Modeling Historical and Future Spatio-Temporal Relationships of Moving Objects in Databases

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Abstract. Moving object databases have recently found large interest in the database community, geographical information systems, and geosciences. So far, moving object models have focused exclusively either on past or future movements. The so-called *Balloon Model* is the first attempt to treat past and future movements of moving objects in a consistent and integrated manner. Based on a new set of spatio-temporal data types and operations as well as former research, in this paper, we propose a design of *spatio-temporal predicates* on Balloon objects. These predicates explore the topological relationships of Balloon objects over time and take into account both past and future movements. We present new kinds of queries to demonstrate the use of these predicates.

1 Introduction

Research in spatio-temporal databases have recently received a lot of interest in many disciplines such as robotics, mobile computing, and geographical science. Much of the research in this field focuses on defining data models for continuously changing geometric objects typically known as *moving objects*. While most previous approaches assume that we have precise knowledge about the objects' movements (i.e., historical movements), some recent research considers the problem of predicting the future movements of moving objects in specific environments. The lack of a generic data model for the future movements and the separation of past and future movement models for moving objects have fueled a new development in this field. Recently, we have proposed a new moving object model called *balloon model* which considers both the past and the future movements of moving objects while preserving their temporal consistency.

With this new model, a new set of moving data types and operations for balloon objects are introduced. At the same time, new kinds of interesting queries can be posed. For instance, assuming that hurricane Katrina is making its way across the Gulf of Mexico, we can ask a question like "What is the chance that hurricane Katrina will make land fall in New Orleans?" Although this question can be answered by examining the projected path of the hurricane which is modeled as a balloon object, some other questions require the use of a spatio-temporal relationship or predicate between balloon objects. For example, we can post a query "List all airplanes that will potentially cross

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the projected path of hurricane Katrina." Here, we can model each airplane as a *balloon point* consisting of a moving point past and a moving point prediction since an airplane may have a defined route. We can also model the hurricane as a balloon point but with a moving region prediction since a hurricane does not have a defined route. The answer to this query requires the evaluation of the *balloon predicate* "potentially cross" between each airplane and the hurricane. Even though in the past, spatio-temporal predicates have been defined between moving objects with precisely known movements, spatio-temporal predicates between balloon objects taking into account the uncertainty of future relationships have not been defined.

The goal of this paper is to propose a spatio-temporal predicate model for defining *balloon predicates* between balloon objects. Since balloon objects are defined as a *temporal composition* of the past and future movements of moving objects, a balloon predicate between two balloon objects is defined based on a temporal composition of the spatio-temporal predicates between their past and future movements. With this model, users can specify balloon predicates and use them in queries.

We present the paper by first providing a brief overview of the existing moving object model and spatio-temporal predicate (STP) model for moving objects in Section 2. We then give a description of the balloon model in Section 3 as a foundation for defining our STPs for balloon objects in Section 4. Having defined the predicate model, we explore the querying possibilities of balloon predicates in Section 5. Finally, in Section 6, we draw some conclusions and discuss future work.

2 Related Work

Within the past decade, there have been several major developments of STP models. Among these developments, STP models for moving objects have received wide-spread interest in both application and research directions. Each of these models is defined on the basis of a specific moving object data model which only considers either the relationship between the past movements or future movements of moving objects.

2.1 A Spatio-Temporal Predicate Model for Past Movements

The STP model presented in [4] characterizes the developments of topological relationship between moving objects which are defined by a moving object model proposed in [7, 2, 1]. To simplify our discussion, we refer to these models as the traditional STP model and traditional moving object (MO) model respectively. The traditional MO model defines a moving object as a function from time to space. For an arbitrary data type α, the corresponding moving type of α is a function $\tau(\alpha)$ that provides the mapping from the temporal domain to α, i.e., $\tau(\alpha) = time \rightarrow \alpha$. By instantiating this definition with spatial data types like *point*, *line*, and *region*, moving data types such as moving point (*mpoint*), moving line (*mline*), and moving region (*mregion*) are obtained. Figure 1(a) and 1(b) illustrate a moving point and a moving region respectively.

The spatio-temporal predicate $stp(\tau(\alpha), \tau(\beta))$ between two moving objects of type $\tau(\alpha)$ and $\tau(\beta)$ is defined by the traditional STP model as a sequence of alternating spatial predicates that only hold for a period of time (period predicates) and those that

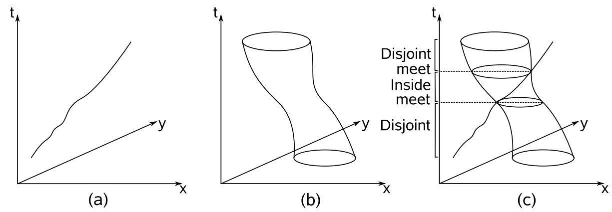

Fig. 1. Examples of a moving point (a), a moving region (b), and a crossing situation (c).

can hold for an instant of time (instant predicates). For example, the predicate *Cross* between a moving point and a moving region is defined as $Cross := Disjoint \triangleright meet \triangleright Inside \triangleright meet \triangleright Disjoint$ where *Disjoint* and *Inside* are period predicates, *meet* is an instant predicate, and the symbol $\triangleright$ signifies a development or a change of relationship. Figure 1(c) depicts the spatio-temporal predicate *cross*. From another perspective, a spatio-temporal predicate between two moving objects is a *temporal composition* of period and instant predicates between the two objects. This view of a spatio-temporal predicate is made obvious in later works such as the Query-By-Trace [5] model which focuses on visual specification of spatio-temporal predicates for use in query. Although the traditional STP model is able to effectively capture the development of relationship over time, it is defined based on the traditional moving object model which assumes that we have precise knowledge about the movements of moving objects, i.e.past movements. The aspect of uncertainty such as the relationship between future movement predictions of moving objects is not part of the model. In reality, the ability to model and query such relationship is of great importance to many applications. In our balloon predicate model, we make use of this traditional STP model to characterize the relationship between the past and future movements of balloon objects.

2.2 A Spatio-Temporal Predicate Model for Future Movements

With regard to the future movements of moving objects, the STP model presented in [6] captures the uncertainty aspect of the future relationship between a moving object, more specifically a moving point, and a static region. The future movement of a moving point is defined by a future *motion plan* or *trajectory* and a threshold value signifying an acceptable deviation of the actual movement from the trajectory. The application of a threshold around a future trajectory creates a *trajectory volume* which represents the set of all possible future motion curves. A STP is then defined based on the relationship between the *spatial projection* of such a trajectory volume and a static region. Depending on this relationship, the uncertainty of a future STP can be captured and represented by using any combination of the prefixes *sometimes*, *always*, *possibly*, and *definitely*. While this model is able to model future STPs to a certain extent, it is limited to only those relationships between a moving point and a static region. In contrast, our balloon predicate model is a generic model which supports both the past and future relationships between any combination of balloon object types, thus any combination of moving object types.

3 Foundation Data Model for Balloon Predicates

To motivate the approach for representing moving objects, consider a scenario of modeling a hurricane. It is desirable to be able to model this hurricane as a single moving object consisting of its past movement up until its current state and continued by its future prediction. Due to the fact that existing moving object models only support either the past or a restricted type of future movements of moving objects, there is a need for a generic data model which can handle both the past and future movements of moving objects. A first step in this direction is made with the FuMMO model presented in [8] which emphasizes the separation between prediction methods and future data models and offers a generic data model for future movements of moving objects. Based on this idea and the need for a unique and consistent representation of moving objects, the balloon model is proposed in [9] as a generic data model for supporting both the past and future movements of moving objects.

3.1 The Balloon Model

In this model, a balloon object is defined as a temporal composition of the past component and the future component of the object. The connection point of this composition is known as the object's *present* denoted by t_p and represents the instant of the latest known state of the object. The past temporal domain $time_h$ of the past component is defined as $time_h = (-\infty, t_p]$. Similarly, the future temporal domain $time_f$ of the future component is defined as $time_f = (t_p, +\infty)$. Each of these components is defined as a traditional moving object with a specific continuity property. To capture the uncertainty aspect of future movements, the future component also consists of a *moving confidence distribution* indicating the confidence level of each point of the future movement. Whereas the past component can be of type *mpoint*, *mline*, or *mregion*, the future component can be of type *fpoint*, *fline*, or *fregion* each consisting of a moving geometry and a moving confidence distribution. The separation of the moving geometry and the moving confidence distribution in the future component allows us to use a traditional moving data type to represent this moving geometry. It turns out that not all combinations of moving object types are valid. For example, it is not possible to use a moving point to represent the potential future extent of a moving region. If this were possible, it would mean that a region can evolve to collapse its dimension into a single point in the future. This proves to be impossible based on the definition of the continuity of movements described in [9]. In fact, the future component must be based on a moving object whose spatial dimension is greater than or equal to that of the past component. Hence, only six valid combinations exist which translate to six balloon data types. Let α and β be a spatial data type. In general, a balloon data type is defined by a type constructor $\Omega(\alpha, \beta) = \tau(\alpha) \times \varphi(\beta)$ where $\tau(\alpha)$ represents the past component (see Section 2.1) and $\varphi(\beta)$ models the future component including the moving confidence distribution.

3.2 Data Model Considerations for Balloon Predicates

Defining the relationship between uncertain movements of moving objects is a very complex task. For instance, consider a prediction of an airplane that crosses a prediction of a hurricane. It is not necessary that the airplane will always cross the hurricane;

it may only get close to or touch the actual hurricane even though its prediction crosses the hurricane's prediction. However, there is a chance that the airplane would cross the hurricane as well. The quantification of this chance depends on a complex calculation of the moving confidence distributions of both objects. Since these distributions can be represented in many forms, e.g., using probabilistic or fuzzy concepts, considering this quantification as part of a predicate model here proves to be extremely complex. As a first step in an attempt to model spatio-temporal predicates between balloon objects, we therefore present the model in its most simplest and understandable form as possible. Thus, in this paper, we consider only the existence of a chance that a relationship can occur between uncertain movements instead of modeling the quantification of this chance, which can be done in further research. For this reason, we can focus only on the moving geometry of the future movement and replace $\varphi(\beta)$ by simply $\tau(\beta)$. Therefore, the balloon data type constructor can be written as $\Omega(\alpha,\beta) = \tau(\alpha) \times \tau(\beta)$. Based on this type constructor, the six balloon data types can be instantiated as follows.

$$\begin{aligned} &balloon\_pp = mpoint \times mpoint && balloon\_ll = mline \times mline \\ &balloon\_pl = mpoint \times mline && balloon\_lr = mline \times mregion \\ &balloon\_pr = mpoint \times mregion && balloon\_rr = mregion \times mregion \end{aligned}$$

For a balloon object $b = (b_p, b_f) \in \Omega(\alpha,\beta)$, the first moving object b_p, called the *past part*, describes the past movement of b. The second moving object b_f, called the *future part*, describes the collection of future potential movements of b, that is, it is the geometry of a future prediction of potential positions or extent of the balloon object. Figure 2(a) and 2(b) illustrate a $balloon\_pp$ and a $balloon\_pr$ object respectively.

4 Predicates on Balloon Objects

In this section, we define balloon predicates and explore their properties. After describing our general mechanism for defining balloon predicates in Section 4.1, we then discuss how such a predicate can be specified using traditional STPs in Section 4.2. Finally, we determine the canonical collection of balloon predicates in Section 4.3.

4.1 General Mechanism for Balloon Predicates

The approach we present here is based on two main goals. The first goal is to develop a formalism that works independently of the data types to which it is applied. It is desired

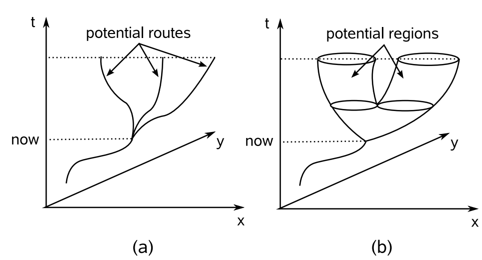

Fig. 2. Examples of a $balloon\_pp$ object (a) and a $balloon\_pr$ object (b).

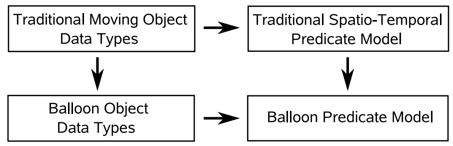

Fig. 3. Relations between traditional moving object data model and balloon data model.

that the formalism can be equally applied to any pair of balloon objects irrespective of their data types. The second goal concerns the importance of making use of existing definitions of traditional STPs. Since balloon objects, as described in Section 3, are constructed based on traditional moving objects. It is only consistent to let balloon predicates be constructed from traditional STPs. With this goal, we can benefit from both theoretical and implementation advantages such that the formalism and implementation of balloon predicates can make use of the existing work done for traditional moving object data model. Figure 3 shows the relationships between traditional moving object data model and balloon object data model.

The general method we propose characterizes balloon predicates based on the idea that as two spatial objects move over time, the relationship between them may also change over time. By specifying this changing relationship as a predicate, we can ask a true/false question of whether or not such a changing relationship occurs. Thus, we can define a balloon predicate as a function from balloon objects to Boolean (that is, bool).

Definition 1. A balloon predicate is a function of the form $\Omega(\alpha_1, \beta_1) \times \Omega(\alpha_2, \beta_2) \rightarrow$ *bool* for α_1, β_1, α_2, $\beta_2 \in \{point, line, region\}$.

The change of relationship over time between two balloon objects indicates that there is a sequence of relationships that hold at different times. This suggests that a balloon predicate can also be modeled as a development (sequence) of spatial and spatio-temporal predicates. Due to the fact that a balloon object consists of a past part followed by a future part, the specification of a balloon predicate must also take into account the uncertainty of future relationships between the objects. To do this, let us first explore how relationships between balloon objects can be modeled.

Each balloon object has a defined present state at its present instant t_p which separate the past part and the future part. Between two balloon objects $A = (A_p, A_f)$ and $B = (B_p, B_f)$, A's present instant may either be earlier, at the same time, or later than B's present instant. In each of these scenarios, certain sequences of spatio-temporal relationships are possible between the parts of A and B. Here, we are only interested in the relationship between a part of A and another part of B whose temporal domains overlap since, in this case, the two parts may be defined on the same period of time. Figure 4 illustrates all the possible related pairs for each scenario between parts of A and B.

Although there are four possible types of relationships between all parts of balloon objects, it turns out that in any case, there are at most three types of relationships that may exist between parts of any two balloon objects. These include *past/past*, *past/future* or *future/past*, and *future/future* relationships. The past/future and future/past relationships cannot exist at the same time due to the temporal composition between the past and future parts of a balloon object.

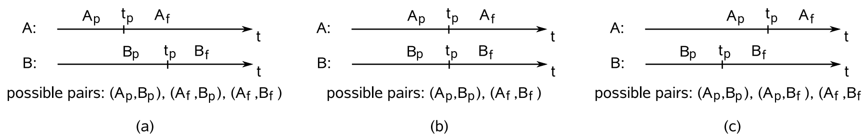

Fig. 4. Possible relationships between parts of balloon objects *A* and *B* when *A*'s present instant is earlier (a), at the same time (b), or later (c) than that of *B*'s.

4.2 Specification Based on Traditional STPs

If we observe more closely, all the relationships between the parts of two balloon objects that may exist in a scenario form a development such that the entire relationship between the two balloon objects can be seen as a sequence of these relationships between their parts. For example, consider an airplane represented by a *balloon_pp* object $P = (P_p, P_f)$ and a hurricane represented by a *balloon_pr* object $R = (R_p, R_f)$ (Figure 5). In the past, *P* has been disjoint from *R*'s path as well as part of *R*'s predicted future. However, the future route of *P* crosses the predicted future of *R*.

The relationship between *P* and *R* can be described as a development or sequence of uncertain spatial and spatio-temporal predicates which hold at different times, i.e., $Disjoint_u \triangleright meet_u \triangleright Inside_u \triangleright meet_u \triangleright Disjoint_u$ (the subscript $_u$ indicates uncertain predicates). However, these spatial and spatio-temporal predicates may represent relationships between different parts of the balloon objects. For instance, the first *Disjoint* predicate is actually a temporal composition of three different types of disjointedness between the corresponding parts of *P* and *R*, i.e., $Disjoint(P_p, R_p) \triangleright Disjoint_u(P_p, R_f) \triangleright Disjoint_u(P_f, R_f)$. The rest of the predicates represent relationships between the future parts of both objects. Hence, we can expand the original sequence as $Disjoint(P_p, R_p) \triangleright Disjoint_u(P_p, R_f) \triangleright Disjoint_u(P_f, R_f) \triangleright meet_u(P_f, R_f) \triangleright Inside_u(P_f, R_f) \triangleright meet_u(P_f, R_f) \triangleright Disjoint_u(P_f, R_f)$. In this sequence, the subsequence $Disjoint_u(P_f, R_f) \triangleright meet_u(P_f, R_f) \triangleright Inside_u(P_f, R_f) \triangleright meet_u(P_f, R_f) \triangleright Disjoint_u(P_f, R_f)$ can be represented by an STP $Cross_u(P_f, R_f)$, as shown in Section 2.1, since they are applied to the same future parts of the two balloon objects. Thus, we have $Disjoint(P_p, R_p) \triangleright Disjoint_u(P_p, R_f) \triangleright Cross_u(P_f, R_f)$.

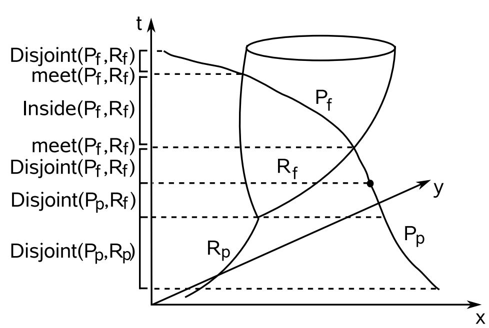

Fig. 5. A future crossing situation between a *balloon_pp* object *P* and a *balloon_pr* object *R*.

As a result, we are left with a sequence of three STPs each applied to different combination pairs of parts of the balloon objects. This example illustrates that balloon predicates can be appropriately modeled by sequences of three STPs between the related parts of balloon objects. Hence, we can specify balloon predicates based on the traditional STPs as follows:

Definition 2. Let P and R be two balloon objects of type $\Omega(\alpha_1, \beta_1)$ and $\Omega(\alpha_2, \beta_2)$ respectively. A balloon predicate between P and R is a sequence of spatio-temporal predicates: $\langle stp(\tau(\alpha_1), \tau(\alpha_2)), (stp(\tau(\alpha_1), \tau(\beta_2)) | stp(\tau(\beta_1), \tau(\alpha_2))), stp(\tau(\beta_1), \tau(\beta_2))\rangle$.

We consider an STP between two moving objects to be meaningful if and only if there exists a period of time for which both objects are defined. Hence, each element of the above sequence is meaningful only if the relationship between the corresponding parts is meaningful. The predicate of the first element in the sequence represents an interaction that *did occur*. The first and second alternative predicates of the second element in the sequence represents an interaction that *might occur* and *may occur* respectively. These predicate options reflect the constraint described in Section 4.1 which dictates that the two predicates cannot exist at the same time. The predicate of the third element in the sequence denotes an interaction that *probably will occur*. The combinations of multiple of these interactions represents a more complex relationship between balloon objects. For example, an interaction that *did occur* in the past and *probably will occur* in the future can indicate that it *probably always occurs*. Table 1 shows an example of assigning a meaningful prefix to the name for each pairwise combination between these interactions. Other combinations with larger number of interactions also exist, but it is usually not obvious to name these relationships. Here are some examples of balloon predicates:

$$
\begin{aligned}
did\_cross &:= \langle Cross(\tau(\alpha_1), \tau(\alpha_2))\rangle \\
probably\_will\_cross &:= \langle Cross_u(\tau(\beta_1), \tau(\beta_2))\rangle \\
may\_have\_been\_disjoint &:= \langle Disjoint_u(\tau(\alpha_1), \tau(\beta_2)), Disjoint_u(\tau(\beta_1), \tau(\beta_2))\rangle \\
probably\_always\_inside &:= \langle Inside(\tau(\alpha_1), \tau(\alpha_2)), Inside_u(\tau(\beta_1), \tau(\beta_2))\rangle
\end{aligned}
$$

4.3 Canonical Collection of Balloon Predicates

Having defined a model for balloon predicates, we can now search for a canonical collection of balloon predicates. The use of traditional STPs in the definition of balloon predicates suggests that the canonical collection of balloon predicates can be expressed in terms of the canonical collection of traditional STPs, which is provided in [4]. Another important factor that affects the canonical collection is whether dependencies exist

	did	might	may	probably will
did	-	might have	may have	probably always
might	might have	-	-	may have been
may	may have	-	-	probably will have
probably will	probably always	may have been	probably will have	-

Table 1. Assigning naming prefixes to pairwise combinations of interactions.

	balloon_pp	*balloon_pr*	*balloon_rr*
balloon_pp	4,394	14,924	43,904
balloon_pr	14,924	1,600,144	136,996,944
balloon_rr	43,904	136,996,944	21,237,972,784

Table 2. Number of balloon predicates between *balloon_pp*, *balloon_pr*, and *balloon_rr* objects.

between the three elements of the sequence. More specifically, we need to investigate whether the existence of a STP as an element of the sequence can prevent or restrict another STP from representing another element of the sequence.

According to [4], the dependency between STPs, which are parts of a continuous development, is expressed using a *development graph*. This graph describes all the possible developments of STPs which correspond to continuous topological changes of moving objects. For example, if a moving point is inside a moving region, it must meet the boundary of the moving region before it can be disjoint from the region. This constraint relies on the continuity of the moving point. If we allow discontinuity such as a period of unknown movement as in the case of the balloon model, then such constraint cannot be applied. Although the past part and the future part of a balloon object cannot temporally overlap each other, it is possible that they can be separated by a period of unknown movement. Further, there can also be periods of unknown movement within the past or the future part of a balloon object. Due to the possible discontinuity of balloon objects, we can deduce that each element of the predicate sequence, which is a STP between the parts of two balloon objects, are independent of each other. Thus, all the combinations of the STPs involved are possible. This means that the canonical collection of balloon predicates can be determined solely based on the canonical collections of the traditional STPs involved. As provided in [4], there are 13 distinct temporal evolutions between two moving points without repetitions, 28 between a moving point and a moving region, and 2,198 between two moving regions. With this information, we can determine, for example, the number of distinct, non-repetitive balloon predicates between two *balloon_pp* objects to be $13 \times (13+13) \times 13 = 4,394$. Each of the three numbers of the multiplication represents the number of distinct STPs for each element of the sequence. Similarly, we can determine the number of balloon predicates between all type combinations of *balloon_pp*, *balloon_pr*, and *balloon_rr* as shown in Table 2 below. Since the numbers of STPs that involve moving line objects are not available in [4], we omit those balloon predicates that involve balloon objects which are based on moving line objects.

5 Using Balloon Predicates in Queries

Due to the large numbers of possible balloon predicates, it is essential to consider all the different ways in which these predicates can be used in queries. Either the user is provided with a small, application-specific set of balloon predicates, or the user is allowed to construct balloon predicates according to his needs. Several mechanisms are available which enable users to specify and use balloon predicates in queries. One solution to this problem is to use the *spatio-temporal query language* (STQL) [3] to support textual specifications of balloon predicates in queries. Assuming that all necessary data for hurricanes and airplanes are available in a database. We can define, for example, a balloon predicate *potentially_cross* and use it in a query as follows:

```
DEFINE potentially_cross AS <Cross(future/future)>;
SELECT flights.id FROM flights, hurricanes
WHERE flights.route potentially_cross hurricanes.path;
```

Another solution is to use the *visual query language* [5]. By extending this concept to allow a graphical specification of a sequence of developments, we can use this mechanism to specify balloon predicates and use them in queries.

6 Conclusions

Modeling spatio-temporal predicates between spatio-temporal objects with uncertainty movements is a very challenging task. In this paper, we take a first step in this direction by first focusing on modeling the spatio-temporal relationships between the geometries of precise and uncertain movements of spatial objects. In doing so, we show that relationships between balloon objects are composed of a sequence of certain and uncertain relationships between their parts. With the understanding of the existence of these relationships, the next step is to consider the quantification of the chances in which such relationships can occur.

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