Modeling of Moving Objects in a Video Database *

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Abstract

Modeling moving objects has become a topic of increasing interest in the area of video databases. Two key aspects of such modeling are spatial and temporal relationships. In this paper we introduce an innovative way to represent the trajectory of a single moving object and the relative spatio-temporal relations between multiple moving objects. The representation supports a rich set of spatial topological and directional relations. It also supports both quantitative and qualitative user queries about moving objects. Algorithms for matching trajectories and spatio-temporal relations of moving objects are designed to facilitate query processing. These algorithms can handle both exact and similarity matches. We also discuss the integration of our moving object model, based on a video model, in an object-oriented system. Some query examples are provided to further validate the expressiveness of our model.

Keywords: multimedia, temporal, spatial, moving object, database, video.

1 Introduction

In the last few years, there has been significant research in modeling video systems [OT93, LG93, WDG94, SW94, GBT94, DDI+95, TK96, LGÖS97]. While there has been some research on spatial issues, the major focus has been on temporal aspects. There are only a few projects that have explored both spatial and temporal relationships. The most striking difference between still images and videos stems from movements and variations. Retrieving moving objects, which requires both spatial and temporal knowledge, is part of content-based querying. Typical applications are: automated surveillance systems, industrial monitoring, road traffic monitoring, video databases etc. Modeling moving objects has received some research attention recently [DG94, IB95, SAG95, ABL95, YYHI96], but it is certainly in its infancy. Most research in this area focuses on tracking the movement of a single object, i.e., the *trajectory* of an object over a period of time, which is certainly very important. For example, object trajectories are needed for many useful video annotation tasks such as describing activities at city street intersections, sporting events, pedestrian mall

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traffic, cell movements from quantitative fluorescence microscopy, groups of animals and meteorological objects [IB95]. However, another important aspect of moving objects is their relative spatial relationships. It is important that these relationships be represented qualitatively instead of quantitatively (using the coordinates) both to save space and to simplify reasoning.

To the best of our knowledge, no research has studied the relationships between moving objects in video databases. We believe that such support is essential for a video database because queries could exploit these relationships. For example, a coach may have particular interest in the relative movement of his players during a game so that they can achieve the best cooperation. Alternatively, we may be interested in finding objects whose movements match user drawings in cases where it is difficult to verbally describe complex movements. Typical queries about moving objects might be: "*Find all the objects which have a similar trajectory to this one*", "*Find a video clip where a dog approaches a person from the left*", "*Find a video clip which matches a scene I sketched*", etc. These queries are so common that any video database should be able to support them.

In this paper we introduce an innovative way of modeling the trajectory of a single moving object and the relative spatio-temporal relations between multiple moving objects. The proposed model is integrated into TIGUKAT[1] [ÖPS+95], which is an experimental object database management system (ODBMS) under development at the University of Alberta. However, the model is general and can be incorporated to other ODBMSs. The major contributions of this paper are:

- A new way of qualitatively representing the trajectory of a moving object and the relative spatio-temporal relations between moving objects is introduced. Such representations are based on Allen's temporal interval algebra [All83], and they support a rich set of spatial topological and directional relations.

- Algorithms for matching trajectories and spatio-temporal relations of moving objects are designed to facilitate query processing. The algorithms can handle both exact and similarity matches.

- A novel approach to integrating this moving object model with a video model in an ODBMS is presented. The resulting system supports a broad range of user queries, especially for systems with graphical user interfaces.

[1]TIGUKAT (tee-goo-kat) is a term in the language of Canadian Inuit people meaning "objects." The Canadian Inuits (Eskimos) are native to Canada with an ancestry originating in the Arctic regions.

The rest of the paper is organized as follows. Section 2 reviews the related work in object spatial representations and modeling of spatio-temporal semantics. Section 3 introduces our representation of object spatial properties and relationships. The new model captures the trajectories of moving objects and relative spatial relationships between moving objects. Matching algorithms are also discussed. Section 4 describes a video model which captures common objects in videos. An integration of the moving object model into an ODBMS is also presented. Section 5 uses query examples to show the expressiveness of our spatio-temporal representation. Section 6 summarizes our work and discusses possible future work.

2 Related Work

Video content analysis has received a lot of research attention in recent years [GBT94, BC95, IKO+96, YYL96]. A major goal of these works is to achieve automatic extraction of feature semantics from a video and to support content-based video retrieval. Feature extraction includes object recognition, spatio-temporal encoding, scene analysis, etc. We do not address feature extraction in this paper, but a few prototype systems [SZ94, LPE96, SK96, YYL96] have been reported that can be used in conjunction with our work. A survey of technologies for parsing and indexing digital videos is in [AL96].

Egenhofer [EF91] has specified eight fundamental topological relations that can hold between two planar regions. These relations are computed using four intersections over the *boundary* and *interior* of pointsets between two regions embedded in a two-dimensional space. These four intersections result in eight topological relations: *disjoint, contains, inside, meet, equal, covers, covered_by*, and *overlap*. In a later paper [EAT92], Egenhofer studies gradual changes of these topological relations over time within the context of geographical information systems (GISs). It has been recognized that a qualitative change occurs if the deformation of an object affects its topological relation with respect to another object. A computational model is presented to describe the changes. Most importantly it reveals the internal relationships which are useful in describing the closeness of topological relations. Part of our work is, in a sense, an extension of [EAT92] by considering directional relations as well as topological relations and time.

The Video Semantic Directed Graph (VSDG) model is a graph-based conceptual video model [DDI+95]. One feature of the VSDG model is an unbiased representation that provides a reference framework for constructing a user's view of video data. The spatio-temporal semantics is captured by *conceptual spatial objects* and *conceptual temporal objects*. This model, which is able to capture some actions, such as walking and basketball slum-dunks, uses Allen's temporal interval algebra [All83] to model spatial relations among objects.

Dimitrova and Golshani [DG94] describe a method of computing the trajectories of objects. The objective of this work is to discover motion using a dual hierarchy consisting of spatial and temporal parts for *video sequence* representation. Video sequences are identified by objects present in the scene and their respective motion. Motion vectors extracted during the motion compensation phase of video encoding are used. The motion information extraction is then used at an intermediate level by motion tracing and at a high level by associating an object and a set of trajectories with recognizable activities and events. The focus is on trajectories of objects at a high level and relations between moving objects are not studied.

Intille and Bobick propose an interesting model that uses a *closed-world assumption* to track object motions [IB95]. A closed-world is a region of space and time in which the specific context is adequate to determine all possible objects present in that region. Besides using closed-worlds to circumscribe the knowledge relevant to tracking, they also exploit them to reduce complexity. Two types of entities exist in a closed-world, *objects* and *image regions*. An important feature of this model is that the knowledge of the domain dictates how objects can interact and is independent of how the scene is captured for vision analysis. After an image region within a video frame is selected, each pixel within this region is assigned to one of the objects within its closed-world. Context-specific features are used to construct templates for tracking each moving object in the closed-world. Then, objects are tracked to the next frame using the templates. They describe a prototype for tracking football players. However, a major drawback of this model is its lack of generality and its heavy dependence on domain knowledge.

The Video Query By Example (V-QBE) system [YYHI96] is simple but only deals with the trajectory of a single moving object. A unified model for spatial and temporal information is proposed in [Wor94]. A *bitemporal relation*, including both event time and database time, is applied to objects in the system. This model is designed for GISs. There is also some research on moving objects that result from camera motions [ABL95, SAG95], such as *booming, tilting, panning, zooming* etc. We do not consider these types of movement in this paper. More work on motion detection can be found in [BH94, GD95].

3 Spatial Properties of Salient Objects

A *salient object* is an interesting physical object in a video frame. Each frame usually has many salient objects, e.g. persons, houses, cars, etc. In this section, we first describe the spatial representation of salient objects and briefly introduce Allen's temporal interval algebra. We then provide complete definitions of spatial directional and topological relations. Based on these definitions, we introduce the moving object model and matching algorithms. We use the term objects to refer to salient objects whenever this will not cause confusion.

3.1 Spatial Representations

It is a common strategy in spatial access methods to store object approximations and use these approximations to index the data space in order to efficiently retrieve the potential objects that satisfy the result of a query [PTSE95]. Depending on the application domain, there are several options in choosing object approximations. Minimum Bounding Rectangles (MBRs) have been used extensively to approximate objects because they need only two points for their representation. While MBRs demonstrate some disadvantages when approximating non-convex or diagonal objects, they are the most commonly used approximations in spatial applications. Hence, we use MBRs to represent objects in our system. We also assume there is always a finite set (possibly empty) of salient objects for a given video.

Definition 1 The *spatial property* of a salient object A_i is defined by (X_i, Y_i, C_i) where $X_i = [x_{s_i}, x_{f_i}], Y_i = [y_{s_i}, y_{f_i}]$. x_{s_i} and x_{f_i} are A_i's projection on the X axis with $x_{s_i} \leq x_{f_i}$ and similarly for y_{s_i} and y_{f_i}. The two intervals are represented by A_{ix} and A_{iy} respectively. C_i is the centroid of A_i and is represented by a two dimensional point (x_i, y_i). Note it is not necessary that a centroid have to be the center of the MBR. This representation can be naturally extended by considering the time dimension which captures the spatial property of a salient object A_i at time t: (X_i^t, Y_i^t, C_i^t)

Basically, the spatial property of an object is described by its minimum bounding box and a representative point, called the centroid or mass point. In video modeling we must also consider the time dimension, as the spatial property of an object may change over time. For example, suppose the spatial property of A_i is $(X_i^{t_1}, Y_i^{t_1}, C_i^{t_1})$ at time t_1 and it becomes $(X_i^{t_2}, Y_i^{t_2}, C_i^{t_2})$ at time t_2. The displacement of A_i over time interval $I = [t_s, t_f]$ is $DISP(A_i, I) \equiv \sqrt{(x_i^{t_s} - x_i^{t_f})^2 + (y_i^{t_s} - y_i^{t_f})^2}$ which is the movement of the centroid of A_i. Also the Euclidean distance between two objects A_i and A_j at time t_k is $\mathit{DIST}(A_i, A_j, t_k) \equiv \sqrt{(x_i^{t_k} - x_j^{t_k})^2 + (y_i^{t_k} - y_j^{t_k})^2}$ which is also characterized by the centroid of A_i and A_j.

3.2 Spatial Relationships

Spatial qualitative relations between objects are very important in multimedia databases because they implicitly support *fuzzy queries* which are captured by similarity matching or qualitative reasoning. Allen [All83] gives a temporal interval algebra (Table 1) for representing and reasoning about temporal relations between events represented as intervals. The temporal interval algebra essentially consists of the topological relations in one dimensional space, enhanced by the distinction of the order of the space. The order is used to capture the directional aspects in addition to the topological relations. Since the starting points of an interval are scalar values, we can define an *ordering* directly over a list of intervals.

Definition 2 Let $I = \langle [t_{s_1}, t_{f_1}], [t_{s_2}, t_{f_2}], \ldots, [t_{s_n}, t_{f_n}] \rangle$ be a finite list of intervals. I is *ordered* if and only if $t_{s_i} \leq t_{s_{i+1}}$ $(\forall i \ \ 1 \leq i \leq n-1)$.

We consider 12 directional relations in our model and classify them into the following three categories: *strict directional relations* (north, south, west, and east), *mixed directional relations* (northeast, southeast, northwest, and southwest), and *positional relations* (above, below, left, and right). The definitions of these relations in terms of Allen's temporal algebra are given in Table 2. The symbols $\wedge$ and $\vee$ are the standard logical *AND* and *OR* operators, respectively. A short notation $\{\}$ is used to substitute the $\vee$ operator over interval relations. For example $A_{ix}\,\{\mathtt{b}, \mathtt{m}, \mathtt{o}\}\,A_{jx}$ is equivalent to $A_{ix}\,\mathtt{b}\,A_{jx} \vee A_{ix}\,\mathtt{m}\,A_{jx} \vee A_{ix}\,\mathtt{o}\,A_{jx}$. Detailed description of these definitions can be found in [LÖS96]. To simplify our description, we consider only 2D space. The extension to 3D space is straightforward.

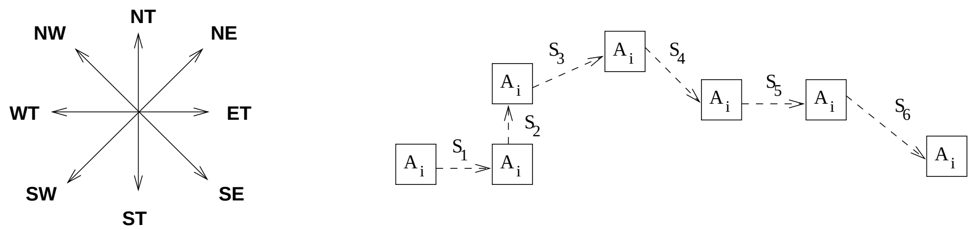
3.3 Modeling Moving Objects

A *moving object* is a salient object which changes its position over time. We assume moving objects are rigid or consist of rigid parts connected together and these rigid parts are never disintegrated. For any moving object we consider eight possible directions shown in Figure 1(a).

Definition 3 Let A_i be a moving object and the *motion* of A_i over time interval I_i is (S_i, d_i, I_i) where $S_i = \mathit{DISP}(A_i, I_i)$ is the displacement of A_i and d_i is a direction whose domain is the union of strict and

Relation	Symbol	Inverse	Meaning
B before C	`b`	`bi`	BBB CCC
B meets C	`m`	`mi`	BBBCCC
B overlaps C	`o`	`oi`	BBB CCC
B during C	`d`	`di`	BBB CCCCC
B starts C	`s`	`si`	BBB CCCCC
B finishes C	`f`	`fi`	BBB CCCCC
B equal C	`e`	`e`	BBB CCC

Table 1: 13 Temporal Interval Relations



(a) Eight Moving Directions (b) Trajectory of Object A_i

Figure 1:

mixed directional relations. For a given ordered list of time intervals $\langle I_1, I_2, \ldots, I_n\rangle$, the *trajectory* of A_i can be described by a list of motions

$$\langle (S_1, d_1, I_1), (S_2, d_2, I_2), \ldots, (S_n, d_n, I_n)\rangle.$$

Example 1 Figure 1(b) shows a trajectory of object A_i. The trajectory consists of a sequence of motions which can be expressed by $\langle (S_1, \texttt{ET}, I_1), (S_2, \texttt{NT}, I_2), (S_3, \texttt{NE}, I_3), (S_4, \texttt{SE}, I_4), (S_5, \texttt{ET}, I_5), (S_6, \texttt{SE}, I_6)\rangle$.

Being able to model a moving object is quite useful from a querying perspective. However, this model is at a very low level in the sense that the computation of a displacement could be very expensive for each object in every frame of a video. Even if we only sample representative frames, the processing is still time-consuming. Moreover, it is very difficult, if not impossible, to capture the relationships of a moving object with other salient objects (either moving or non-moving) using such a quantitative basis. A model

Relation	Meaning	Definition
$A_i\,\mathtt{ST}\,A_j$	South	$A_{ix}\,\{\mathtt{d},\mathtt{di},\mathtt{s},\mathtt{si},\mathtt{f},\mathtt{fi},\mathtt{e}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{b},\mathtt{m}\}\,A_{jy}$
$A_i\,\mathtt{NT}\,A_j$	North	$A_{ix}\,\{\mathtt{d},\mathtt{di},\mathtt{s},\mathtt{si},\mathtt{f},\mathtt{fi},\mathtt{e}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{bi},\mathtt{mi}\}\,A_{jy}$
$A_i\,\mathtt{WT}\,A_j$	West	$A_{ix}\,\{\mathtt{b},\mathtt{m}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{d},\mathtt{di},\mathtt{s},\mathtt{si},\mathtt{f},\mathtt{fi},\mathtt{e}\}\,A_{jy}$
$A_i\,\mathtt{ET}\,A_j$	East	$A_{ix}\,\{\mathtt{bi},\mathtt{mi}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{d},\mathtt{di},\mathtt{s},\mathtt{si},\mathtt{f},\mathtt{fi},\mathtt{e}\}\,A_{jy}$
$A_i\,\mathtt{NW}\,A_j$	Northwest	$(A_{ix}\,\{\mathtt{b},\mathtt{m}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{bi},\mathtt{mi},\mathtt{oi}\}\,A_{jy}) \vee (A_{ix}\,\{\mathtt{o}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{bi},\mathtt{mi}\}\,A_{jy})$
$A_i\,\mathtt{NE}\,A_j$	Northeast	$(A_{ix}\,\{\mathtt{bi},\mathtt{mi}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{bi},\mathtt{mi},\mathtt{oi}\}\,A_{jy}) \vee (A_{ix}\,\{\mathtt{oi}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{bi},\mathtt{mi}\}\,A_{jy})$
$A_i\,\mathtt{SW}\,A_j$	Southwest	$(A_{ix}\,\{\mathtt{b},\mathtt{m}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{b},\mathtt{m},\mathtt{o}\}\,A_{jy}) \vee (A_{ix}\,\{\mathtt{o}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{b},\mathtt{m}\}\,A_{jy})$
$A_i\,\mathtt{SE}\,A_j$	Southeast	$(A_{ix}\,\{\mathtt{b},\mathtt{m}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{b},\mathtt{m},\mathtt{o}\}\,A_{jy}) \vee (A_{ix}\,\{\mathtt{oi}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{b},\mathtt{m}\}\,A_{jy})$
$A_i\,\mathtt{LT}\,A_j$	Left	$A_{ix}\,\{\mathtt{b},\mathtt{m}\}\,A_{jx}$
$A_i\,\mathtt{RT}\,A_j$	Right	$A_{ix}\,\{\mathtt{bi},\mathtt{mi}\}\,A_{jx}$
$A_i\,\mathtt{BL}\,A_j$	Below	$A_{iy}\,\{\mathtt{b},\mathtt{m}\}\,A_{jy}$
$A_i\,\mathtt{AB}\,A_j$	Above	$A_{iy}\,\{\mathtt{bi},\mathtt{mi}\}\,A_{jy}$
$A_i\,\mathtt{EQ}\,A_j$	Equal	$A_{ix}\,\{\mathtt{e}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{e}\}\,A_{jy}$
$A_i\,\mathtt{IN}\,A_j$	Inside	$A_{ix}\,\{\mathtt{d}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{d}\}\,A_{jy}$
$A_i\,\mathtt{CT}\,A_j$	Contain	$A_{ix}\,\{\mathtt{di}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{di}\}\,A_{jy}$
$A_i\,\mathtt{CV}\,A_j$	Cover	$(A_{ix}\,\{\mathtt{di}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{fi},\mathtt{si},\mathtt{e}\}\,A_{jy}) \vee (A_{ix}\,\{\mathtt{e}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{di},\mathtt{fi},\mathtt{si}\}\,A_{jy}) \vee$ $(A_{ix}\,\{\mathtt{fi},\mathtt{si}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{di},\mathtt{fi},\mathtt{si},\mathtt{e}\}\,A_{jy})$
$A_i\,\mathtt{CB}\,A_j$	Covered By	$(A_{ix}\,\{\mathtt{d}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{f},\mathtt{s},\mathtt{e}\}\,A_{jy}) \vee (A_{ix}\,\{\mathtt{e}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{d},\mathtt{f},\mathtt{s}\}\,A_{jy}) \vee$ $(A_{ix}\,\{\mathtt{f},\mathtt{s}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{d},\mathtt{f},\mathtt{s},\mathtt{e}\}\,A_{jy})$
$A_i\,\mathtt{OL}\,A_j$	Overlap	$A_{ix}\,\{\mathtt{d},\mathtt{di},\mathtt{s},\mathtt{si},\mathtt{f},\mathtt{fi},\mathtt{o},\mathtt{oi},\mathtt{e}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{d},\mathtt{di},\mathtt{s},\mathtt{si},\mathtt{f},\mathtt{fi},\mathtt{o},\mathtt{oi},\mathtt{e}\}\,A_{jy}$
$A_i\,\mathtt{TC}\,A_j$	Touch	$(A_{ix}\,\{\mathtt{m},\mathtt{mi}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{d},\mathtt{di},\mathtt{s},\mathtt{si},\mathtt{f},\mathtt{fi},\mathtt{o},\mathtt{oi},\mathtt{m},\mathtt{mi},\mathtt{e}\}\,A_{jy}) \vee$ $(A_{ix}\,\{\mathtt{d},\mathtt{di},\mathtt{s},\mathtt{si},\mathtt{f},\mathtt{fi},\mathtt{o},\mathtt{oi},\mathtt{m},\mathtt{mi},\mathtt{e}\}\,A_{jx} \wedge A_{iy}\,\{\mathtt{m},\mathtt{mi}\}\,A_{jy})$
$A_i\,\mathtt{DJ}\,A_j$	Disjoint	$A_{ix}\,\{\mathtt{b},\mathtt{bi}\}\,A_{jx} \vee A_{iy}\,\{\mathtt{b},\mathtt{bi}\}\,A_{jy}$

Table 2: Directional and Topological Relation Definitions

that can describe how an object moves and how an object relates to other objects is clearly more expressive than the above model. In the remainder, we describe such a model.

Definition 4 Let A_i and A_j be two moving objects. Their *moving spatio-temporal relationship* (abbreviated as *mst-relation*) during time interval I_k is $A_i\ (\alpha, \beta, I_k)\ A_j$ where α is any topological relation and β is either one of the 12 directional relations or `NULL` which means no directional relation. Both $A_i \alpha A_j$ and $A_i \beta A_j$ are true during the interval I_k. For a given ordered list of time intervals $\langle I_1, I_2, \ldots, I_n \rangle$, all the mst-relations of A_i and A_j are defined by an *mst-list*:

$$\langle (\alpha_1, \beta_1, I_1), (\alpha_2, \beta_2, I_2), \ldots, (\alpha_n, \beta_n, I_n) \rangle.$$

From the definition, we can see that the spatial relationships over a time period between moving objects are captured by both their topological and directional relations. `NULL` is necessary because two objects may have no any directional relation, such as when A_i is *inside* of A_j. The following example further illustrates the concept of an mst-relation and an mst-list. It also indicates that the mst-relations of two objects are neither symmetric nor unique.

Example 2 Figure 2 shows two moving objects that approach, overlap, and then move away from each other. This figure might represent two friends meeting on a street, shaking hands or hugging, and then passing each other. During time intervals I_1 and I_2, the mst-relations between A_i and A_j are $(\mathtt{DJ}, \mathtt{WT}, I_1)$ and $(\mathtt{DJ}, \mathtt{WT}, I_2)$. Other relations are A_i $(\mathtt{TC}, \mathtt{WT}, I_3)$ A_j, A_i $(\mathtt{OL}, \mathtt{NULL}, I_4)$ A_j, A_i $(\mathtt{TC}, \mathtt{ET}, I_5)$ A_j, and A_i $(\mathtt{DJ}, \mathtt{ET}, I_6)$ A_j. Note that the mst-relation between A_j and A_i at interval I_3 is $(\mathtt{TC}, \mathtt{ET}, I_3)$, which is different from A_i $(\mathtt{TC}, \mathtt{WT}, I_3)$ A_j. Hence, generally $A_i \theta A_j \neq A_j \theta A_i$ where θ is an mst-relation. Such a non-symmetric property is caused by the directional relations. However, we can always derive the mst-relation between A_j and A_i from the mst-relation between A_i and A_j using inverse directional relations. The mst-list of A_i and A_j over ordered time interval $\langle I_1, I_2, \ldots, I_6\rangle$ is $\langle(\mathtt{DJ}, \mathtt{WT}, I_1), (\mathtt{DJ}, \mathtt{WT}, I_2), (\mathtt{TC}, \mathtt{WT}, I_3), (\mathtt{OL}, \mathtt{NULL}, I_4), (\mathtt{TC}, \mathtt{ET}, I_5), (\mathtt{DJ}, \mathtt{ET}, I_6)\rangle$. The mst-list is not unique. For example, since, $A_i \,\mathtt{WT}\, A_j$ can deduce $A_i \,\mathtt{LT}\, A_j$ and $A_i \,\mathtt{ET}\, A_j$ can deduce $A_i \,\mathtt{RT}\, A_j$ according to the definitions of spatial directional relations, we can have another mst-list for A_i and A_j:
$\langle(\mathtt{DJ}, \mathtt{LT}, I_1), (\mathtt{DJ}, \mathtt{LT}, I_2), (\mathtt{TC}, \mathtt{LT}, I_3), (\mathtt{OL}, \mathtt{NULL}, I_4), (\mathtt{TC}, \mathtt{RT}, I_5), (\mathtt{DJ}, \mathtt{RT}, I_6)\rangle$.

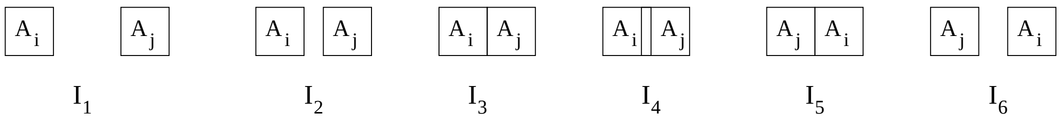


Figure 2: Two Moving Objects

3.4 Matching Moving Objects

Matching trajectories and mst-lists are useful in handling user queries. In this subsection we introduce two algorithms to accomplish such a task. Consider a video ODBMS and the query "*Is there any object whose trajectory matches the trajectory of object* A?". A's trajectory, denoted by $\langle T_1, T_2, \ldots, T_m\rangle$, can be given through a graphical user interface. Therefore, we need a systematic way to find any object from the database whose trajectory matches A's. The problem can be restated slightly differently: Does the trajectory of A match the trajectory $\langle U_1, U_2, \ldots, U_n\rangle$ of any object B? To facilitate the retrieval of a particular motion from a trajectory, a set of linked lists is used to represent the trajectory of B. Each list head corresponds to a directional relation and each entry consists of an integer and a pointer to the next element. The integer represents the relative order of a particular displacement in the trajectory and it can be viewed as an index to the object's time intervals. For example, Figure 3(a) shows a linked list representation for the trajectory of Figure 1(b). The first entry in Figure 3(a) indicates that the object is displaced in the `NT` direction as the second move in its trajectory.

(a) Ai's Trajectory Link List

(b) Link List for an MST-set

Figure 3: Data Structures for Trajectory and MST-list

Similarly we can have a linked list representation for an mst-list of two moving objects. The only change we need is to accommodate topological relations. The data structure of the linked list for mst-lists is shown in Figure 3(b). The first column, T_t, is a topological relation with $1 \leq t \leq 8$ and the second column R_{tr_i} is a directional relation or `NULL` with $1 \leq r_i \leq 13$ $(1 \leq i \leq t)$.

We are now in a position to introduce our algorithms for matching objects' trajectories. Figure 4 presents an algorithm to test whether object A's trajectory matches object B's trajectory. The structure *linklist* is exactly the same structure as in Figure 3(a). Only B's trajectory must be represented by this structure. Statement (3) indicates that if the number of motions of A is higher than the number of motions of B, then A does not match B. Although in this case B may match A, we consider this to be a different case. Statements (4) and (5) look for B's first motion which is exactly the same as A's first motion. If there is no such match, FALSE is returned. Otherwise, the proper head pointer of B's linked list is located and from there a sequential comparison is conducted within the trajectories of A and B. The matching algorithm is efficient. The first **while** statement is a constant (no bigger than 8) and the second **while** statement combined with its inner **while** statement is equivalent to the size of A's trajectory at most. Therefore, the worst case is either when a match is found or a failure during last comparison. Both cases

```
TrajectoryMatch(A, B)
INPUT: A = {T_1, T_2, ..., T_m}: A's trajectory
    B = {U_1, U_2, ..., U_n}: B's trajectory and represented by
        struct linklist { int ID; struct linklist *next; } DIR[8];
OUTPUT: TRUE /* A and B's trajectories match */
          FALSE /* A and B's trajectories do not match */
        int i, k = 1;
        struct linklist x; /* temporal variable */
        if (m > n) return FALSE;
        while (DIR[k] ≠ empty AND T_1 ≠ DIR[k].ID) k++;
        if (DIR[k] == empty) return FALSE;
        x = DIR[k].next;
        while (x ≠ empty) {
            i = 1;
            while (i ≤ m AND (i + x.ID)< n) {
                if (T_i ≠ x.ID) break;
                    i++;
            } /* end of inner while */
            if (i > m) return TRUE;
            x = x.next;
        } /* end of outer while */
        return FALSE;
```

Figure 4: Trajectory Match Algorithm

require at least A's trajectory size comparison because it is less than B's trajectory size.

A similar algorithm for mst-lists is given in Figure 5. The only change is the data structure of the linked list. Here, we have to consider the topological relations. The data values are captured by TOPID (topological) and DIRID (directional) in the algorithm. This change results in some related changes in mst-list comparisons.

These two algorithms are exact match algorithms. However, it is well-known that exact match queries *normally* generate few results in multimedia systems. Therefore, fuzzy (similarity) queries must be supported. A query is *fuzzy* if the properties of objects being queried are not precisely defined (like a *big region*) or the comparison operators in the query cannot provide exact matches. Again let us consider object trajectories first. In the case of object displacement, the similarity of two displacements can be measured by a predefined *tolerance*. However, in the case of directional relations a new measurement metric has to be introduced to describe the similarity. Our approach to this problem is to manually assign a

```
MstMatch(A, B)
INPUT: A = {M_1, M_2, ..., M_m}: object A's trajectory
    B = {N_1, N_2, ..., N_n}: B's trajectory and represented by
        struct linklist { int TOPID, DIRID; struct linklist *next; } TOPDIR[8 * 13];
OUTPUT: TRUE /* A and B's trajectories match */
        FALSE /* A and B's trajectories do not match */
(1)     int i, k = 1;
(2)     struct linklist x; /* temporal variable */
(3)     if (m > n) return FALSE;
(4)     while (TOPDIR[k] ≠ empty ∧ (M_1 ≠ TOPDIR[k].TOPID ∨ M_1 ≠ TOPDIR[k].DIRID))
            k++;
(5)     if (TOPDIR[k] == empty) return FALSE;
(6)     x = TOPDIR[k].next;
(7)     while (x ≠ empty) {
(8)         i = 1;
(9)         while (i ≤ m ∧ (i + x.TOPID) < n) {
(10)            if (M_i ≠ x.TOPID ∨ M_i ≠ x.DIRID) break;
(11)                i++;
(12)        } /* end of inner while */
(13)        if (i > m) return TRUE;
(14)        x = x.next;
(15)    } /* end of outer while */
(16)    return FALSE;
```

Figure 5: MST-Relation Match Algorithm

distance value between any two directional relations as shown in the first eight columns and the first eight rows of Table 3. For example, $distance(\texttt{NT}, \texttt{NW}) = 1$. The way these values are assigned is completely determined by their *closeness* to each other. For example, *northwest* and *northeast* should have the same closeness value to direction *north*. They should be *closer* to the *north* than *west*, *east*, and *south* are. The smallest value of a distance is zero which is an exact match and the the biggest value of a distance is four which is the opposite direction. For example, the distance of north (`NT`) versus south (`ST`) is 4. The other table entries will be discussed later.

Definition 5 Let $\{T_1, T_2, \ldots, T_m\}$ $(m \geq 1)$ be the trajectory of A, $\{U_1, U_2, \ldots, U_n\}$ be the trajectory of B, and $m \leq n$. *minDiffTraj*(A, B) is the smallest distance between A and B calculated as follows:

$$minDiffTraj(A, B) \ = \ MIN \ \{\sum_{i=1}^{m} distance(T_i, U_{i+j})\} \quad (\forall j \ 0 \leq j \leq n - i).$$

The largest difference between A and B occurs only if A's direction of movement is always opposite to

B's direction in all the comparisons. Such a case can be quantified by *maxDiffTraj*$(A, B) = 4 * m$ since the maximum number of comparing motions is m. In order to present a uniform standard for measuring similarity to end users, a normalized similarity function for the trajectory of A and B is defined as

$$TrajSim(A, B) = \frac{\mathit{maxDiffTraj}(A, B) - \mathit{minDiffTraj}(A, B)}{\mathit{maxDiffTraj}(A, B)}.$$

Function $TrajSim(A, B)$ defines a similarity degree of the trajectories of A and B and its domain is $[0, 1]$. For example, in the case *minDiffTraj*$(A, B) = 0$, we have $TrajSim(A, B) = 1$ which indicates an exact match. In the case *minDiffTraj*(A, B) = *maxDiffTraj*(A, B), we have $TrajSim(A, B) = 0$ which indicates that A always moves in the opposite direction of B, and that the similarity between A and B's trajectories is minimum.

The similarity function of two mst-lists can be defined in a similar manner. The directional relations must be extended to include positional relations and `NULL`, as presented in Table 3. The distance values of positional relations are assigned in the same manner as we did for other directional relations. The distance values between `NULL` and directional relations are assigned as an average distance among others, which is 2. In the case of assigning distance values for topological relations the problem is more complicated. A distance scheme of topological relations is presented in [EAT92] which we adopt as Table 4. The rationale of this scheme is based on the *closeness* of these relations when they evolve from one to other. Hence, we can compute the similarity function for mst-lists using a function analogous to $TrajSim$.

	NT	NW	NE	WT	SW	ET	SE	ST	LT	RT	AB	BL	NULL
NT	0	1	1	2	3	2	3	4	3	3	1	4	2
NW	1	0	2	1	2	3	4	3	2	4	2	4	2
NE	1	2	0	3	4	1	2	3	4	2	2	4	2
WT	2	1	3	0	1	4	3	2	1	4	3	3	2
SW	3	2	4	1	0	3	2	1	2	4	4	2	2
ET	2	3	1	4	3	0	1	2	4	1	3	3	2
SE	3	4	2	3	2	1	0	1	4	2	4	2	2
ST	4	3	3	2	1	2	1	0	3	3	4	1	2
LT	3	2	4	1	2	4	4	3	0	4	2	2	2
RT	3	4	2	4	4	1	2	3	4	0	2	2	2
AB	1	2	2	3	4	3	4	4	2	2	0	4	2
BL	4	4	4	3	2	3	2	1	2	2	4	0	2
NULL	2	2	2	2	2	2	2	2	2	2	2	2	0

Table 3: Distances of Directional Relations

	DJ	TC	EQ	IN	CB	CT	CV	OL
DJ	0	1	6	4	5	4	5	4
TC	1	0	5	5	4	5	4	3
EQ	6	5	0	4	3	4	3	6
IN	4	5	4	0	1	6	7	4
CB	5	4	3	1	0	7	6	3
CT	4	5	4	6	7	0	1	4
CV	5	4	3	7	6	1	0	3
OL	4	3	6	4	3	4	3	0

Table 4: Distances of Topological Relations (Table 1 in [EAT92])

Definition 6 Let $\{M_1, M_2, \ldots, M_m\}$ $(m \geq 1)$ be the mst-list of A, $\{N_1, N_2, \ldots, N_n\}$ be the mst-list of B, and $m \leq n$. *minDiffMst*(A, B) is the smallest distance between A and B:

$$minDiffMst(A,B) \;=\; MIN\ \{\sum_{i=1}^{m} distance(M_i, N_{i+j})\} \quad (\forall j\ 0 \leq j \leq n-i)$$

where $distance(M_i, N_{i+j}) = distance(\alpha(M_i, N_{i+j})) + distance(\beta(M_i, N_{i+j}))$ where α and β are the topological relation and the directional relation of an mst-relation respectively. $maxDiffMst(A,B) = 4*m+7*m$ since the maximum distance value of a topological relation is 7. An mst-list similarity function is defined as

$$MstSim(A,B) = \frac{maxDiffMst(A,B) - minDiffMst(A,B)}{maxDiffMst(A,B)}.$$

We do not consider the time intervals during the match because it is less important than the spatial relations. If there is some interest in knowing the time length of a motion, the extension to the algorithms is straightforward.

4 Integrating the Moving Object Model into an ODBMS

4.1 The ODBMS Support

To have proper database management support for continuous media, this model needs to be integrated into a data model. We work within the framework of a uniform, behavioral object model such as the one supported by the TIGUKAT system [ÖPS+95]. The important characteristics of the model, from the perspective of this paper, are its *behaviorality* and and its *uniformity*. The model is *behavioral* in the sense that all access and manipulation of objects is based on the application of behaviors to objects. The model is *uniform* in that every component of information, including its semantics, is modeled as a *first-class object* with well-defined behavior. The typical object-oriented features, such as strong object identity, abstract types, strong typing, complex objects, full encapsulation, multiple inheritance, and parametric types are also supported.

The primitive objects of the model include: *atomic entities* (reals, integers, strings, etc.); *types* for defining common features of objects; *behaviors* for specifying the semantics of operations that may be performed on objects; *functions* for specifying implementations of behaviors over types; *classes* for automatic classification of objects based on type; and *collections* for supporting general heterogeneous groupings of objects. In this paper, a reference prefixed by "T_" refers to a type, "**C_**" to a class, "*B_*" to a behavior, and "T_X< T_Y >" to the type T_X parameterized by the type T_Y. For example, `T_person` refers to a type, **C_person** to its class, *B_age* to one of its behaviors and `T_collection< T_person >` to the type of collections of persons. A reference such as *David*, without a prefix, denotes some other application specific reference. Consequently, the model separates the definition of object characteristics (a *type*) from the mechanism for maintaining instances of a particular type (a *class*). The primitive type system is a complete lattice with the `T_object` type as the root of the lattice and the `T_null` type as the base.

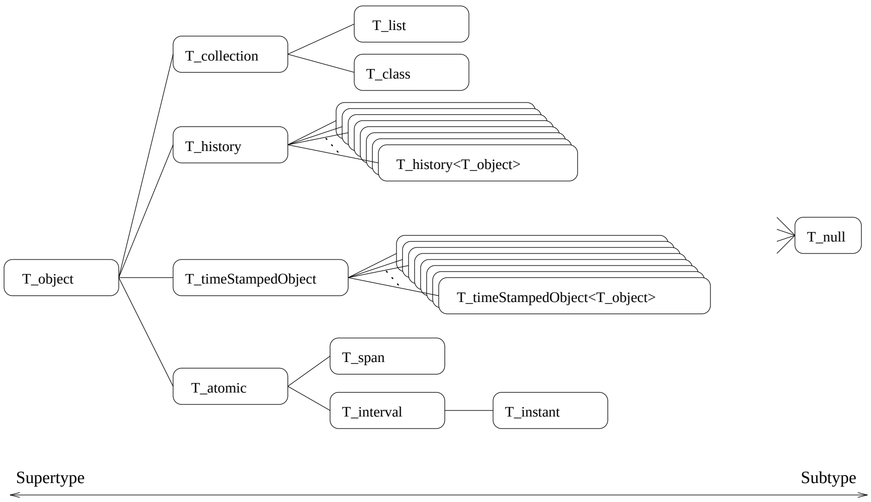


Figure 6: The Basic Time Type Hierarchy

Temporality has been added to this model [GLÖS96] as type and behavior extensions to the type system discussed above. Figure 6 gives part of the time type hierarchy that includes the temporal ontology and temporal history features of the temporal model. Unary operators which return the lower bound, upper bound, and length of the time interval are defined. The model supports a rich set of ordering operations among intervals, e.g., *before*, *overlaps*, *during*, etc. (see Table 1) as well as set-theoretic operations, viz. *union*, *intersection* and *difference*. A time duration can be added or subtracted from a time interval to return another time interval. A time interval can be expanded or shrunk by a specified time duration.

A *time instant* (*moment*, *chronon*, etc.) is a specific anchored moment in time. A time instant can be compared with a time interval to check if it falls before, within, or after the time interval. A *time span* is an unanchored relative duration of time; it is basically an atomic cardinal quantity, independent of any time instant or time interval. One requirement of a temporal model is an ability to adequately represent and manage histories of objects and real-world events. Our model represents the temporal histories of objects whose type, is `T_X` as objects of the `T_history<T_X>` type as shown in Figure 6. A temporal history consists of objects and their associated timestamps (time intervals or time instants). A *timestamped object* knows its timestamp and its associated object (value) at (during) the timestamp. A temporal history is made up of such objects. Table 5 gives the behaviors defined on histories and timestamped objects. Behavior *B_history* defined on `T_history<T_X>` returns the set (collection) of all timestamped objects that comprise the history. Another behavior defined on history objects, *B_insert*, timestamps and inserts an object into the history. The *B_validObjects* behavior allows the user to get the objects in the history that were valid at (during) the given time.

`T_history<T_X>`	*B_history*:	`T_collection<T_timeStampedObject<T_X>>`
	B_insert:	`T_X,T_interval` → `T_boolean`
	B_validObjects:	`T_interval` → `T_collection<T_timeStampedObject<T_X>>`
`T_timeStampedObject<T_X>`	*B_value*:	`T_X`
	B_timeStamp:	`T_interval`

Table 5: Behaviors on Histories and Time-stamped Objects

Each timestamped object is an instance of the `T_timeStampedObject<T_X>` type. This type represents objects and their corresponding timestamps. Behaviors *B_value* and *B_timeStamp*, defined on `T_timeStampedObject`, return the value and the timestamp of a timestamped object, respectively.

4.2 Integrating Moving Objects

Figure 7 shows our video type system. `T_discrete` defines all discrete value types so that all the subtypes of `T_discrete` are enumerated types. The types that are in a grey shade will be discussed in this paper. Detailed descriptions of the rest of the types can be found in [LGÖS97]. For the completeness of the discussion we list all the primitive behaviors of `T_video`, `T_clip`, and `T_frame` in Table 6 without giving any explanation.

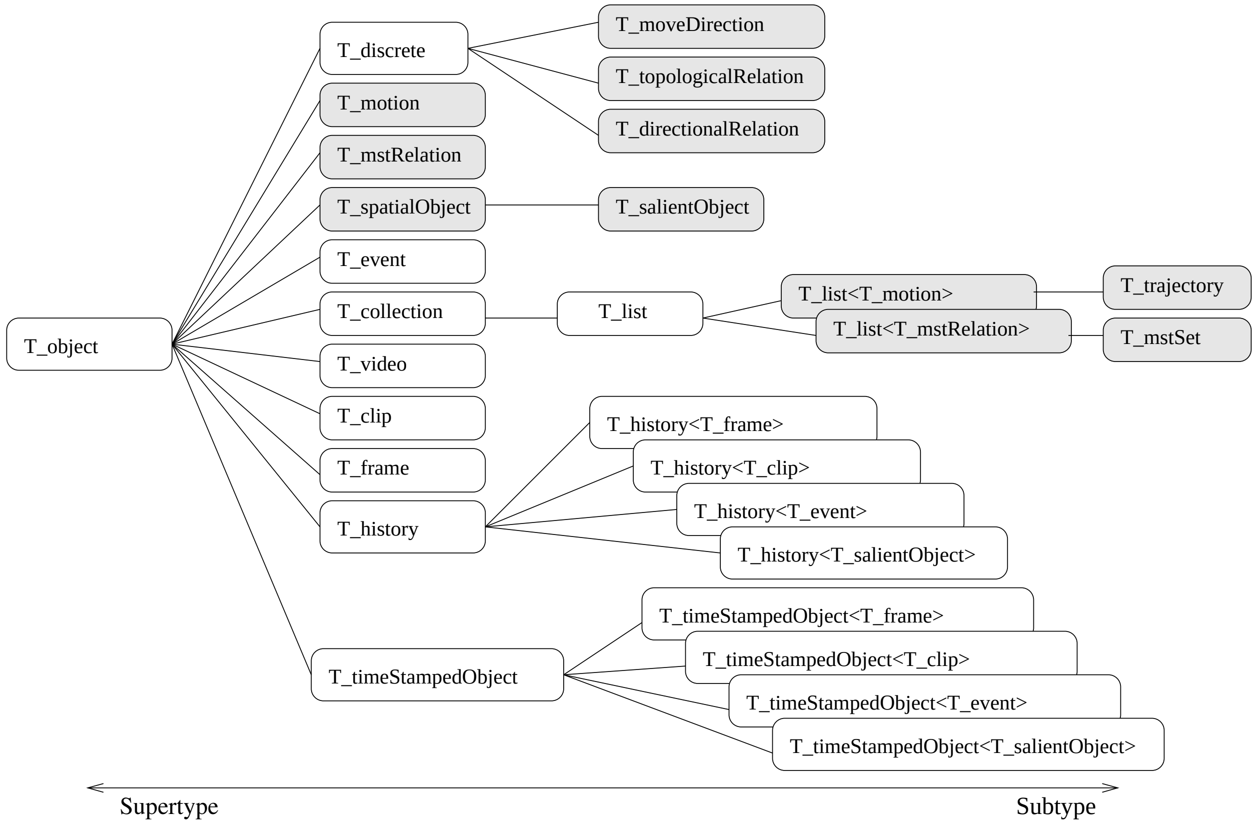


Figure 7: The Video Type System

The semantics or contents of a video are usually expressed by its *features* which include video attributes and the relationships between these attributes. Typical video features are salient objects and *events*. We focus on salient objects, more specifically moving salient objects. Since objects can appear multiple times in a clip or a video, we model the history of an object as a timestamped object of type `T_history` < `T_salientObject` >. The behavior *B_salientObjects* of `T_clip` returns all the objects within a clip. Using histories to model objects enables us to uniformly capture the temporal semantics of video data because a video is modeled as a history of clips and a clip is modeled as a history of frames.

Any object occupying some space is an instance of `T_spatialObject`. Table 7 shows the behavior signatures of spatial objects. The behaviors *B_xinterval* and *B_yinterval* of type `T_spatialObject` define an object's 2D intervals and are computed from the projections of the object's MBR over x and y axes. The behavior *B_centroid* returns the centroid of the object while the behavior *B_area* returns the area of

T_video	*B_clips*:	T_history<T_clip>
	B_length:	T_span
	B_publisher:	T_collection<T_company>
	B_producer:	T_collection<T_person>
	B_date:	T_date
	B_play:	T_boolean
T_clip	*B_frames*:	T_history< T_frame >
	B_salientObjects:	T_collection<T_timeStampedObject<T_salientObject>>
	B_events:	T_collection<T_timeStampedObject<T_event>>
	B_format:	T_videoFormat
T_frame	*B_location*:	T_instant
	B_content:	T_image

Table 6: Primitive Behavior Signatures of Videos, Clips, and Frames

T_spatialObject	*B_xinterval*:	T_interval
	B_yinterval:	T_interval
	B_centroid:	T_point
	B_area:	T_real
	B_displacement:	T_instant,T_instant → T_real
	B_distance:	T_spatialObject, T_instant → T_real
	B_south:	T_spatialObject → T_boolean
	B_north:	T_spatialObject → T_boolean
	B_west:	T_spatialObject → T_boolean
	B_east:	T_spatialObject → T_boolean
	B_northwest:	T_spatialObject → T_boolean
	B_northeast:	T_spatialObject → T_boolean
	B_southwest:	T_spatialObject → T_boolean
	B_southeast:	T_spatialObject → T_boolean
	B_left:	T_spatialObject → T_boolean
	B_right:	T_spatialObject → T_boolean
	B_below:	T_spatialObject → T_boolean
	B_above:	T_spatialObject → T_boolean
	B_equal:	T_spatialObject → T_boolean
	B_inside:	T_spatialObject → T_boolean
	B_contain:	T_spatialObject → T_boolean
	B_overlap:	T_spatialObject → T_boolean
	B_cover:	T_spatialObject → T_boolean
	B_coveredBy:	T_spatialObject → T_boolean
	B_touch:	T_spatialObject → T_boolean
	B_disjoint:	T_spatialObject → T_boolean
T_salientObject	*B_inClips*:	T_video → T_collection<T_timeStampedObject<T_clip>>
	B_trajectory:	T_trajectory
	B_mstSet:	T_salientObject → T_mstSet
T_trajectory	*B_exactMatch*:	T_trajectory → T_boolean
	B_simMatch:	T_trajectory → T_real
	B_subtrajectory:	T_interval → T_trajectory
T_mstSet	*B_exactMatch*:	T_mstSet → T_boolean
	B_simMatch:	T_mstSet → T_real
	B_submstSet:	T_interval → T_mstSet
T_motion	*B_displacement*:	T_interval → T_real
	B_moveDirection:	T_moveDirection
T_mstRelation	*B_topology*:	T_topologicalRelation
	B_direction:	T_directionalRelation
	B_interval:	T_interval

Table 7: Primitive Behavior Signatures of Spatial and Salient Objects

the region occupied by the object. The distance between objects at a certain time and the displacement of an object over time are captured by *B_distance* and *B_displacement*.

In type `T_salientObject`, a subtype of `T_spatialObject`, the behavior *B_inClips* returns all the clips in which the object appears. *B_trajectory* of `T_salientObject` returns type `T_trajectory` which is a list of moving object's motions (`T_list` $<$ `T_motion` $>$). A *list* is an ordered collection. Similarly, the behavior *B_mstSet* returns type `T_mstSet` which is a list of two moving objects' mst-relations (`T_list`$<$`T_mstRelation`$>$). *B_exactMatch* is the exact match algorithm (for either trajectories or mst-lists) described in Figure 4 and Figure 5. *B_simMatch* of `T_trajectory` returns the similarity degree of two trajectories, which is captured by the similarity function $trajSim(A, B)$. The returned value is a real number between 0 and 1. The behavior *B_simMatch* of `T_mstSets` is the similarity function $mstSim(A, B)$ for two moving objects' mst-list. *B_subtrajectory* and *B_submstSet* return part of a trajectory and part of an mst-list, respectively, for a given time interval. `T_motion` describes one motion of a moving object while `T_mstRelation` describes one mst-relation of two moving objects. `T_moveDirection`, `T_topologicalRelation`, and `T_directionalRelation` are enumerated types and they represent the eight moving directions, the eight topological relations, and the twelve directional relations plus `NULL`, respectively.

Example 3 Let *mary* and *dog* be two timestamped salient objects. Their spatial relations at time t (or frame t) can be decided by first restricting *mary* and *dog* to a common time interval. That is, we assume t is a time interval t (whose starting time and ending times are both t) and that both t.*B_during*(*mary*.*B_timeStamp*) and t.*B_during*(*dog*.*B_timeStamp*) are true. Then we compare the spatial intervals of *mary* and *dog* according to the definitions given in Table 2 to check what topological and directional relations exist. These spatial intervals of *mary* can be extracted by *mary*.*B_value*.*B_xinterval* and *mary*.*B_value*.*B_yinterval*. Similarly, we have *dog*.*B_value*.*B_xinterval* and *dog*.*B_value*.*B_yinterval* for the spatial intervals of *dog*. The trajectory of *dog* is expressed by *dog*.*B_trajectory*. The mst-list of *dog* and *mary* is captured by *dog*.*B_mstSet*(*mary*).

5 Query Examples

In this section we present some examples to show the expressiveness of our model from the point of view of spatial properties. We use Object Query Language (OQL) [Cat94] which is proposed by Object Database

Management Group (ODMG), a consortium of object database management system (ODBMS) vendors and interested parties working on standards to allow portability of customer software across ODBMS products. Syntactically, OQL is very similar to SQL. It is currently supported by most major ODBMS vendors and its popularity should increase as the ODBMS market grows. OQL defines an orthogonal expression language, in the sense that all operators can be composed with each other as long as the types of the operands are correct. It deals with complex objects without changing the set construct and the select-from-where clause. It also includes high-level primitives to deal with bulk objects like structures, lists, and arrays. As a stand-alone language, OQL allows users to query objects by using their names as entry points into a database. We assume that all the queries are posted to a particular video instance *myVideo* and salient objects and events are timestamped objects as discussed in Section 4.

Query 1 In clip c find all the objects which have a similar trajectory as shown in Figure 1(b) denoted by *myTraj*.

select x.value
from x **in** *c.B_SalientObjects*
where *x.B_value.B_trajectory.B_simMatch(myTraj)* $> r$

where c is a clip object instance provided by users. For each object x in clip c, the trajectory of x is checked against *myTraj*. Such a comparison is determined by the similarity matching function between this two trajectories. r is a predefined (or user-provided) threshold valued between $[0, 1]$ for qualifying a match.

Query 2 Find clips in which object a is to the left of object b and later the two exchange their positions.

select c
from *x1,x2,y1,y2* **in** *c.B_salientObjects*, c **in** **C_clip**
where *x1.B_value*=a **and** *y1.B_value*=b **and** *x2.B_value*=a **and** *y2.B_value*=b **and**
x1.B_timeStamp = *y1.B_timeStamp* **and** *x1.B_value.B_left(y1.B_value)* **and**
x2.B_timeStamp = *y2.B_timeStamp* **and** *y2.B_value.B_left(x2.B_value)* **and**
x2.B_timeStamp.B_after(x1.B_timeStamp)

Suppose clip c is the one we are looking for. Then there must be two timestamped objects, denoted by *x1* and *y1* respectively, in c's salient object set so that *x1* is a and *y1* is b. Similarly, two other timestamped objects, denoted by *x2* and *y2* respectively, must exist in c's salient object set so that *x2* is a and *y2* is b. The major difference between *x1* and *x2* is in their time stamps. Here we require that *x2* appears later than *x1* (*x2.B_timeStamp.B_after(x1.B_timeStamp)*). Therefore, if *x1* is to the left of *y1* at the time *x1.B_timeStamp* and *y2* is to the left of *x2* at time *x2.B_timeStamp*, we are sure that a and b

have exchanged their directional positions. Such a query might be expressed by Figure 2 in Example 2 using a graphical user interface. Let *myMstSet* represent the specified mst-list, we could simplify the query as

select c
from x,y **in** $c.B\_salientObjects$, c **in** **C_clip**
where $x.B\_value{=}a$ **and** $y.B\_value{=}b$ **and** $x.B\_value.B\_mstSet(y.B\_value).B\_exactMatch(myMstSet)$

Query 3 Find clips in which a dog approaches Mary from the left.

select c
from $x1,x2,y1,y2$ **in** $c.B\_salientObjects$, c **in** **C_clip**
where $x1.B\_value{=}dog$ **and** $y1.B\_value{=}mary$ **and** $x2.B\_value{=}dog$ **and** $y2.B\_value{=}mary$ **and**
$x1.B\_timeStamp = y1.B\_timeStamp$ **and** $x1.B\_value.B\_left(y1.B\_value)$ **and**
$x2.B\_timeStamp = y2.B\_timeStamp$ **and** $x2.B\_value.B\_left(y2.B\_value)$ **and**
$x2.B\_timeStamp.B\_after(x1.B\_timeStamp)$ **and**
$x1.B\_value.B\_displacement(x1.B\_timeStamp,\ x2.B\_timeStamp) >= h1$ **and**
$xy.B\_value.B\_displacement(x1.B\_timeStamp,\ x2.B\_timeStamp) <= h2$ **and**

where *dog* and *mary* are the references of two instances of `T_salientObject`. Suppose clip c is what we are looking for and two salient objects, denoted by $x1$ and $x2$, are introduced to represent *dog* and to reflect different timestamps. The same strategy is used for the object *mary*. Then, we compute the *dog*'s displacement over the time period and enforce this displacement to be greater than some predefined value $h1$ to insure enough movement is achieved. Furthermore, the displacement of *mary* is also computed and is required to be less than a predefined value $h2$. This particular requirement of *mary* is to guarantee that it is the dog approaching Mary from the left, instead of Mary approaching the dog from the right.

This query can also be expressed using the mst-list described in Figure 8 and we denote such an mst-list as *dogMaryMstSet*. Then, the query is

select c
from x,y **in** $c.B\_salientObjects$, c **in** **C_clip**
where $x.B\_value{=}dog$ **and** $y.B\_value{=}mary$ **and**
$x.B\_value.B\_mstSet(y.B\_value).B\_simMatch(dogMaryMstSet) >= r$

However, this mst-list does not distinguish whether it is the *dog* approaching *mary* from the left or it is *mary* approaching the *dog* from the right. An *after* constraint must be put into this expression. One way to solve this problem is to make sure that *mary*'s displacement changes very little over the time interval as we did before.

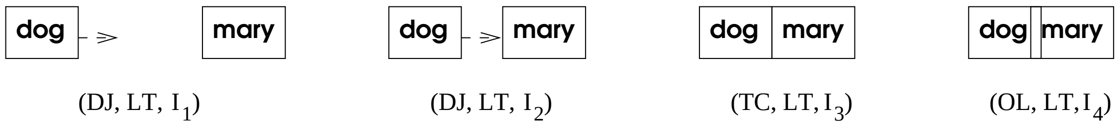


Figure 8: *dog* Approaches *mary* from Left

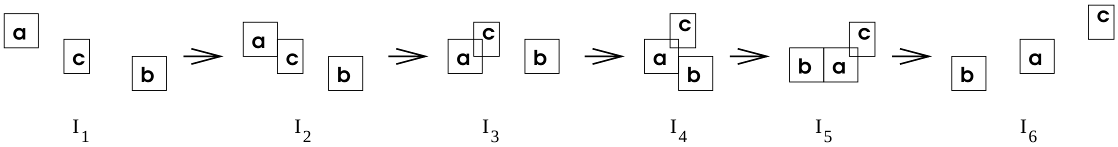


Figure 9: A Scene of Objects a, b, and c

Query 4 Retrieve all the clips which matches the scene described in Figure 9.

select *clip*
from *x,y,z* **in** *clip.B_salientObjects*, *clip* **in** **C_clip**
where *x.B_value=a* **and** *y.B_value=b* **and** *z.B_value=c* **and**
x.B_value.B_mstSet(y.B_value).B_exactMatch(abMstSet) **and**
x.B_value.B_mstSet(z.B_value).B_exactMatch(acMstSet) **and**
y.B_value.B_mstSet(z.B_value).B_exactMatch(bcMstSet)

Here, *abMstSet*, *acMstSet*, and *bcMstSet* are the mst-lists between a and b, a and b, and b and c. Furthermore, $abMstSet = \{(\mathtt{DJ}, \mathtt{NW}, I_1), (\mathtt{DJ}, \mathtt{NW}, I_2), (\mathtt{DJ}, \mathtt{LT}, I_3), (\mathtt{TC}, \mathtt{NW}, I_4), (\mathtt{TC}, \mathtt{ET}, I_5), (\mathtt{DJ}, \mathtt{NE}, I_6)\}$, $acMstSet = \{(\mathtt{DJ}, \mathtt{NW}, I_1), (\mathtt{TC}, \mathtt{NW}, I_2), (\mathtt{OL}, \mathtt{NULL}, I_3), (\mathtt{OL}, \mathtt{NULL}, I_4), (\mathtt{OL}, \mathtt{NULL}, I_5), (\mathtt{DJ}, \mathtt{SW}, I_6)\}$, and $bcMstSet = \{(\mathtt{DJ}, \mathtt{SE}, I_1), (\mathtt{DJ}, \mathtt{SE}, I_2), (\mathtt{DJ}, \mathtt{NE}, I_3), (\mathtt{DJ}, \mathtt{SE}, I_4), (\mathtt{DJ}, \mathtt{SW}, I_5), (\mathtt{DJ}, \mathtt{SW}, I_6)\}$. The scene in Figure 9 can be interpreted as part of a basketball game: at time I_1, players a and b are trying to catch the ball c, but a is faster so he touches the ball first and grabs it; since b does not get the ball, he has to try to block a's advance at time I_3; then players a and b are collide with each other, but a is still holding the ball c; at time I_5 a manages to have passed b and shoots the ball. It is a very difficult query if it is expressed verbally. We see that the query has been greatly simplified using the concept of moving spatial-temporal sets.

6 Conclusions

The most striking difference between images and videos stems from movements and variations which involve both spatial and temporal knowledge of objects. Moving objects are a very important feature of a multimedia ODBMS. In this paper we concentrate on modeling video moving objects. In particular we present a way of representing the trajectory of a moving object and we are the first to propose a model for the relative spatio-temporal relations between moving objects. The proposed representation supports a rich set of spatial topological and directional relations and it captures not only quantitative properties of objects, but also qualitative properties of objects. Algorithms for matching trajectories and spatio-temporal relations of moving objects are designed to facilitate query processing. These algorithms can handle both exact and similarity matches. A novel approach to integrating such a moving object model into an ODBMS is presented and the expressiveness of such an integrated system is demonstrated by means of example queries within the context of the TIGUKAT system. The extension of the model to three dimensional space is straightforward. We strongly believe that such a system, combined with a graphical user interface, can result in a powerful video retrieval system.

The time interval differences between moving objects are not considered in our model. Some research in matching the similarity of time intervals has been done [FRM94] and it will be interesting if we can incorporate this part into our model. In order to gain some experience, we are building a prototype based on this model and a video query language which can facilitate video queries that support spatial, temporal, and spatio-temporal queries. This will also help us to querying moving objects in a video object database.

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