Modeling Ontological Concepts of Motions with Two Projection-Based Spatial Models

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Abstract. To model human concepts of motions is essential for the development of the systems and machines that collaborate with ordinary people on spatio-dynamic tasks. This paper applies two projection-based spatial models, Double Cross and $RfDL_{3\text{-}12}$, to the modeling of human concepts of motions on a plane, making use of the ability of these two models to illustrate where and how a landmark extends around/on a path. For generalization, we adopt a set of formal motion concepts defined in an existing spatial ontology called GUM. These motion concepts are associated with the motion patterns modeled by Double Cross and $RfDL_{3\text{-}12}$, considering two scenarios where the landmarks are represented by points and regions, respectively. For the latter scenario, we identify the motion patterns whose characterization cannot be clearly determined. In addition, we find that the knowledge of landmarks' convexity is useful for characterizing motion patterns.

Keywords. motion concepts, route descriptions, projection-based spatial models, Double Cross, RfDL, GUM, spatial ontology

Introduction

To model how ordinary people conceptualize motions in their living environments is essential for the development of the systems and machines that collaborate with those people on spatio-dynamic tasks, such as intelligent vehicles, mobile robots, and security monitoring systems, especially if they equip with natural language interfaces. Traditionally, many researchers have discussed a number of expressions and notions that people use for describing motions, such as *into*, *across*, and *over* [1-5], *past* and *along* [6, 7], and *turn before/after/at* [8]. This paper adds another speculation on such human concepts of motions with the aid of two spatial models—Double Cross [9, 10] and $RfDL_{3\text{-}12}$ [11]. These models can be used for illustrating where and how a landmark extends around/over a path and, accordingly, they may cover such expressions in behavioral descriptions as "*go toward*", "*pass … on the right*", "*go into*", and "*go across*". Indeed, based on the analysis of human route instructions to an intelligent semi-autonomous wheelchair in buildings [12], Krieg-Brückner and Shi [13] insist that Double Cross nicely captures the semantics of human route instructions in combination with *Route Graph* [14, 15]. Route Graph is a graph-based model of navigational knowledge that consists of landmarks, decision points, and route segments. These landmarks are conceptualized as points within the framework of Double Cross. On the

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other hand, the corpus in [16], which collects the route instructions given to a small robot traveling in a miniature town, observes the subjects' use of expressions that presume spatial extent of landmarks, such as "***follow** it **around***" and "*keep going until you hit **the end of** the train station*". This motivated us to develop a spatial model called $\mathsf{RfDL}_{3\text{-}12}$ [11], which captures the characteristics of spatial arrangements between a path and a region-like landmark using a similar framework.

The aim of this paper is to analyze the applicability of Double Cross and $\mathsf{RfDL}_{3\text{-}12}$ to model a number of human concepts of motions on a plane in a comparative way. In our previous work, we studied several concrete expressions in behavioral descriptions, such as *approach*, *go toward*, and *pass by* [11]. However, in natural dialogues, people use thousands of expressions for describing motions. Thus, in this work, we consider more generic concepts of motions that underlie such individual expressions. For instance, the expressions "*go across …*" and "*pass through …*", as well as "*gehen über …*" in German and "*…-wo toorinukeru*" in Japanese, are mapped to the same motion concept if their slight nuance is neglected. Such generalization is definitely useful to expand the coverage of our approach. For this purpose, we adopt the motion concepts defined in an existing spatial ontology, called *Generalized Upper Model extended with space components* (GUM) [17].

The remainder of this paper is organized as follows: Section 1 reviews Double Cross and $\mathsf{RfDL}_{3\text{-}12}$, highlighting their potential for characterizing motion patterns. Section 2 gives an overview of the ontological specifications of motion concepts defined in GUM. Sections 3 and 4 associate the motion concepts in GUM with the motion patterns modeled by Double Cross and $\mathsf{RfDL}_{3\text{-}12}$, respectively. Finally, Section 5 concludes with a discussion of future problems.

1. Double Cross and $\mathbf{RfDL}_{3\text{-}12}$

When an agent moves stepwise on a plane with the aid of landmarks, each step of movement is mapped to a spatial arrangement between a directed line (*DLine*) and another spatial object (a point, a line, or a region) in a two-dimensional Euclidean space $\mathbf{R}^2$. The DLine represents the *route segment* [14, 15] (i.e., the course of movement in each step), while the second object represents the landmark.

In the last two decades, a number of spatial models of DLine-object arrangements have been developed; for instance, Double Cross [9, 10] and Orientation Calculi [13] capture the directional and topological characteristics of DLine-point arrangements, the 9^+-intersection for DLine-region relations [18] captures the topological characteristics of DLine-region arrangements, and $\mathsf{RfDL}_{3\text{-}12}$ [11] captures the directional characteristics of DLine-region arrangements, as well as a certain degree of topological information (Section 4.2). Finally, Goyal and Egenhofer [19] discuss cardinal directions between arbitrary objects, which may include DLine-point, DLine-region, and DLine-line pairs.

The 9^+-intersection for DLine-region relations [18] illustrates where the DLine starts, passes, and ends with respect to the region's interior, boundary, and exterior. Accordingly, this model can be used for capturing such topology-relevant concepts as "*go into*" and "*go across*" [18]. However, if the DLine does not intersect with the region, any DLine-region arrangement is mapped to a single topological pattern (i.e., *disjoint* relation), even though people can distinguish such arrangements in more detail, describing them as "*go toward …*", "*pass … on the left*", "*go until … comes to the left*", and so forth. These expressions typically refer to the landmark's direction as seen from the route segment. This motivated us to examine the spatial models that emphasize the directional characteristics of DLine-object arrangements as a foundation for modeling human concepts of motions.

Typically, directional characteristics of spatial arrangements are captured with the aid of a *frame of spatial reference* [20]. The frame of spatial reference is projected onto the space with its center on one object (called *relatum*), such that the space around/on the relatum is partitioned into a set of *fields*. Then, the arrangement between the relatum and another object (called *referent*) is characterized by the field or the set of fields where the referent takes place. The frames of spatial reference are categorized into the following three types [20]:

- *absolute frame*, whose orientation is determined extrinsically by the environment (e.g., the frame of cardinal directions in [19]);
- *intrinsic frame*, whose orientation is determined by the intrinsic orientation of the relatum (typically represented by a DLine or a directed point); and
- *relative frame*, whose orientation is determined by the direction from the third object (*viewer*) to the relatum.

The models of spatial arrangements that adopt a frame of spatial reference is generally called *projection-based models* [21]. For modeling motion concepts, two types of projection-based models are potentially useful [22]. One is the projection-based models whose relatum is represented by a DLine (e.g., Double Cross [9, 10], Bipartite Arrangements [23], Orientation Calculi [13], and RfDL [11]). This type may illustrate where and how the landmark (referent) extends around/over the route segment (relatum). Thus, they can capture such mover-centric concepts as "*go toward*" and "*pass … on the right*". Another useful type is the projection-based models whose referent is represented by a point (e.g., Single Cross [9], Ternary Point Configuration Calculus [24]). This type may illustrate the relative location of the end-point of the route segment (referent) with respect to the landmark (relatum). Thus, they can capture such goal-oriented concepts as "*walk to the front of*" and "*go to the north of*". Note these concepts are essentially the combination of a motion verb and an expression of the goal location accompanied by a preposition "*to*", and the goal expression itself is static. On the other hand, the mover-centric concepts are motion-oriented by nature. This is why we focus on the first type of spatial models in this paper.

Double Cross [9, 10] is viewed as a projection-based model whose relatum and referent are represented by a DLine and a point, respectively [10]. It adopts a ‡-shaped intrinsic frame that distinguishes three fields on the DLine and twelve fields around it. We call the former three fields *En* (*entry*), *I* (*interior*), and *Ex* (*exit*), and the latter twelve fields *LB* (*left back*), *SB* (*straight back*), *RB* (*right back*), *LEn* (*left at entry*), *REn* (*right at entry*), *LI* (*left of interior*), *RI* (*right of interior*), *LEx* (*left at exit*), *REx* (*right at exit*), *LF* (*left front*), *SF* (*straight front*), and *RF* (*right front*) (Figure 1a). Naturally, Double Cross distinguishes fifteen patterns of DLine-point arrangements based on which field contains the point.

RfDL (*<u>R</u>egion-in-the-frame-of-<u>D</u>irected-<u>L</u>ine*) [11] is a series of projection-based models whose relatum and referent are represented by a DLine and a simple region, respectively. Simple regions are single-component regions without disconnected interior, holes, spikes, punctuating points, or cuts [25]. For simplification, simple regions are called *regions* from now. Following Orientation Calculi [13], RfDL considers eight types of intrinsic frames based on the combinatorial use/non-use of *left-right*, *front-side-back*, and *entry-interior-exit* distinctions with respect to the DLine (Figure 1b). Each frame partitions the space around/on the DLine into two to fifteen fields, including zero- and one-dimensional fields that fill the gap between two-dimensional ones. These eight frames naturally yield eight models with different levels of granularities, since the patterns of DLine-region arrangements are distinguished by the set of fields over which the region extends. Each model is called RfDL$_{m-n}$, where m/n indicates the number of fields on/around the DLine. The finest model RfDL$_{3-12}$ adopts a ‡-shaped intrinsic frame that distinguishes three fields on the DLine and twelve fields around the DLine. This frame is actually equivalent to the frame adopted by Double Cross (Figure 1a). As a result, RfDL$_{3-12}$ has a strong correspondence with Double Cross. Even though a region can take place more than one field, RfDL$_{3-12}$ distinguishes not $2^{3+12} = 32768$ patterns, but only 1772 patterns, due to the following two constraints:

- the region must extend over one or more two-dimensional fields; and
- the set of fields over which the region extends must be connected, even if *En* and *Ex* are removed from this set.

We also identified that RfDL$_{1-1}$, RfDL$_{1-4}$, RfDL$_{1-8}$, RfDL$_{1-12}$, RfDL$_{3-1}$, RfDL$_{3-4}$, and RfDL$_{3-8}$ distinguish 2, 23, 142, 479, 8, 92, and 520 patterns, respectively. Such coarser models are potentially useful for the prevention of overspecification, although it is out of the scope of this paper.

For simplification, patterns of DLine-point arrangements modeled by Double Cross are called *DC patterns*, while patterns of DLine-region arrangements modeled by RfDL$_{3-12}$ are called *RfDL$_{3-12}$ patterns*. Both DC patterns and RfDL$_{3-12}$ patterns are represented by icons with 3×5 cells (Figure 1c). The icons' fifteen cells geometrically correspond to the fifteen fields that each model considers. The marked cells indicate the fields over which the referent extends.

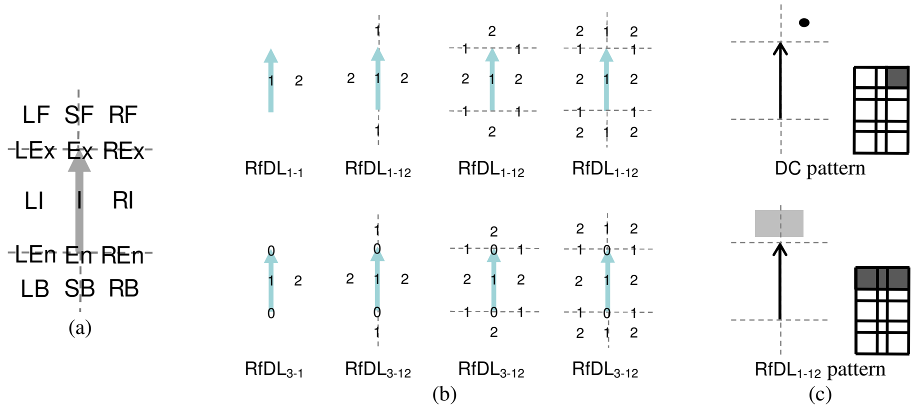


Figure 1. (a) Fifteen fields around/on a DLine that Double Cross and RfDL$_{3-12}$ consider. (b) Sets of fields that RfDL models consider, where the number assigned to each field indicates its dimension. (c) Iconic representations of spatial arrangements modeled by Double Cross and RfDL$_{3-12}$.

2. Conceptualization of Motions

A number of researchers in robotics have studied how people instruct mobile robots, in pursuit of natural dialogue-based interactions. They have often sought a small number of concepts that underlie the large diversity of expressions observed in their corpus [6, 17, 26]. Recently, based on a series of empirical studies, several ontological representations of natural space and spatial actions have been developed [17, 27]. The intermediate use of such ontological representations allows us to avoid the mapping from countless number of expressions to the domain model. Thus, in this work, we adopt the set of motion concepts specified in one of the existing spatial ontologies, called *Generalized Upper Model 3.0 extended with space components* (GUM) [17].

To conceptualize a route description that consists of a series of statements about successive actions to be taken, GUM provides a concept called Generalized Route. Generalized Route may contain representations of directional motions (e.g., *go toward the campus*), path representations (e.g., *pass the post office on the left*, *go along the tramway*), representations of goal-driven motions (e.g., *go to the red building*), and so forth. Table 1 summarizes the GUM's specifications relevant to motions. The representations of directional motions are covered by General Directional Destination/Source, the path representations are covered by Path Representing External Indication/Placement, and the representations of goal-driven motions are covered by Containment Destination. Note that the motion concepts in Table 1 do not strictly follow the original notations in GUM, but are reorganized by the authors such that the motion-relevant aspect of each concept is emphasized.

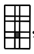
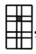
The concepts in Table 1 belong to two more generic concepts in GUM; one is Relative Spatial Modality, which denotes the position of a remote landmark (e.g., *pass the park on the right*), and another is Functional Spatial Modality, which specifies the interaction between a route segment and a landmark (e.g., *go into the park*). In the former concept, the landmark's direction as seen from the route segment becomes critical information for characterizing the motion. For such characterization, we can use the concepts for specifying the landmark's directions, such as Cardinal Directional and Projective Relations (including Vertical Projection and Horizontal Projection). Since we are considering planar movement, Horizontal Projection can be particularly used together with General Directional Destination (e.g., *go until the post office comes to the right*) and Path Representing External Indication (e.g., *pass the park on the right*).

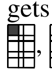
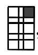
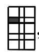
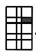
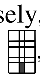
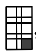
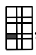
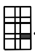
Table 1. GUM's specifications relevant to motions.

GUM Specification	Characterizing Factors	Examples	Applicability to Landmarks Modeled by: Points	Applicability to Landmarks Modeled by: Regions
General Directional Destination	directional relation to a landmark on the end-point side	*go toward the bus stop* *approach the park*	√	√
General Directional Source	directional relation to a landmark on the start-point side	*go away from the bus stop*	√	√
Path Representing External Indication	an approach to a landmark at a midway point	*pass the bus stop* *go by the park*	√	√
Path Representing External Placement	constant distance to a landmark during the movement	*go along the park*		√
Containment Destination	the end-point located in the landmark	*go to the bus stop* *go into the park*	√	√
Containment Source	the start-point located in the landmark	*leave the bus stop* *go out of the park*	√	√
Path Representing Internal Indication	the route segment located (partially) in the landmark	*go via the bus stop* *go across the park*	√	√
Parthood	the route segment located completely in the landmark	*walk in the park*		√

3. Motion Concepts Referring to Point-Like Landmarks

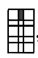
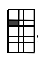
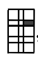
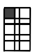
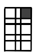
This and the next sections explore the association between motion concepts in GUM and motion patterns modeled by Double Cross and $RfDL_{3\text{-}12}$. We start from the simple scenario where the landmark is represented by a point. Suppose that the route segment and the landmark are mapped to a DLine $\overrightarrow{ab}$ and a point p, respectively. Then, the motion pattern is mapped to a DC pattern $\overrightarrow{ab} : p$. It is assumed that the distance between $\overrightarrow{ab}$ and p is small whenever a DC pattern holds between them.

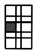
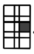
If the route segment intersects with the point-like landmark (i.e., $p \in \overrightarrow{ab}$), a key factor for characterizing the motion is the part of the route segment that intersects with the landmark. In GUM, Containment Source (e.g., *leave*) refers to a motion pattern that starts from a landmark, Containment Destination (e.g., *go to*) refers to a motion pattern that ends at a landmark, and Path Representing Internal Indication (e.g., *go via*) refers to a motion pattern that passes through a landmark. The spatial contexts of these three motion concepts are mapped to DC patterns , , and , respectively.

If the route segment does not intersect with the point-like landmark (i.e., $p \notin \overrightarrow{ab}$), there are several strategies to characterize the motion patterns. For instance, we can refer to the direction of the route segment's end-point with respect to the landmark (e.g., *go to the front of*), even though DC patterns do not capture this information. Instead, DC patterns may indicate whether the moving agent gets closer to or farther from the landmark during the movement. For instance, General Directional Destination (e.g., *approach*), which refer to the motion patterns where the agent gets closer to the landmark during the movement, corresponds to five DC patterns , , , , and . Conversely, General Directional Source (e.g., *go away from*) corresponds to five DC patterns , , , , and .

In natural dialogues, people may distinguish *approaching* motion patterns in more detail, using such expressions as "*go toward the bus stop*" and "*go until the bus stop comes to the left*". We, therefore, introduce the following sub-concepts of General Directional Destination:

- General Directional Destination Front, which refers to a motion pattern where the front extension of the route segment penetrates the landmark (e.g., *go toward*);
- General Directional Destination Left, which refers to a motion pattern where the line that orthogonally passes through the route segment's end-point intersects with the landmark only on the left side of the route segment (e.g., *go until … comes to the left*);
- General Directional Destination Right;
- General Directional Destination Left-Front, where the landmark is located entirely or *mostly* at the left front of the route segment's end-point (e.g., *approach … on the left front*); and
- General Directional Destination Right-Front.

The spatial context of these five sub-concepts are mapped to the DC patterns , , , , and , respectively. Precisely speaking, these five sub-concepts are the combinations of General Directional Destination and Horizontal Projection. In a similar way, five sub-concepts of General Directional Source are defined.

Another motion concept that DC patterns may capture is Path Representing External Indication (e.g., *go by*). This concept refers to a motion pattern where the moving agent approaches the landmark at a midway point on the route segment—in other words, the agent gets closer to the landmark and then farther from it before arriving at the end-point. Such motion patterns are mapped to two DC patterns  and . Naturally, two sub-concepts of Path Representing External Indication, namely Path Representing External Indication Left and Path Representing External Indication Right (e.g., *go by … on the left/right*), are distinguished based on which side of the route segment the agent approaches the landmark.

In this way, General Directional Destination, General Directional Source, and Path Representing External Indication, as well as their sub-concepts, are assigned distinctively to the fifteen fields that Double Cross considers (Figure 2).

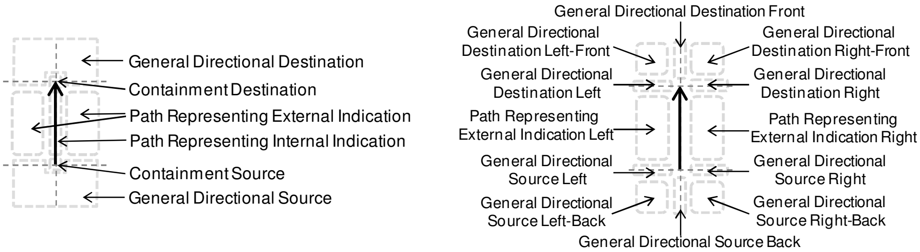
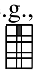
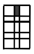


Figure 2. Motion concepts assigned to the fifteen fields that Double Cross considers.

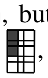
4. Motion Concepts Referring to Region-Like Landmarks

Next, we consider the scenario where the landmark is represented by a simple region. Suppose that the route segment and the landmark are mapped to a DLine $\overrightarrow{ab}$ and a simple region *R*, respectively. Then, the motion pattern is mapped to an $\text{RfDL}_{3\text{-}12}$ pattern $\overrightarrow{ab}:R$. It is assumed that the distance between $\overrightarrow{ab}$ and *R* is small whenever an $\text{RfDL}_{3\text{-}12}$ pattern holds between them. We take a similar approach as before, but we have to care about the difference between region-like landmarks and point-like landmarks. For instance, let us consider General Directional Destination Front (e.g., *go toward*). When the landmark is represented by a point, only one DC pattern  is mapped to this concept. On the other hand, when the landmark is represented by a region, multiple $\text{RfDL}_{3\text{-}12}$ patterns, such as , , and , are mapped to this concept, but  is not (because it cannot be an $\text{RfDL}_{3\text{-}12}$ pattern). Like this example, each concept corresponds to a set of $\text{RfDL}_{3\text{-}12}$ patterns, which are determined by the specific conditions identified in the following discussion.

4.1. Disjoint Patterns

We first focus on the motion patterns where the route segment does not intersect with the region-like landmark (i.e., $\overrightarrow{ab} \cap R = \phi$). Such *disjoint* motion patterns are mapped to 127 of 1772 $\text{RfDL}_{3\text{-}12}$ patterns. These patterns are associated with the same set of motion concepts as the disjoint DLine-point patterns; that is, General Directional

Destination, General Directional Source, Path Representing External Indication, and their sub-concepts.

General Directional Destination refers to a motion pattern where the moving agent gets closer to the landmark (e.g., *approach*). This time, however, it is not always possible to decide clearly whether a given motion pattern fits with this concept or not. For instance, the motion pattern in Figure 3b probably fits with the concept of General Directional Destination, but Figure 3c does not, although they are represented by the same $RfDL_{3\text{-}12}$ pattern , and obviously there are a variety of in-between patterns whose characterization is difficult. On the other hand, we can clearly say that the motion pattern in Figure 3a fits with General Directional Destination, because the distance between the moving agent and every point in the region-like landmark decreases monotonically during the movement. Also, it is clear that the motion patterns in Figures 3d-e cannot fit with General Directional Destination, because the region-like landmark has no point inside to which the distance from the moving agent decreases monotonically during the movement. From this observation, we derived the following two conditions:

- SC_{GDD} (strong condition of General Directional Destination)—the motion pattern is mapped to $\overrightarrow{ab}:R$ where the region R extends at least one field among $\overrightarrow{ab}$'s *SF*, *LF*, *RF*, *LEx*, or *REx*, but no other field, and;
- WC_{GDD} (weak condition of General Directional Destination)—the motion pattern is mapped to $\overrightarrow{ab}:R$ where the region 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 motion pattern satisfies the strong condition SC_{GDD}, then this pattern always fits with General Directional Destination (Figure 3a). On the other hand, if a motion pattern does not satisfy the weak condition WC_{GDD}, then this pattern does not fit with General Directional Destination (Figure 3d-e). Note that if a motion pattern satisfies the strong condition SC_{GDD}, then this pattern also satisfies the weak condition WC_{GDD} (and this is why they are named *strong* and *weak* conditions). Note also that the weak condition WC_{GDD} includes the condition "*R* extends neither *En*, *I*, nor *En*", which comes from this section's presumption $\overrightarrow{ab} \cap R = \phi$.

If a motion pattern satisfies the weak condition WC_{GDD}, but not the strong condition SC_{GDD}, then this motion pattern *may* or *may not* fit with General Directional Destination (Figures 3b-c). In such a case, we need further criteria to judge whether (or *how much*) the motion pattern fits with General Directional Destination; for instance, the relative area of the landmark in which the distance between arbitrary point and the moving agent decreases monotonically during the movement, or the relative length of period during which the nearest distance between the moving agent and the region-like landmark decreases can be used as the criteria of this evaluation.

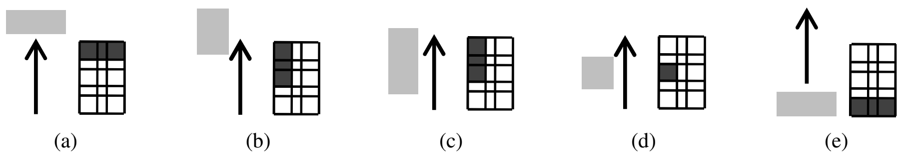


Figure 3. (a-b) Motion patterns that fit with the concept of General Directional Destination and (c-e) those that do not, together with the $RfDL_{3\text{-}12}$ patterns that represent these motion patterns.

In a similar way, we developed the strong and weak conditions of the five sub-concepts of General Directional Destination following their definitions in Section 3. For instance, SC_{GDDF} (strong condition of General Directional Destination Front) was derived as the combination of SC_{GDD} (strong condition of General Directional Destination) and the additional condition of General Directional Destination Front—*the front extension of the route segment penetrates the landmark* (Section 3). Similarly, WC_{GDDF} (weak condition of General Directional Destination Front) is derived as the combination of WC_{GDD} and the same additional condition of General Directional Destination Front.

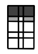
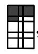
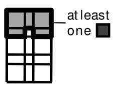
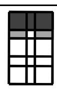
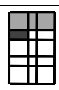
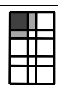
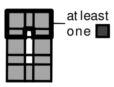
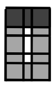
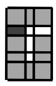
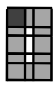
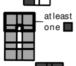
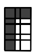
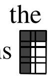
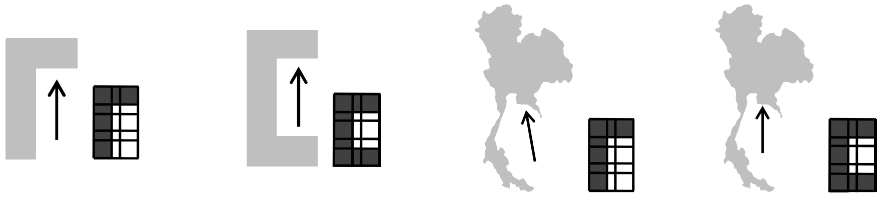
The developed conditions are summarized in Table 2. The conditions are represented visually by icons with 3×5 cells. Just like the icons of $RfDL_{3\text{-}12}$ patterns, the icons' fifteen cells correspond to the fifteen fields that $RfDL_{3\text{-}12}$ considers, but at this time they have three colors; black, gray, and white cells indicate the fields over which the region must, may, and cannot extend. For instance, the condition icon  indicates that the region must extend over *LF*, *SF*, *RF*, may extend over *LEx* or *REx*, but cannot extend over all other fields. This condition is satisfied by four $RfDL_{3\text{-}12}$ patterns , , , and . As this example indicates, there are visual correspondence between each condition icon and the icons of $RfDL_{3\text{-}12}$ patterns that satisfy this condition.

Table 2. Strong and weak conditions of General Directional Destination and its sub-concepts, together with the numbers of $RfDL_{3\text{-}12}$ patterns that satisfy each condition without/with the region's convexity assumption.

	General Directional Destination	General Directional Destination Front	General Directional Destination Left	General Directional Destination Left-Front
Strong Condition	 12, 11	 4, 3	 3, 3	 4, 4
Weak Condition	 102, 43	 46, 9	 31, 19	 67, 21

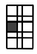
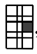
The strong conditions in Table 2 look intuitive, as the icons visualize the images of prototypical path-landmark arrangements that fit with each motion concept. On the other hand, the weak conditions in Table 2 may not look straightforward. For instance, $RfDL_{3\text{-}12}$ patterns  and  satisfy the weak condition of General Directional Destination (i.e., ), but the motion patterns in Figures 4a-b, which are 'typical' instances of  and , do not fit nicely with General Directional Destination (i.e., it is difficult to say that they are *approaching* patterns). On the other hand, the motion patterns in Figures 4c-d, which also correspond to the same $RfDL_{3\text{-}12}$ patterns  and , probably fit nicely with General Directional Destination, because the moving agent gets closer to the most/principal part of Thailand. Like this example, the weak condition of each concept covers *all* $RfDL_{3\text{-}12}$ patterns whose instantial motion patterns may fit with each concept and, as a result, the condition may look not straightforward.

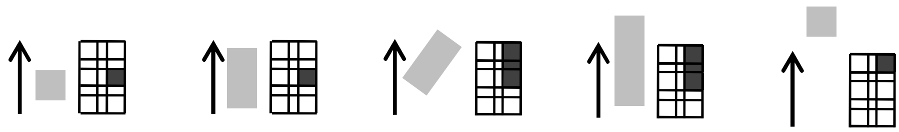


(a) (b) (c) (d)

Figure 4. Motion patterns that satisfy the weak condition of General Directional Destination, together with the $RfDL_{3\text{-}12}$ patterns that represent these motion patterns.

The second concept, General Directional Source, is the direct opposite of General Directional Destination. Consequently, the sufficient and weak conditions for General Directional Source and its five sub-concepts are derived from Table 2, simply by flipping the icon vertically.

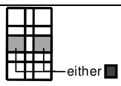
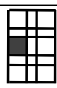
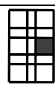
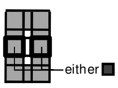
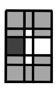
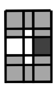
The third concept, Path Representing External Indication, refers to a motion pattern where the moving agent approaches the landmark at a midway point of the route segment (e.g., *go by*). If a motion pattern is mapped to an $RfDL_{3\text{-}12}$ relation  or , this pattern always fits with this concept, because the moving agent gets closer to every point in the region-like landmark and then farther from it (Figures 5a-b). Conversely, if a motion pattern is mapped to an $RfDL_{3\text{-}12}$ pattern where the region extends over neither *LI* nor *RI*, this pattern never fits with Path Representing External Indication (Figure 5e). Otherwise, we need further criteria to judge whether or how much the motion pattern fits with Path Representing External Indication (Figures 5c-d). Based on this observation, the strong and weak conditions of Path Representing External Indication, as well as those of its two sub-concepts, are developed (Table 3).



(a) (b) (c) (d) (e)

Figure 5. (a-c) Motion patterns that fit with the concept of Path Representing External Indication and (d-e) those that do not, together with the $RfDL_{3\text{-}12}$ patterns that represent these motion patterns.

Table 3. Strong conditions of Path Representing External Indication and its two sub-concepts, together with the numbers of $RfDL_{3\text{-}12}$ patterns that satisfy each condition without/with the region's convexity assumption.

	Path Representing External Indication	Path Representing External Indication Left	Path Representing External Indication Right
Strong Condition	 2, 2	 1, 1	 1, 1
Weak Condition	 72, 42	 36, 21	 36, 21

Tables 2-3 show the numbers of RfDL$_{3\text{-}12}$ patterns that satisfy each condition, as well as the number of those patterns if the region is convex. Since many region-like landmarks in the real world are represented by convex regions, such assumption is often meaningful. We found that the number of RfDL$_{3\text{-}12}$ patterns that satisfy each weak condition is large. This stems from the fundamental ambiguity of region-like landmarks, which may take countless shapes. However, if the region is convex, the number of RfDL$_{3\text{-}12}$ patterns that satisfy the weak condition of each concept drastically decreases and becomes closer to the number of RfDL$_{3\text{-}12}$ patterns that satisfy the strong condition. This indicates that the knowledge of the landmark's convexity is helpful to judge the directional characteristics of motion patterns.

4.2. Non-Disjoint Patterns

Next, we focus on the motion patterns where the route segment intersects with the region-like landmark (i.e., $\overrightarrow{ab} \cap R \neq \phi$), which are mapped to 1645 of 1772 RfDL$_{3\text{-}12}$ patterns. A key factor for characterizing such motion patterns is topological information; i.e., how the route segment intersects with the region. Thus, we consider three topological categories, Cross, Within, and Touch, following OpenGIS's classification of topological line-region relation [28].

4.2.1. Cross

According to OpenGIS's definition [28], "*a line crosses a region*" refers to a configuration where the line's interior intersects with both the interior and exterior of the region. Motion patterns where the route segment *crosses* the region-like landmark are associated with three concepts in GUM: Containment Destination, Containment Source, and Path Representing Internal Indication (Figure 6). These three concepts correspond to such expressions as "*go into*", "*go out of*" and "*go across*", respectively. In addition, if the landmark's spatial extent is not significant, these three concepts may be associated with such expressions as "*go to*", "*leave*" and "*go via*", respectively.

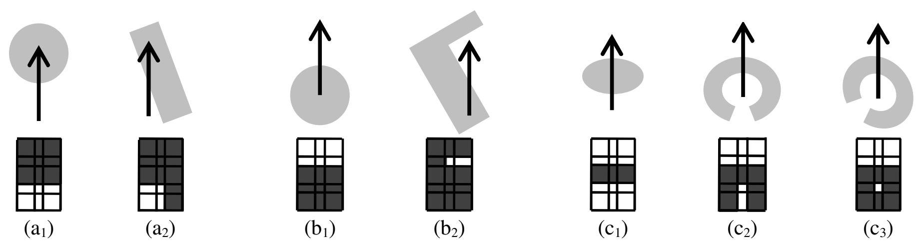


Figure 6. Motion patterns that fit with (a$_{1\text{-}2}$) Containment Destination, (b$_{1\text{-}2}$) Containment Source, and (c$_{1\text{-}3}$) Path Representing Internal Indication, together with the RfDL$_{3\text{-}12}$ patterns that represent these motion patterns.

Table 4 shows the strong and weak conditions of Containment Destination, Containment Source, and Path Representing Internal Indication. The strong condition of Containment Destination requires the region's convexity, because unless the region is convex, RfDL$_{3\text{-}12}$ patterns cannot guarantee that the DLine ends at the region's interior even if the region extends over *Ex* and all fields around it (compare Figure 6a$_1$ with Figure 8d$_2$). For the same reason, the strong condition of Containment Destination Source requires the region's convexity. On the other hand, the strong condition of Path

Representing Internal Indication does not require the region's convexity, because we can guarantee that the DLine goes across the region when the region extends over *LI*, *I*, and *RI*, but not all field around *En* and not all field around *Ex* (compare Figure 6c_2 with Figure 8b_2).

4.2.2. Within

In [28], "*a line is within a region*" means that the line intersects with the region's interior, but not its exterior. In GUM, the concept of Parthood, which corresponds to such expressions as "*walk in the park*", refers to a motion pattern where the route segment *goes within* a region-like landmark (Figures 7a-d). Even though GUM has no refinement of Parthood, Figures 7a-d implies that we can topologically distinguish at least four sub-concepts of Parthood, based on whether the route segment starts from and ends at the landmark's interior or boundary. The strong and weak conditions of Parthood are shown in Table 4. The strong condition requires the region's convexity, because unless the region is convex, $RfDL_{3\text{-}12}$ patterns cannot guarantee that the DLine's interior does not intersect with the region's exterior, even if the region extends over the DLine's *LI*, *I*, *RI*, *En*, and *Ex* (compare Figure 7a with Figure 7e).

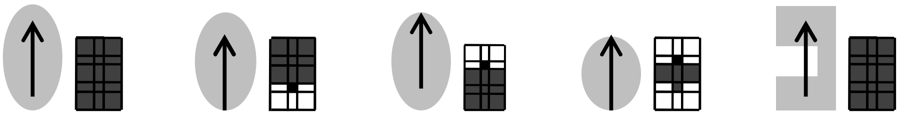
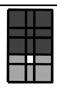
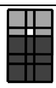
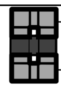
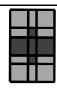
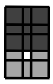
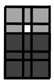
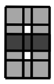
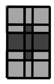


Figure 7. (a-d) Motion patterns that fit with the concept of Parthood and (e) the pattern that does not, together with the $RfDL_{3\text{-}12}$ patterns that represent these motion patterns.

Table 4. Strong and weak conditions of Containment Destination, Containment Source, Path Representing Internal Indication, and Parthood, together with the numbers of $RfDL_{3\text{-}12}$ patterns that satisfy each condition without/with the region's convexity assumption.

	Containment Destination	Containment Source	Path Representing Internal Indication	Parthood
Strong Condition	 & Region's convexity –, 5	 & Region's convexity –, 5	 not all ■ / not all ■ 225, 25	 & Region's convexity –, 169
Weak Condition	 16, 5	 16, 5	 256, 25	 256, 169

4.2.3. Touch

In [28], "*a line touches with a region*" means that the line intersects with the region's boundary, but not its interior. We found that the current version of GUM has no specification that exactly refers to a motion pattern where the route segment *touches* the region-like landmark. Thus, here we discuss the concept of Touch and its sub-concepts apart from GUM. As shown in Figure 8, we can topologically distinguish three sub-concepts of Touch—Touch at Entry, Touch at Interior, and Touch at Exit—which refer to the motion patterns where the route segment touches the region-like landmark only at its start point, interior, and end-point, respectively. The strong and weak conditions of Touch and its three sub-concepts are shown in Table 5. Interestingly, Touch at Entry has a strong condition only, because we can guarantee that the DLine touches the region only at its start-point whenever the region extends over *En*, but neither *I* nor *Ex*, and vice versa. Similarly, Touch at Exit has a strong condition only. On the other hand, Touch at interior has both strong and weak conditions, because we cannot guarantee that the DLine touches the region when the region extends over *LI*, *I*, and *RI*, in addition to all fields around *En* or *Ex* (compare Figures $8b_2$ with Figure $6c_3$). Similarly, Touch has both strong and weak conditions, since Touch is a superclass of Touch at interior.

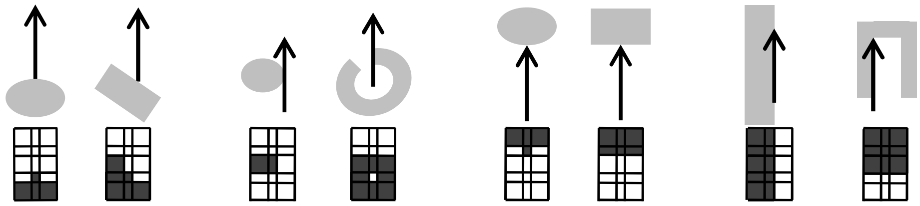
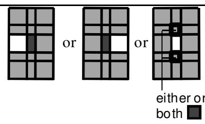
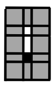
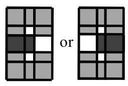
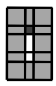
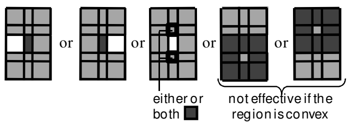
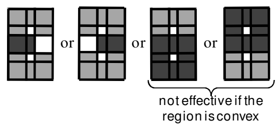


Figure 8. Motion patterns that fit with the concept of Touch, as well as ($a_{1\text{-}2}$) Touch at Entry, ($b_{1\text{-}2}$) Touch at Interior, and ($c_{1\text{-}2}$) Touch at Exit, together with the $RfDL_{3\text{-}12}$ patterns that represent these motion patterns.

Table 5. Strong and weak conditions of Touch and its sub-concepts, together with the numbers of $RfDL_{3\text{-}12}$ patterns that satisfy each condition without/with the region's convexity assumption.

	Touch	Touch at Entry	Touch at Interior	Touch at Exit
Strong Condition	 621, 250	 115, 48	 72, 18	 115, 48
Weak Condition	 745, 250	Same as above	 103, 18	Same as above

4.2.4. Comparison

In Sections 4.2.1-4.2.3, we observed that $RfDL_{3\text{-}12}$ patterns capture a certain degree of topological information, even though $RfDL_{3\text{-}12}$'s frame of reference primarily highlights directional distinctions. Interestingly, Tables 4-5 show that under the region's convexity assumption the number of $RfDL_{3\text{-}12}$ patterns that satisfy the strong condition of each concept is always same with the number of $RfDL_{3\text{-}12}$ patterns that satisfy the weak condition of the same concept. Consequently, when the landmark is represented by a convex region, we can map a given motion pattern to topology-relevant motion concepts without ambiguity. This indicates that the knowledge of the region's convexity is highly helpful to judge the topological characteristics of motion patterns, in addition to the directional characteristics of motion patterns (Section 3).

5. Conclusions and Future Work

To model human concept of motions is an effective approach to enrich the communication between people and computers/machines collaborating on spatio-dynamic tasks. The previous analyses on human instructions to an intelligent semi-autonomous wheelchairs [12] or mobile robots [16] observed many expressions that refer to landmarks, specifying their direction or their intersection with the route. Thus, based on Double Cross and its new counterpart for DLine-region arrangements, $RfDL_{3-12}$, this paper explored the modeling of a number of motion concepts that stand on a mover-centric viewpoint. When the landmarks are represented by points, the motion concepts were associated distinctively with the motion patterns modeled by Double Cross. On the other hand, when the landmarks are represented by region, the correspondence between the motion concepts and the motion patterns modeled by $RfDL_{3-12}$ had certain ambiguity, even though under the region's convexity assumption topology-related concepts were clearly associated with the motion patterns. In order to decide the appropriate characterization of ambiguous motion patterns, we may need further criteria other than $RfDL_{3-12}$ patterns, which are left for future work. This paper also demonstrated that the specification in GUM, as an upper model, is very useful to capture a number of motion concepts in a generic and domain-independent way.

We are currently investigating to apply our findings to the interface of an intelligent semi-autonomous wheelchair *Rolland* [29], such that elderly or impaired people can intuitively control the wheelchair through natural dialogue. Even though Double Cross and $RfDL_{3-12}$ cover lots of motion concepts, we still need other spatial models that feature different aspects of spatial contexts, in order to cover a wide variety of concepts used in route instructions. For instance, to cover the concepts of goal-oriented motions (e.g., *go to the front of*, *go behind*), we need a projection-based model whose referent is a point (Section 1). To model the remaining motion concepts by additional spatial models and to realize the comprehensive use of multiple spatial models for the interpretation of behavioral descriptions is left for future work.

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