y \in \{Above(A), OverlapsAbove(O_A), Contains(C_y), Inside(I_y), OverlpasBelow(O_B), Below(B)\}$.

3.2.2 Metrical Relationships

Metrical relations concern distance and orientation relations (Bloch, 2005). We consider a 2D representation of the space given by $(O, \overrightarrow{i}, \overrightarrow{j})$. The origin O is a reference system that can be intrinsic or egocentric. In the following, a rectangle denotd ε represents a spatial entity. Its symmetry center will be known as the spatial entity name. $P_x(\varepsilon)$ (resp. $P_y(\varepsilon)$) denotes the projection of ε on $(\overrightarrow{i})$ axis (resp. $(\overrightarrow{j})$ axis).

In HRI under spatial constraints, fuzzy information is a key point as said in section 2. In this work, vagueness and ambiguity concern the vagueness of the relationship itself. Indeed, we don't need to evaluate if a spatial entity is in north of a referent spatial entity since spatial entities are crisp. The application of fuzzy approach mainly concerns the distance relationship. The aim is to find a way to represent the symbolic direction and distance relationship (based on linguistic variables) by a numerical direction and distance and vice versa.

Directional Relationships. We describe directional relations through cardinal direction : *West of*, *North of*, *East of* and *South of*. We associate for every semantic direction semantic *West of*, *East of*, *North of* and *South of* following respective functions $West_R$, $East_R$, $North_R$ (R is a referent object) and $South_R$. $West_R(\varepsilon)$ denotes ε is left of R given by $West_R(\varepsilon) = \{P_x(\varepsilon) - P_x(R) \leqslant 0\}$. $East_R(\varepsilon)$ denotes ε is right of R given by $East_R(\varepsilon) = \{P_x(\varepsilon) - P_x(R) \geqslant 0\}$. $North_R(\varepsilon)$ denotes ε is in north of R given by $North_R(\varepsilon) = \{P_y(\varepsilon) - P_y(R) \geqslant 0\}$. $South_R(\varepsilon)$ denotes ε is in south of R given by $South_R(\varepsilon) = \{P_y(\varepsilon) - P_y(R) \leqslant 0\}$.

The representation of the 8 cardinal relationships is possible by combining these four functions. Consider the example of the directional relation the bench b is north and east of coffee machine c_m. This corresponds to the combination of $North_{c_m}(b)$ and $East_{c_m}(b)$:

$$North_{c_m}(b) \oplus East_{c_m}(b) = \begin{cases} P_x(b) - P_x(c_m) \geqslant 0 \\ P_y(b) - P_y(c_m) \geqslant 0 \end{cases} \quad (1)$$

This representation allows us to express other directional relations (at the same level, between, ...).

Distance Relationships. We consider four linguistic variables to describe distance relations: *close to*, *close to enough*, *far from enough*, *far from*. We note $d(\varepsilon, r)$ in $\mathbb{R}^+$ the euclidean distance between the point of symmetry of two rectangles representing two regions (r referent object and ε target object). The aim is to find a way to represent the four linguistic variables already defined to evaluate distance by a numeric value to evaluate it. To do so, we consider two degrees, defined in (Schockaert, 2008), $N_{(\alpha,\beta)}(p,q)$ (2) and $F_{(\alpha,\beta)}(p,q)$ (3). The degree N represents two points p and q are near each other and the degree F represents how p is far from q ($\alpha, \beta > 0$). We have defined a hierarchical space organization. This has an impact on the distance evaluation. Indeed, the distance of $2m$ in a city is considered as *near*, however, $2m$ in an office is considered as *far*. From these information, we define for each hierarchical level an α and a β depending on the scale of this level.

$$N_{(\alpha,\beta)}(p,q) = \begin{cases} 1 & \text{if } d(p,q) \leq \alpha \\ 0 & \text{if } d(p,q) \geq \alpha + \beta \\ \frac{\alpha+\beta-d(p,q)}{\beta} & \text{otherwise } \beta \neq 0 \end{cases} \quad (2)$$

$$F_{(\alpha,\beta)}(p,q) = \begin{cases} 1 & \text{if } d(p,q) > \alpha + \beta \\ 0 & \text{if } d(p,q) \leq \alpha \\ \frac{d(p,q)-\alpha}{\beta} & \text{otherwise } \beta \neq 0 \end{cases} \quad (3)$$

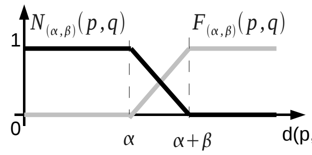

Figure 2: Graphical representation of relationship between $N_{(\alpha,\beta)}(p,q)$ and $F_{(\alpha,\beta)}(p,q)$.

From equations 2 and 3 and organization given in figure 2, it is easy to deduce that: (1) if $d \in [0, \alpha]$ then

d is considered as *close*, (2) if $d \in]\alpha, \alpha + \frac{\beta}{2}]$ then d is considered as *close enough*, (3) if $d \in]\alpha + \frac{\beta}{2}, \alpha + \beta]$ then d is considered as *far enough*, (4) if $d \in]\alpha + \beta, +\infty[$ then d is considered as *far*.

4 IMPLEMENTATION

As a formal language, we opted for OWL DL formalism (McGuinness et al., 2004; Baader et al., 2003). This formalism benefits from the compactness and expressiveness of DL. Indeed, an important characteristic of DL is their reasoning capabilities of inferring implicit knowledge from the explicitly represented knowledge. In this section, we describe how we present and reason about spatial knowledge.

4.1 Spatial Entities as Concepts

One of important concepts of *SpaceOntology* is the concept **Space** (`Space⊑ ⊤`) (`⊤` for Thing[1]). This concept represents a global environment (i.e a country, a city, ...). Also, we define a concept **Regions**. This concept is a subclass of concept **Space** (`Regions⊑ Space`). Thus, we can consider the hierarchical definition of space. Indeed, a region itself is a space in the next hierarchical level. Furthermore, the hierarchical relationship between concepts **Space** and **Regions** is given by subsumption. We offer the following links *consistsOf* and *isPartOf*. The link *consistsOf* can express that space consists of one or more regions. The link *isPartOf* can express one region may belong to one or more spaces. These relationships are symmetrical and transitive.

```
Space ⊑ ⊤ ⊓ ∃ consistsOf.Regions ⊓ ⩾ 1
consistsOf
```

```
Regions ⊑ Space ⊓ ∃ isPartOf.Space ⊓ ⩾ 1
consistsOf
```

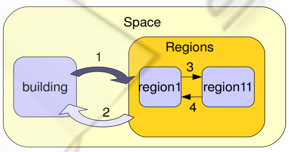

Figure 3: Links between concepts and their instantiation.

From these links and their properties, we can compose relationships between these two concepts. For instance, the composite (2) relationship in figure 3, is derived from the transitive links *isPartOf* (4) between $region1_1$ with $region1$ and $region1$ with $building$. Through this relationship we can deduce that $region1_1$ is part of the $building$.

4.2 Spatial Relations as Concepts

A spatial relation is not considered in our ontology as a property between two regions but as a concept on its own; **SpatialRelations**(`SpatialRelations⊑ ⊤`). This concept represents a set of all spatial relations between two regions. A **SpatialRelations** subsumes **TopologicalRelations** and **MetricRelations** which itself subsumes **DirectionalRelations** and **DistanceRelations** which itself subsumes **DistanceAccordingToActions** and **DistanceAccordingToHierarchicalLevel**.

4.2.1 HasRelation Concept

To define a spatial relationship between two regions describing a given configuration, we need to link these regions with a spatial relationship.

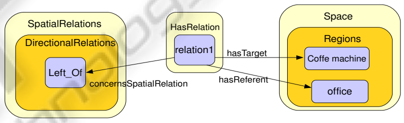

Figure 4: Links between concepts and their instantiation.

As already defined, a spatial relationship is given by the concept **SpatialRelations**. We define the link **HasRelation** as a concept which refers to the set of spatial relations for which target and reference entities are defined. This concept is useful to describe spatial configurations.

```
HasRelation ⊑ ⊤ ⊓ ∃
concernsSpatialRelation.SpatialRelations ⊓ = 1
concernsSpatialRelation ⊓ ∃
hasReferent.Regions ⊓ ⩾ 1 hasReferent ⊓ ∃
hasTarget.Regions ⊓ = 1 hasTarget
```

Consider as an example that human asks the robot to enter into "the office left of the coffee machine". In *SpaceOntology*, this expression is formalized as follows. First, identify this expression by *relation*1. We note `relation1:HasRelation`[2]. We consider that *relation*1 is an instantiation of the concept **HasRelation**. Left_{of} is an instantiation of the concept **DirectionalRelations** according to a defined reference system for spatial relations (`Left`$_{of}$`:DirectionalRelations`). The office and

[1]Thing is an OWL class that represents the set containing all individuals. Because of this all classes are subclasses of OWL:Thing.

[2]These symbols are defined in description logics syntax and interpretation

the coffee machine are instantiations of the concept **Regions** (`office:Regions` and `coffee:Regions`).

5 OPERATING *SPACEONTOLOGY*

In this section, we present the exploitation of our ontology and the methods for reasoning. As already mentioned, we developed an ontology to provide a basis spatial data to be used after in planning problems to improve HRI. Exploitation of ontology is necessary for path planning between two positions. In this paper, we present how and by which methods from ontology we can extract the paths between two positions even if the information is incomplete. Work on path planing is the subject of future work.

5.1 Example

Consider an HRI problem in a building. A human asks the robot to fetch a bottle near the coffee machine located in the hallway of the third floor. Then, to bring back the bottle to the human who is on the first floor (initial robot position's). Specifically, robot should compute the path between its position and bottle position's, catching the bottle and after to give it to human. To explain the reasoning, we consider in the following only the first part of the task, namely; fetching the bottle.

5.2 Reasoning

In *SpaceOntology*, we insisted on two key notions: hierarchy of space and spatial relationships. Thus, we rely on these notions for reasoning.

Consider the example given in section 5.1. By giving a map with all the corridors and all access, defining a path by considering the size of the map becomes quickly expensive. Hierarchical organization of space simplifies the path computation. Indeed, it helps to decompose the problem into 3 sub-problems: (1) from initial position reach an access point to the third floor, (2) from this access point plan to reach the third floor and (3) from arrival position on the third floor, plan to reach the coffee machine.

Reasoning for the first and last steps requires more detailed information than the second step. For this step, we must ignore the details given in two other steps. However, considering floors like black boxes does not guarantee the path quality. Consider that quality is related to speed. Passing through certain corridors with big distances can be faster than through the ones with short distances but with many obstacles. Thus, hierarchical organization of a space, involves reasoning at each level.

Thus, we can construct a path between any two given locations in an accurate (i.e in room number 3) or approximate (i.e somewhere on the first floor). In this paper, we do not present an algorithm for finding paths, but rather we present a structure generated from the ontology providing a set of possible paths between two positions by considering the space hierarchy. For the target object, in our case the bottle, we define the concept of *target zone*. Considering the hierarchy of the environment, we define the target zone as $T_Z^l(o)$, where l is the hierarchy level and o the object or region targeted. Thus, we can deduce from *SpaceOntology* a hierarchy for the target zone. This allows us to determine the most abstract target zone ($T_Z^0(o)$ = *building*) and the more detailed one ($T_Z^3(o)$= *region of coffee machine*).

Another key knowledge in this work are spatial relationships. They allow, given an environment, to describe its spatial configuration (obstacle position's). For instance, we can describe that the corridor H is adjacent to the door *doorB* of the office B. Here, an example from *SpaceOntology.owl* allowing to illustrate the example.

```
<HasRelationWithIntersection rdf:ID="relation3">
 <intersectionresult>
   <Regions rdf:ID="doorB"/>
 </intersectionresult>
 <hasTarget>
    <Regions rdf:ID="corriderH"/>
 </hasTarget>
 <hasReferent>
    <Regions rdf:ID="officeB"/>
 </hasReferent>
 <concernsSpatialRelation>
    <TopologicalRelations rdf:ID="leftinside">
       <isahRelation rdf:resource="#Horiz_L"/>
       <isavRelation rdf:resource="#Ver_Iy"/>
    </TopologicalRelations>
 </concernsSpatialRelation>
</HasRelationWithIntersection>
```

As already mentioned, our strategy of searching a path is to find a path divided into different portions. Each part belongs to a single hierarchical level. To do this, we need a structure for this type of dedicated research. This structure is generated from *SpaceOntology*. Thus, we define the *Crossing Network Graph*.

5.2.1 Crossing Network Graph

A *Crossing Network Graph*(Γ_G) is a directed graph. A node in this graph represents a network of passage. The nodes are organised hierarchically. The arcs represent relationships between nodes as described in *SpaceOntology*.

A *Crossing Network*(Γ) is a graph whose nodes are *Crossing Network*. Edges represent spatial adjacency relations between two nodes described in *SpaceOntology* giving a contact point between these nodes, known as gateways. A gateway (i.e door, passing lane, ...) allows transitions between adjacent spaces and between spaces adjacent in different hierarchical levels. Edges are labeled by a couple (*pass*, *dist*), where *pass* gives the gateway connecting these regions (or networks) and *dist* is the distance separating these regions (or networks) passing through this gateway. There are two types of crossing networks: (1) Low-level crossing Networks are crossing networks whose nodes are crossing networks. It used such a network mainly as we have not reached the level of specialization wanted (or fixed). (2) High-level crossing Networks are crossing networks whose nodes are the regions. It used when level of specialization desired (or fixed) is reached.

The construction of *Crossing Network Graph* is done from the abstract level to fixed detailed level. First, we consider the target zone of the most abstract level. In the same way, we consider the initial zone of the most abstract level in the ontology. We select the most abstract target zone and initial zone targeted areas as these two zones are included in the same region. For instance, we consider the third floor (target zone) and the first floor (initial). It requires setting different gateways allowed to exit the initial zone and enter to the target zone. From the spatial relationships of adjacency defined *SpaceOntology*, we can find with backward mechanism all possible paths to reach the initial region.

6 CONCLUSIONS

This paper presents a spatial representation using an ontology allowing us to represent and reason on spatial objects represented from different point of views (human and robot). Future work will concern to integrate it in planning by extending the planning language PDDL. This is an innovative concept. In this paper, several aspects are still cause for thought as the assessment of a relationship without a fixed target or the implementation of an algorithm to generate a path according to some optimality criteria. These points will be the subject of future work.

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