Interpreting Motion Expressions in Route Instructions Using Two Projection-Based Spatial Models

Yohei Kurata and Hui Shi

SFB/TR 8 Spatial Cognition, Universität Bremen
Postfach 330 440, 28334 Bremen, Germany
{ykurata, shi}@informatik.uni-bremen.de

Abstract. This paper explores the applicability of two formal models of spatial relations, *Double Cross* and *RfDL*$_{3\text{-}12}$, to interpret some typical expressions that people use for describing a route. The relations in these two models allow the qualitative representation of the location and spatial extent of a landmark as seen from a route segment. We explore the correspondence between the relations in these two models and the motion expressions that refer to a point-like and a region-like landmark, respectively, which consist of the same set of direction-related expressions and specific sets of topology-related expressions. Through this exploration, we identify intrinsic ambiguities in the direction-related motion expressions that refer to a region-like landmark. Finally, we propose the generalization of our approach by using a spatial ontology, which potentially enables the mobile robots to interpret a large variety of expressions in human route instructions.

1 Introduction

A dialogue-based interface is a promising technology for the robots that work together with ordinary people. Especially, the mobile robots that navigate in human living spaces, such as the intelligent semi-autonomous wheelchair *Rolland* [1], should be equipped with an ability to communicate verbally with human users about their navigation plans. Formal models of qualitative spatial relations between a directed line segment (*DLine*) and another geometric object are helpful for developing such a technology [2], because those relations capture the prominent characteristics of route-landmark arrangements based on how people conceptualize the spatial context, and the existing studies report that many expressions in human route descriptions concern the actions associated with landmarks [3, 4]. Thus, this paper explores two formal models of such DLine-object relations, *Double Cross* [5, 6] and *RfDL*$_{3\text{-}12}$ [7], to interpret some typical expressions that people use for describing motions in a flat human-scale space. DLine-point relations in Double Cross (in short, *DC relations*) allow us to represent the location of a point-like landmark as seen from a route segment. Similarly, DLine-region relations in RfDL$_{3\text{-}12}$ (in short, *RfDL*$_{3\text{-}12}$ *relations*) allow the representation of both the location and spatial extent of a region-like landmark as seen from a route segment. The presence of motion expressions that presume the landmark's spatial extent observed in [8-9], such as "*go into* …" and "*go* *to the end of* …”, motivated us to study $RfDL_{3-12}$ relations in addition to DC relations. This paper focuses on the motion expressions that concern the relation between a landmark and an entire route segment. Meanwhile, we do not discuss the interpretation of goal-oriented motion expressions, such as “*go to the left of* …”, which concern the spatial relations between a landmark and a potential goal. Such landmark-location relations are used not only for describing motions, but also for describing static scenes and, accordingly, they are already well studied (e.g., [12]).

The reminder of this paper is structured as follows: Section 2 reviews Double Cross and $RfDL_{3-12}$. Section 3 identifies the correspondence between DC relations and motion expressions. Then, Section 4 explores the correspondence between $RfDL_{3-12}$ relations and motion expressions, finding some issues in such associations. Finally, Section 5 concludes with a short discussion about the generalization of our approach.

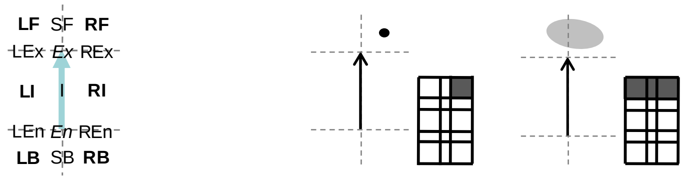
2 Double Cross and $RfDL_{3-12}$

When an agent moves straightly in a space guided by a landmark, its movement pattern is represented by the spatial arrangement between a directed line segment (*DLine*) and another geometric object. The DLine represents the route segment on which the agent proceeds, while another object corresponds to the landmark. The landmark is represented by a point if its spatial extent is not significant; otherwise, the landmark is represented as a region (or possibly a line if its width is not significant).

Double Cross is a model of spatial relations between three points [5], which are also viewed as the relations between a straight DLine and a point [6]. Double Cross projects a ‡-shaped intrinsic frame of spatial reference [11] onto the space, by which twelve fields around the DLine and three fields on the DLine are defined (Fig. 1a). In this paper, these 15 fields are called *LF* (*left front*)**,** *SF* (*straight front*), *RF* (*right front*)**,** *LEx* (*left at exit*), *Ex* (*exit*), *REx* (*right at exit*), *LI* (*left of interior*), *I* (*interior*), *RI* (*right of interior*), *LEn* (*left at entry*), *En* (*entry*), *REn* (*right at entry*), *LB* (*left back*), *SB* (*straight back*), and *RB* (*right back*). Based on which field contains the point, Double Cross distinguishes 15 DLine-point relations.

RfDL (*Region-in-the-frame-of-Directed-Line*) is a series of projection-based models of spatial relations between a straight DLine and a simple region. Based on the use or non-use of *left-right*, *front-side-back*, and *entry-interior-exterior* distinctions with respect to the DLine, $2^3 = 8$ types of DLine-centric intrinsic frames are introduced. The spatial relation in each model is defined as the set of fields over which the region extends. The finest model, called $RfDL_{3-12}$, distinguishes 1772 DLine-region relations [7] based on the ‡-shaped frame that distinguishes 15 fields (Fig. 1a). These 15 fields are the same with those of Double Cross and, therefore, $RfDL_{3-12}$ has a strong correspondence with Double Cross.

Both DC relations and $RfDL_{3-12}$ relations are represented by icons (Fig. 1b). The icons have 3×5 blocks, which geometrically correspond to the 15 fields that each model considers. The icon of a DC relation has one marked block, which indicates the field that contains the point. The icon of an $RfDL_{3-12}$ relation has one or more marked block, which indicates the set of fields over which the region extends. Accordingly, in both models, relations are distinguished visually by the icons’ marking patterns.



(a) (b)

Fig. 1. (a) Fifteen fields that Double Cross and $RfDL_{3\text{-}12}$ consider. (b) Examples of a DC relation and an $RfDL_{3\text{-}12}$ relation represented by icons.

3 DC Relations and Motion Expressions

This section explores the correspondence between DC relations and some motion expressions that refer to a point-like landmark (e.g., a bus stop). Suppose that the route segment and the landmark are mapped to a DLine $\overrightarrow{ab}$ and a point *p*, respectively. Then, the movement pattern is mapped to a DC relation $\overrightarrow{ab}:p$. We assume that the distance between $\overrightarrow{ab}$ and *p* is small enough for people to recognize *p* as a landmark along $\overrightarrow{ab}$ whenever a DC relation holds between them.

"*Approach*" is a motion expression that refers to a movement during which the distance between the moving agent and the landmark decreases, but does not become zero. Thus, this expression corresponds to five DC relations where *p* is located at $\overrightarrow{ab}$'s *SF*, *LF*, *RF*, *LEx*, or *REx*. "*Approach*" is further distinguished into five sub-expressions: "*go toward*", "*go until … comes to the left*", "*go until … comes to the right*", "*approach … on the left front*", and "*approach … on the right front*". These five expressions are mapped uniquely to the five DC relations where *p* is located at $\overrightarrow{ab}$'s *SF*, *LEx*, *REx*, *LF*, and *RF*, respectively.

The motion expression opposite to "*approach*" is "*go away from*". This expression corresponds to five DC relations where *p* is located at $\overrightarrow{ab}$'s *SB*, *LB*, *RB*, *LEn*, or *REn*. Similarly, "*go away from*" can be distinguished into five sub-expressions, "*go straight away from*", "*go away from … on the left back*", "*go away from … on the right back*", "*go away from … on the left*", "*go away from … on the right*", which are mapped uniquely to the five DC relations where *p* is located at $\overrightarrow{ab}$'s *SB*, *LB*, *RB*, *LEn*, and *REn*, respectively.

"*Pass by*" is a motion expression that refers to the movement where the landmark is located ahead at the beginning and later comes behind the moving agent. Thus, this expression corresponds to two DC relations where *p* is located at $\overrightarrow{ab}$'s *LI* or *RI*. Naturally, "*pass by*" is distinguished into "*pass by … on the left*" and "*pass by … on the right*" depending on whether *p* is located at $\overrightarrow{ab}$'s *LI* or *RI*.

In this way, three expressions, "*approach*", "*go away from*", and "*pass by*", and their twelve sub-expressions are assigned distinctively to the twelve fields around $\overrightarrow{ab}$ (Fig. 2). All of these expressions presume the state where the point-like landmark is located around the route segment. If the landmark is located on the segment' start-point, interior, and end-point (i.e., if the movement is characterized by the DC relations where p is located at $\overrightarrow{ab}$'s *En*, *I*, and *Ex*), then "*depart from*", "*pass*", and "*arrive at*" are the typical expressions that fit with the movement pattern, respectively. These three expressions concern the topological characteristics of the route-landmark arrangement (i.e., how the route intersects with the landmark).

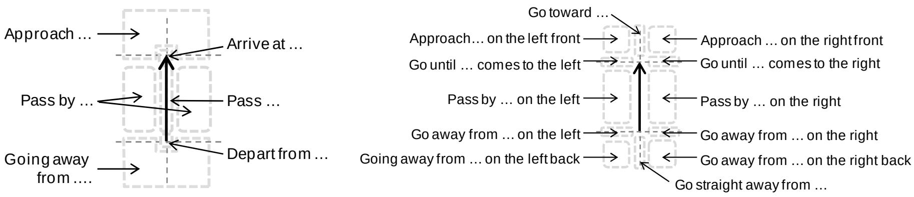


Fig. 2. Motion expressions assigned distinctively to the fields on/around a route segment.

4 RfDL$_{3\text{-}12}$ Relations and Motion Expressions

Next, we consider the situation where the landmark is represented by a region. Suppose that the route and the landmark are mapped to a DLine $\overrightarrow{ab}$ and a region R, respectively. Then, the movement pattern is mapped to an RfDL$_{3\text{-}12}$ relation $\overrightarrow{ab}:R$.

For the situation where the landmark is located around the route segment, we can consider the same set of motion expressions as before (i.e., "*approach*", "*go away from*", "*pass by*", and their sub-expressions). This time, however, the correspondence between these expressions and spatial relations is not clearly determined. For instance, let us think about "*approach*". It is certain that "*approach*" fits with the movement pattern where the distance between the moving agent and every point on the landmark monotonically decreases (Fig. 3a). Moreover, it is clear that "*approach*" cannot fit with the movement pattern where the landmark has no point inside to which the distance from the moving agent decreases monotonically during the movement (Fig. 3f). Thus, we consider the following two conditions of "*approach*":

- strong condition: the movement pattern is mapped to $\overrightarrow{ab}:R$ where R extends at least one field among $\overrightarrow{ab}$'s *SF*, *LF*, *RF*, *LEx*, or *REx*, but no other field, and;
- weak condition: the movement pattern is mapped to $\overrightarrow{ab}:R$ where R extends over at least one field among $\overrightarrow{ab}$'s *SF*, *LF*, *RF*, *LEx*, or *REx*, and neither *En*, *I*, nor *En*.

If a movement pattern satisfies the strong condition (e.g., Fig. 3a), this pattern always fits with the expression of "*approach*". On the other hand, if a movement pattern does not satisfy the weak condition (e.g., Fig. 3f), this pattern never fits with this expression. Note the movement patterns in Figs. 3b-e satisfy the weak condition, but not the strong condition. The movement patterns in Figs. 3b and 3d may well be described as "*approach*", but those in Figs. 3c and 3e probably not. This indicates the presence of borderline cases between Figs. 3b-c and between Figs. 3d-e, even though the movement patterns of each pair belong to the same RfDL$_{3\text{-}12}$ relation, respectively.

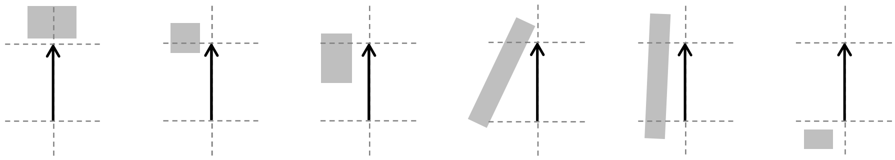


Fig. 3. Example of movement patterns that satisfy (a) both the strong and weak conditions of "*approach*", (b-e) the weak condition only, and (f) neither.

In order to evaluate how well "*approach*" fits with the movement pattern when it satisfies only the weak condition (e.g., Figs. 3b-e), we need further criteria; for instance, the relative length of period during which the nearest distance between the moving agent and the landmark decreases (compare Fig. 3b-c). In addition, the comparison of Fig. 3d-e indicates that it is better to consider a minimum threshold of the speed that the nearest distance decreases. The degree of fitness is then evaluated by the membership function of a fuzzy concept "*approach*" in Eqn. 1, where **a** and **b** are the location vector of the route segment's start-point *a* and end-points *b*, **x** is the location vector of the moving agent, $\frac{-\Delta \text{distance}(\mathbf{x}, R)}{|\Delta \mathbf{x}|}$ is the relative speed that the nearest distance decreases, and α is its threshold (α >0).

$$\mu_{\text{approach}} = \frac{1}{|\mathbf{b}-\mathbf{a}|} \lim_{|\Delta \mathbf{x}| \to 0} \left(\sum_{\mathbf{x} \in [\mathbf{a},\mathbf{b}] \wedge \frac{-\Delta \text{distance}(\mathbf{x},R)}{|\Delta \mathbf{x}|} > \alpha} |\Delta \mathbf{x}| \right) \tag{1}$$

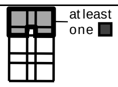
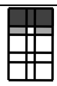
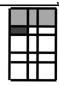
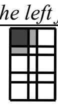
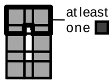
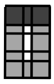
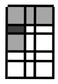
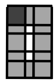
As we considered in the previous section, "*approach*" is further distinguished into five sub-expressions. Their definitions, however, become slightly different when the landmark is represented by a region:

- *"go toward …"* refers to the movement where the landmark stretches across the front extension of the route segment (Fig. 3a);
- *"go until … comes to the left/right"* refers to the movement where the landmark appears the straight left/right of the moving agent when it comes to or *near* the end-point of the route segment (Fig. 3b); and
- *"approach … on the left/right front"* refers to the movement where the landmark *mostly* extends over the left/right front of the moving agent when it arrives at the end-point of the route segment (Fig. 3b).

Table 1 summarizes the strong and weak conditions of "*approach*" and its sub-expressions using icons. These 'condition icons' follow the structure of the icons of $\text{RfDL}_{3\text{-}12}$ relations, where the icon's 15 blocks geometrically correspond to the 15 fields that $\text{RfDL}_{3\text{-}12}$ considers. Black, gray, and white blocks indicate the fields over which the region *R* must, may, and cannot extend, respectively. In addition to these conditions, it is possible to define membership functions that quantify how well each sub-expression fits with a given movement pattern, as we have defined such a function for "approach" (Eqn. 1). This is, however, beyond the scope of this paper.

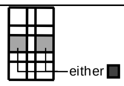
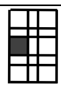
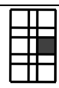
"*Go away from*" is the motion expression that is opposite to "*approach*". Consequently, the strong and weak conditions of this expression, as well as those of its sub-expressions, are derived from Table 1 simply by flipping the icons vertically.

Table 1. Conditions of the motion expression “*approach*” and its sub-expressions imposed on $RfDL_{3\text{-}12}$ relations, together with the number of relations that satisfy the conditions.

	Approach …	*Go toward …*	*Go until … comes to the left*	*Approach … on the left front*
Strong Condition	 12	 4	 3	 4
Weak Condition	 102	 46	 7	 67

The motion expression “*pass by*” that refers to a region-like landmark is essentially the same as “*pass by*” that refers to a point-like landmark. The condition of “*pass by*” (i.e., the landmark is located ahead at the beginning and later comes behind the moving agent) is satisfied if the *R* is entirely contained in $\overrightarrow{ab}$ ’s *LI* or *RI*, but not both. Table 2 shows the conditions of “*pass by*” and its two sub-expressions. As this table indicates, whether these expressions fit with a given movement pattern or not can be determined only from the $RfDL_{3\text{-}12}$ relation that characterize this movement pattern.

Table 2. Conditions of the motion expression “*pass by*” and its sub-expressions imposed on $RfDL_{3\text{-}12}$ relations, together with the number of relations that satisfy these conditions.

Pass by …	*Pass by … on the left*	*Pass by … on the right*
 2	 1	 1

Next, we consider the situation where the landmark is located over the route segment. Such situations are covered by 1645 of the 1772 $RfDL_{3\text{-}12}$ relations. Some of these relations correspond to a unique motion expression. For instance, the $RfDL_{3\text{-}12}$ relations in Figs. 4a-b correspond to the expressions “*go across* …” and “*pass the edge of* …”, respectively. Meanwhile, the $RfDL_{3\text{-}12}$ relation in Fig. 4c corresponds to two different expressions: “*go into* …” and “*go to the edge of … and keep going*”. Like this example, the use of $RfDL_{3\text{-}12}$ relations for characterizing a movement pattern may leave certain ambiguity, because if a certain part of a DLine intersects with a region, the $RfDL_{3\text{-}12}$ relation tells the presence of this intersection, but does not specify whether this DLine’s part intersects with the region’s interior or boundary.

Alternatively, the model of topological DLine-region relations [2] serves as a nice framework for handling the motion expressions that refer to a region-like landmark located over a route segment, because for such a landmark people pay primal attention to whether the moving agent starts from, passes through, or ends at the landmark’s inside, edge, or outside, which are the topological characteristics of route-landmark arrangements. Indeed, topological DLine-region relations capture such motion expressions as “*go into*”, “*go out of*”, “*go across*”, “*go within*”, “*leave the edge of*”, “*arrive at the edge of*”, “*pass the edge of*”, and so forth [2]. This, however, does not necessarily mean that $RfDL_{3-12}$ relations are useless for capturing such topology-related motion expressions. Actually, it is confirmed in [7] that:

- 76.2% of $RfDL_{3-12}$ relations are mapped to a unique topological relation; and
- 100% of $RfDL_{3-12}$ relations are mapped to a unique topological relation when the landmark is represented by a convex region (e.g., rectangles, circles).

Thus, many $RfDL_{3-12}$ relations can be associated with topology-related motion expressions by way of topological DLine-region relations without ambiguity, especially in the indoor environments where many landmarks (e.g., tables, sofas, beds, and closets) are represented by convex regions.

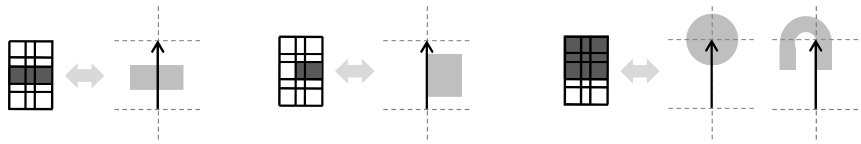


Fig. 4. Examples of $RfDL_{3-12}$ relations that capture topological characteristics of movement patterns (a-b) without and (c) with ambiguity.

5 Conclusions and Future Work

Formal treatment of human route descriptions is essential for developing intelligent dialogue-based interface of the mobile robots that navigate in human living spaces. This paper demonstrated that DC relations and $RfDL_{3-12}$ relations, which allow the qualitative representation of landmarks' location and spatial extent as seen from a route segment, are useful for capturing some typical motion expressions in human route descriptions. We observed that the same set of motion expressions that concern the landmark's direction is applicable to both situations where the landmarks are represented by points or regions, although some expressions may have intrinsic ambiguities for the latter situation. For such ambiguous expressions, it is possible to evaluate how well each expression fits with the movement pattern as a membership value of a fuzzy concept. We also examined different sets of motion expressions that concern the topological characteristics of route-landmark arrangements.

The existing analyses of human route descriptions (e.g., [3, 9]) show the presence of several motion expressions that neither Double Cross nor $RfDL_{3-12}$ may cover, such as "*go to the left of* …" and "*go behind* …" These goal-oriented motion expressions presume landmark-centric frames of spatial reference, whereas both Double Cross and $RfDL_{3-12}$ consider path-centric frames. This indicates the necessity of additional spatial models for capturing more wide range of expressions in human route descriptions (e.g., [12]).

This paper examined some concrete motion expressions in English. This approach looks straightforward, but lacks generality. Alternatively, we are currently investigating the correspondence between DC/$RfDL_{3-12}$ relations and generalized concepts of motions in an upper-level spatial ontology, called the *Generalized Upper*

Model [10]. For instance, the expressions "*go across* …", "*pass through* …", and "*gehen über* …" correspond to the same concept in this ontology, called *Path-Representing-Internal*, if their slight nuance is neglected. If the set of $\text{RfDL}_{3\text{-}12}$ relations that corresponds to this ontological concept is clarified beforehand, mobile robots can determine the possible movement patterns that satisfy the user's such request as "*go across the parking lot*", "*pass through the car park*", and "*gehen Sie über den Parkplatz*". This approach will definitely expand the applicability of our analysis in this paper as a foundation of dialogue-based interface of mobile robots.

Acknowledgments

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