An Improved Direction Relation Detection Model for Spatial Objects

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ABSTRACT  Direction is a common spatial concept that is used in our daily life. It is frequently used as a selection condition in spatial queries. As a result, it is important for spatial databases to provide a mechanism for modeling and processing direction queries and reasoning. Depending on the direction relation matrix, an inverted direction relation matrix and the concept of direction pre-dominance are proposed to improve the detection of direction relation between objects. Direction predicates of spatial systems are also extended. These techniques can improve the veracity of direction queries and reasoning. Experiments show excellent efficiency and performance in view of direction queries.

KEYWORDS  spatial databases; geographic information systems; direction relations; direction relation matrix

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Introduction

Direction is an important spatial concept that is used in many fields such as geographic information systems (GIS) and image interpretation. It is also frequently used as a selection condition in spatial queries. This paper describes detection model of direction relations in spatial database management systems (DBMSs) and geographic information systems. Direction relations describe order in space and constitute an important class of user queries. Despite their importance, direction queries have not been studied extensively in spatial databases. The main reason for this is the lack of well-defined direction relations between actual objects.

In Geography, for example, although the linguistic terms used to describe the direction relation between some pairs of countries are undisputed, this is not always the case. Consider the query “find all provinces east to Hubei province”. Should Jiangsu province belong to the result? The answer to the query depends on the definition of direction relations that may vary for each application. In this paper we define an improved direction relations between two-dimensional objects in different levels of qualitative resolution to match the application needs. Our work extends previous attempts to formalize direction relations, which have concentrated on minimum bounding rectangles.[1,2] Then we show how the relations that we defined can be efficiently used to detect the direction relation in spatial DBMSs. Essentially we compare the efficiency of direction predominance methods on directional detection in the context of GIS applications. The results of this paper are directly applicable to Spatial Databases and GIS where the formalization of spatial relations is crucial for user interfaces.

1 Related Work

There are some important requirements needed
to research direction relationship between spatial objects. One is to satisfy the integrality of spatial relationship. Topological relations, metric relations and direction relations are basic spatial relations. It is difficult to execute spatial direction query without direction relations. Another reason is that previous work has modeled direction as a relational predicate between spatial objects\(^1\). But little work has been done in commercial GIS products. This awkward phase limited the application ranges of GIS.

The determination of direction relations is a trivial task for points in space. Only a comparison of the coordinate values has to be done. Other types of spatial objects like lines or regions, however, require a more sophisticated approach due to the complex spatial extent of those objects. Traditional direction model includes cone-shaped model and minimum bounding rectangle model\(^2\). The cone-shaped model presented in Reference \(^3\) determines direction relations for polygons in the plane. The method considers the four cardinal directions as well as diagonal directions, i.e. the eight directions; north, northeast, east, southeast, south, southwest, west, and northwest. For the minimum bounding rectangle (MBR) model\(^4\), a set of primitive direction relations for points are defined. Based on these relations, further relations for points can be derived. The minimum bounding rectangle model is used more widely in research fields\(^5\).

The general properties of direction relations include: ① Direction relations are binary relationships. Two and only two objects are involved in a single relationship, ② Each direction is semantic symmetry. That is to say, if object A is north to object B, then B is south to A. However, there are situations where neither a relationship nor its semantic inverse holds. Direction relations need more precision model to describe these relations. In most proposed model, M. Egenhofer proposed a model using direction-relation matrix to handle direction relations\(^6\). An improved deep direction relation matrix model is also researched. A further research along the line is to use the model in spatial index and query optimization\(^6\). Another novel proposed model is to describe direction as an abstract data type (ADT)\(^7\), which has formalization definition. Chang et al. designed 2D strings for iconic indexing in image databases\(^8\). A 2D string is a pair of one-dimensional strings that represent the symbolic projections of the objects on the x and y-axis. References \(^8\) and \(^9\) used 2D string to analyze spatial topology and direction relations\(^8\). All these models could not handle precision direction relations and paid little attentions on dynamic direction relations in spatio-temporal systems\(^10\).

2 Direction Relation Model

2.1 Direction relation matrix

The direction relation matrix of two polygons A and B is a \(3 \times 3\) matrix. The matrix has the following formula:

\[
\begin{pmatrix}
NW_A \cap B & N_A \cap B & NE_A \cap B \\
W_A \cap B & O_A \cap B & E_A \cap B \\
SW_A \cap B & S_A \cap B & SE_A \cap B
\end{pmatrix}
\]

where objects A and B are called as reference object and target object, respectively\(^5\). Basic directions \{NW, N, NE, E, SE, S, SW, W, O\} are nine plane areas partitioned by MBR of reference object, elements of the matrix are intersection between target object and partitioned area (in our model, we use 0 to denote empty intersection, and 1 otherwise).

When only one element in the matrix is non-empty, we call it single-item direction relations, and otherwise, it was called as multi-items direction relations\(^1\). The direction relation matrix can describe eight conventional directions in single-item direction relations; NW (northwest), N (north), NE (northeast), E (east), SE (southeast), S (south), SW (southwest) and W (west). However, it cannot give detailed direction between objects for the same direction and multi-items direction relations. Examples are shown in Fig. 1 and Fig. 2. In Fig. 1, direction relation matrix
shows Taiwan has the same direction to the mainland of China; this does not accord with the states that Taiwan is in the southeast of China. The same problem shown in Fig. 2, where object $B_1$ is surrounded by object $A$.

![Fig. 1 Non-conventional single-item direction relations](image1)

Fig. 1 Non-conventional single-item direction relations

![Fig. 2 Complex multi-items direction relations](image2)

Fig. 2 Complex multi-items direction relations

## 2.2 Inverted direction relation matrix

The detection of direction based on direction relation matrix only concentrates on the MBR of reference object. As we depicted, direction relation should consider semantic symmetry between objects. That is to say, we should consider the shape of target object to get precision direction. This need the inverted direction relation matrix. The matrix has the same formulation as that of direction relation matrix; the only difference is the exchanged role of reference object and target object.

The inverted direction relation matrix is a complementarity to direction relation matrix; it can provide more precision directional information because of the consideration of semantic symmetry. For instance, from Fig. 1(b), we may conclude that Taiwan does not have the same direction to the mainland of China. Fig. 3 also indicates $B_1, B_2$ and $B_3$ do not have the same direction to reference object $A$, it is reasonable to say object $B_1$ is surrounded by $A$, but object $B_2$ is still has multi-items direction relations to object $A$.

![Fig. 3 Direction and inverted direction relation matrix of Fig. 2](image3)

Fig. 3 Direction and inverted direction relation matrix of Fig. 2

As a result, both inverted direction relation matrix and direction relation matrix can not determine unique direction between two objects. While considering some similar direction relation, the problem is more evident. Fig. 4 shows that Fig. 4(b) and Fig. 4(c) have the same multi-items direction relation matrix, while intuition shows Fig. 4(a) is more similar to Fig. 4(b). To distinguish this kind of detailed differences, we use a strategy of direction predominance, which is based on metric direction relation matrix. In metric direction relation matrix, each element is the percentage of intersection between reference object and target object under some metric functions (Fig. 5). For polygons, the function is area function, and for line object, it is length function.

![Fig. 4 Similar direction relations](image4)

Fig. 4 Similar direction relations

![Fig. 5 Metric direction relation matrix](image5)

Fig. 5 Metric direction relation matrix

In the metric relation direction matrix, if the value of one element is greater than the other elements, the target object has predominance in that direction to the reference object. Direction dominance may determine direction relations. In
practice, given some critical value, if the maximum value of metric relation direction matrix is greater than the critical value, then it determines the precision direction relation. Usually, the critical value may be between 0.5 and 1. Fig. 6 shows the case of Fig. 4 (b) and Fig. 4 (c). Fig. 6(a) indicates that object B is northeast to A, while Fig. 6(b) indicates that B is north predominance to A.

\[
\begin{bmatrix}
0 & 0.1 & 0.9 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\quad \begin{bmatrix}
0 & 0.55 & 0.45 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

(a) \hspace{1cm} (b)

Fig. 6 Metric relation matrix of direction predominance

3 Predicate extensions of direction relations

In this section, we give predicate extensions of direction relations for spatial objects.

In direction relation matrix, if there is at most three zero elements in the same row and column except the second row and second column, other elements are non-zero; the relation is called surround relation. Thirteen kinds of surround relations are shown in Fig. 7, where the symbol "#" indicates undetermined values.

If the surrounding relation is determined, then we can determine the same relation, and then other relations can be easily determined. In basic direction relations, the cardinal directions such as E, S, W and N have the same semantic, and the diagonal directions such as NE, SE, SW and NW have the same semantic. The direction predicates are shown in Table 1. In Table 1, the predicates surrounding and surrounded by are extended predicates, and the symbol "1 * " indicates the direction predominance, and "not surround" shows that the matrix is not equal to one of surround relation matrixes. For example, if East(A, B) is to be determined with direction predominance, the surround relation must be

\[
\begin{bmatrix}
1 & 1 & 1 \\
1 & # & 1 \\
0 & 0 & 0
\end{bmatrix}
\quad \begin{bmatrix}
1 & 1 & 1 \\
1 & # & 1 \\
0 & 1 & 1
\end{bmatrix}
\quad \begin{bmatrix}
0 & 0 & 0 \\
1 & 1 & 1 \\
1 & 1 & 1
\end{bmatrix}
\quad \begin{bmatrix}
1 & 1 & 0 \\
1 & 1 & 0 \\
1 & 1 & 1
\end{bmatrix}
\quad \begin{bmatrix}
1 & 1 & 0 \\
1 & 1 & 0 \\
1 & 1 & 1
\end{bmatrix}
\quad \begin{bmatrix}
1 & # & 1 \\
1 & # & 1 \\
1 & # & 1
\end{bmatrix}
\quad \begin{bmatrix}
0 & 1 & 1 \\
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\end{bmatrix}
\quad \begin{bmatrix}
1 & 1 & 1 \\
1 & 1 & 1 \\
1 & 1 & 1
\end{bmatrix}
\quad \begin{bmatrix}
1 & 1 & 1 \\
1 & 1 & 1 \\
1 & 1 & 1
\end{bmatrix}
\]

Fig. 7 Surround relation matrix

Table 1 Direction relation matrix

| Direction relation matrix | Inverted direction matrix | Notes | Examples |
|---------------------------|--------------------------|-------|----------|
| East(A, B)                | $\text{dir}=(0,0,0,0,0,0)$ |       | ![East(A, B) example](image) |
| Same(A, B)                | $\text{dir}=(0,0,0,0,0)$ |       | ![Same(A, B) example](image) |
| Northeast (A, B)          | $\text{dir}=(0,0,0,0,0)$ |       | ![Northeast(A, B) example](image) |
| Surrounded by (A, B)      | $\text{dir}=(0,0,0,0,0)$ |       | ![Surrounded by (A, B) example](image) |
| Surrounding (A, B)        | $\text{dir}=(0,0,0,0,0)$ |       | ![Surrounding (A, B) example](image) |
eliminated firstly, then we may use either direction relation matrix or both direction and inverted relation matrixes to get exact relation. This is dependent on applications.

4 Experiments

In the previous sections we have argued that the inverted direction relation matrix and direction predominance matrix can give more precision information for direction detection. In this section we present several experimental results that justify our argument. The main intention of the experiment is to compare the conventional direction query and predominance direction query. The experimental data is the province districts of China. The direction query is "finding all provinces and cities east to Hubei province and no more than 500 km away". The results are illustrated in Fig. 8, Table 2, Fig. 9 and Fig. 10.

From the results, it is evident that the direction predominance strategy can give more reasonable query results. Fig. 8 and Table 2 show the conventional direction query, and six results are obtained. From the results, it is evident that it is not accord with conventional intuition that Jiangxi province is east to Hubei province. Using direction predominance strategy, Fig. 9 and Fig. 10 indicates that Jiangxi and Jiangsu provinces are not included in the results, which are reasonable for conventional intuition. In fact, the inverted predominance direction matrix of Hubei and Jiangxi province is just like (#, #, #, 0.1559, #, #), which also verifies the previous result. Here the critical value is 0.5.

Table 2 Query results without direction predominance

| NO. | SmUserID | AREA | PERIMETER | PROVINCE_ID | PINYIN_NAME |
|-----|----------|------|-----------|-------------|-------------|
| 1   | 1 0      | 100320900000 | 2571351 | 9 | Jiangsu |
| 2   | 0 2      | 140951260000 | 2677982 | 10 | Anhui |
| 3   | 0 3      | 9728945430   | 1777607 | 12 | Shanghai |
| 4   | 0 4      | 5255601700   | 3186256 | 13 | Zhejiang |
| 5   | 0 5      | 101942300000 | 2620791,2999999998 | 14 | Zhejiang |
| 6   | 0 6      | 166776730000 | 2553609,2999999998 | 15 | Jiangd |

Fig. 9 Query results with direction predominance

\[
\begin{pmatrix}
# & # & # \\
# & 0.468 & 9 \\
# & # & #
\end{pmatrix}
\begin{pmatrix}
# & # & # \\
# & 0.676 & 6 \\
# & # & #
\end{pmatrix}
\begin{pmatrix}
# & # & # \\
# & # & 1 \\
# & # & #
\end{pmatrix}
\begin{pmatrix}
# & # & # \\
# & # & 1 \\
# & # & 0.681
\end{pmatrix}
\begin{pmatrix}
# & # & # \\
# & # & 1 \\
# & # & 0.115
\end{pmatrix}
\begin{pmatrix}
# & # & # \\
# & # & #
\end{pmatrix}
\]

Fig. 10 Direction predominance matrix
5 Conclusions

There has been an increasing interest recently about the representation and processing of spatial relations in Spatial Database Systems. This interest has been focused on several topics such as reasoning, consistency checking mechanisms and spatial query languages. In this paper we deal with the detection of spatial direction relations used for spatial applications.

The main contributions of our work includes: (1) depending on the direction relation matrix, an inverted direction relation matrix and the concept of direction predominance are proposed to improve the detection of direction relation between objects and get more precision query results.

(2) direction predicates of spatial systems are also extended. These techniques can improve the veracity of direction queries and reasoning. Experiments show more exact and reasonable results in view of direction queries. The research results enrich the theory of spatial and spatio-temporal systems.

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Notes to Contributors

Contributions are welcomed on one of the following subjects or in related areas:

- GIS
- GPS
- RS
- Cartography
- Geodynamic
- Geo-surveying
- Photogrammetry
- Graphics
- Physical geo-surveying
- Engineering surveying
- Mapping apparatus

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