A Differential Spatio-temporal Model: Primitives and Operators

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Abstract

In this paper, we present a differential change-oriented model for the storage and communication of spatio-temporal information. The focus is on the development of model primitives and operators to support the aggregation of change over time and the propagation of change across resolution. Our investigation is motivated by recent advances in image-based geospatial databases, with constantly increasing update frequencies, and diverse user communities performing queries of various levels of detail. The primitives and operators presented here extend existing qualitative operators to support the management of quantitative and geometric information within a change-oriented spatio-temporal environment. We also show how the design of our model results from 'change semantics' at different granularities. By doing so, advanced communication operations can be addressed within our model in an efficient way.
Keywords: spatio-temporal, change, differential, queries, granularity

1 Introduction

Spatio-temporal applications are increasingly the focus of research activities in the geospatial and database communities. The complexity behind the combination of spatial and temporal representations is well documented (Erwig et al, 1999; Worboys, 1994; Yeh and de Cambray, 1995; Theodoridis et al, 1998), but an efficient solution has yet to emerge (Peuquet, 2001). In early approaches, representations of objects (states) were stored at different time instances. In this case change information was handled indirectly, as it was not stored but could be calculated using the stored data. More recently we saw the introduction of change-oriented approaches, focusing mostly on qualitative attributes of geospatial entities (Peuquet and Wentz, 1995) and variations of these attributes (Hornsby and

Egenhofer, 2000). Approaches addressing the recording of positional information for mobile objects proceeded by reducing these objects to point data and ignoring their spatial extent (Pfoser et al, 2000).

In this paper we present a differential change-oriented model for the storage and communication of spatio-temporal information. We focus on the development of model primitives and operators to support the aggregation of change over time and the propagation of change across resolution. Our investigation is motivated by recent advances in image-based geospatial databases that have constantly increasing update frequencies, and increasingly diverse user communities. The primitives and operators presented here extend the qualitative operators presented by (Worboys, 1992; Hornsby and Egenhofer, 2000) to support the management of qualitative and geometric information within a change-oriented spatio-temporal environment. Thus, they complement the general framework outlined by (Peuquet and Wentz, 1995; Langran, 1993) to support the management of raster and vector geospatial data within a spatio-temporal environment.

Our paper begins with a brief description of our differential change model, followed by a more detailed presentation of change primitives and operators (Section 2). We continue by discussing the use of these operators within a differential spatio-temporal image-based model (Section 3) to demonstrate the resulting improvement in expressiveness and redundancy minimisation.

2 Differential Change Model

Developments in sensor technologies have enabled the continuous collection of geospatial data, and the constant updates of geospatial databases. This supports complex spatio-temporal analysis, but at the same time imposes interesting challenges on detecting changes in geospatial objects and managing this change information. Addressing these challenges we have developed the model of a differential spatio-temporal gazetteer, and differential image-based change detection approaches to populate this model (Agouris et al., 2000; Agouris et al., 2001). We use the term *differential* in our approach to reflect the emphasis put on change as the explicit information that is both captured and stored in our spatio-temporal model. We proceed by storing an initial state of an object (in essence change from non-existence) and all subsequent changes (Fig. 1). An object representation at any instance t_n is obtained through a multi-dimensional aggregation operator of t_0 and all subsequent changes $\Delta t_{i-1,i}$ for i=1,…n.

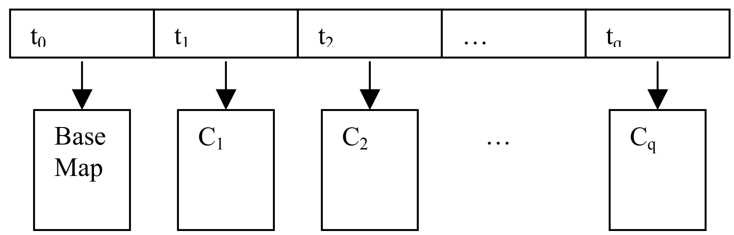


Fig. 1. A snapshot change representation model based on (Peuquet and Wentz, 1995)

This is in accordance with the conceptual model presented by (Peuquet and Wentz, 1995). In addition to being an actual implementation of this model, our approach extends it by including 'change semantics' in multiple granularities. We expand the method to work on non-grid based geometric information, since a significant part of GIS information is in vector format by making use of (Langran, 1993) representation. In addition, we present a set of change primitives and operators that can be used to represent and extract information at an index and a qualitative level within our model. These operators are naturally expressive and extend previous approaches (Worboys, 1992; Hornsby and Egenhofer, 2000) by handling quantitative and geometric information.

2.1 Primitives

Let O_j be an object from the set of objects (O), and that this object is observed in a subset T_n of the set of time instances (T). So we have:

$$\vec{O}_j \in O, T_n \in T \text{ with } T_n = [0, t_1, t_2, t_3, ..., t_n] \tag{1}$$

The representation of an object at a time instance t_n can be expressed as the (continuous) accumulation of changes that appeared from the time that the object was created (t=0) until time t_n. Or mathematically:

$$\vec{O}_j^{t_n} = \int_0^{t_n} \partial \vec{O}_j \tag{2}$$

where the integration is performed over time with limits 0 and t_n($\int_0^{t_n}$). The $\partial \vec{O}_j$ vector expresses the change of object O_j.

The efficient modelling of geospatial change is a challenging issue due to the inherently diverse nature of change itself. Towards this goal we proceed with a multi-dimensional, multi-resolution decomposition of geospatial change. Change dimensionality reflects a *semantic* analysis of the composition of geospatial entities, while resolution expresses various levels of *scale* and *abstraction* when analysing geospatial information. Our goal is to express the inherently multi-dimensional change by a set of 1-D elements, in essence the attributes stored in our change-oriented differential database.

Let's assume that change exists over a multi-dimensional set R_n. We decompose change as an aggregation of j subset dimensional spaces,

$$R^n = [C_1^{a_1}, C_2^{a_2}, ..., C_j^{a_k}] \tag{3}$$

where C_1, C_2,…,C_j define multidimensional subspaces of change, and a_1, a_2,.., a_k are the corresponding dimensions of each subspace. For example C_1 might refer to geometric change, C_2 to thematic state, etc. In this case a_1 would describe the number of dimensions necessary to describe the geometric space (of change), and a_2 would relate to the dimensions of thematic form (e.g. a_2=2, if the only thematic attributes we monitor are colour and use of an object). In a way these subspaces act as the basis of the multi-dimensional change space (R_n).

Following the above analysis we can decompose the multi-dimensional object vector $\vec{O}_j$ to its n 1-D dimensions or basis of change:

$$\vec{O}_j = [O_j^1, O_j^2, ..., O_j^n] \tag{4}$$

So the $\partial\vec{O}_j$ change vector would correspond to:

$$\partial\vec{O}_j = [\delta O_j^1, \delta O_j^2, ..., \delta O_j^n] \tag{5}$$

The δO_j 1-D element of vector $\partial\vec{O}_j$ represents the change that occurred in that dimension. Here we should mention that δO_j, like $\partial\vec{O}_j$, could not be defined without a temporal interval. Throughout the following analysis, we replace consciously $\int_{t_1}^{t_2} \delta O_j$ with δO_j to simplify things.

In order to explore the values of this element, we will define fundamental unary predicates. These predicates hold in a specific temporal interval, but for the time, we omit this.

is_ positive (δO_j) = True	if and only if in δO_j addition exists
is_ negative (δO_j) = True	if and only if in δO_j subtraction exists
is_ empty (δO_j) = True	if and only if δO_j has no change information
is_ null (δO_j) = True	if and only if δO_j has information that leads to no change

Based on the above predicates δO_j can have the following value types:

$$\delta O_j = \begin{cases} + & | \text{ is\_ positive } (\delta O_j) = \text{True} \\ - & | \text{ is\_ negative } (\delta O_j) = \text{True} \\ \mp & | \text{ is\_ negative } (\delta O_j) = \text{True } \wedge \text{ is\_ positive } (\delta O_j) = \text{True} \\ * & | \text{ is\_ empty } (\delta O_j) = \text{True} \\ \varnothing & | \text{ is\_ null } (\delta O_j) = \text{True} \end{cases}$$

The first three value types can contain further qualitative or quantitative descriptors, while the last two are defined explicitly though the value types. For example a {+} type change element might be {+3 feet} if that dimension refers to the width of the road. The third value type {$\mp$} applies when more than one predicate holds true for the specified temporal interval. A good example of this case would be a qualitative dimension, the departments that are using one building. In this case, the building is the object under examination. Within a temporal interval, maybe one department has moved out and a new one came in. In this case, we would have:

$$\int_{t_1}^{t_2} \delta O_j = \{\text{- Computer Science Dept, + Civil Engineering Dept}\} \tag{6}$$

2.2 Handling Change Within our Model

The above defined primitives can be used to create a multi-resolutional change representation (Fig. 2). At the coarser level, we have a general description of change. Change is treated as a whole without going into its' specifics and very general change semantics are used. Values of that level can be one of the following:

$$C_{q,q-1} = [+,-,*,\mp,\varnothing,\rightarrow,\leftarrow] \tag{7}$$

The first five values follow the same concept as the one introduced in the δO_j 1-D elements. More on how these values are defined is provided in the operator's section of this paper. To facilitate computations two new elements are included that act as objects and not change descriptors. The [→] sign denotes the birth of an object and the [←] represents the end of existence.

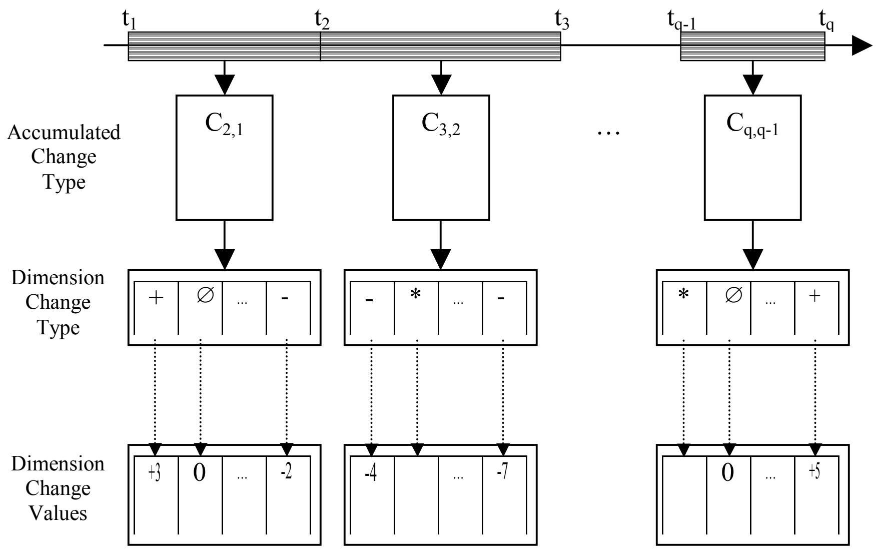


Fig. 2. Proposed change representation model

At the second level of our model, we use the value types of predicate δO_j to provide a summary (index) of change in every dimension. This level can also be described as a fundamental change semantics description in each dimension. Such indexing structures are especially important in distributed environments (Dolin et al, 1997). Since change type is indexed we can also provide a multi-resolutional query approach (Mountrakis et al, 2000) where change is treated as a binary query at first and through propagation rules the requested fields are accessed. By doing so we facilitate faster change information extraction when the specifics of change are not important, just the type/semantics of change.

At the most detailed level, we are storing the values of change in every dimension. The hierarchical structure of our model reduces the access frequency of this level, since only detailed change information triggers such access. In addition, our multi-resolutional environment can support distributed systems where the first two levels can act as indices/pointers to other databases.

2.3 Operators

In our model, we distinguish two types of operators, the ones that function horizontally and the ones that work vertically within the structure of Fig. 2. Horizontal operators *aggregate* change over time, while vertical operators *propagate* change across different resolutions for a specific temporal interval.

2.3.1 Multi-dimensional Change Value Aggregator Operator

The next step in our analysis is to provide a mechanism to aggregate changes over time. We do so by disintegrating the integral of Eq. 2 based on the discrete subset $T_n = [0, t_1, t_2, t_3, ..., t_n]$. Accordingly, we have:

$$\vec{O}_j^{t_n} = \int_0^{t_1} \partial \vec{O}_j \oplus \int_{t_1}^{t_2} \partial \vec{O}_j \oplus ... \oplus \int_{t_{n-1}}^{t_n} \partial \vec{O}_j \tag{8}$$

We make use of a multi-dimensional operator $\oplus$ that allows change aggregation in each dimension separately. Aggregation can be logical or metric, depending on the nature of each dimension. It differs from a common multi-dimensional vector aggregator, by having elements that can be qualitative or quantitative and have one or multiple instances. It compares every dimension of $\partial \vec{O}_j = [\delta O_j^1, \delta O_j^2, ..., \delta O_j^n]$ separately and groups the result as follows:

$$\begin{bmatrix} O_j^1 \\ O_j^2 \\ ... \\ O_j^n \end{bmatrix} = \begin{bmatrix} \int_0^{t_1} \delta O_j^1 \\ \int_0^{t_1} \delta O_j^2 \\ ... \\ \int_0^{t_1} \delta O_j^n \end{bmatrix} \oplus \begin{bmatrix} \int_{t_1}^{t_2} \delta O_j^1 \\ \int_{t_1}^{t_2} \delta O_j^2 \\ ... \\ \int_{t_1}^{t_2} \delta O_j^n \end{bmatrix} \oplus ... \oplus \begin{bmatrix} \int_{t_{n-1}}^{t_n} \delta O_j^1 \\ \int_{t_{n-1}}^{t_n} \delta O_j^2 \\ ... \\ \int_{t_{n-1}}^{t_n} \delta O_j^n \end{bmatrix} \tag{9}$$

Due to sensor limitations and information availability, most spatio-temporal changes are expressed as snapshots in time. In this case the continuous interval can be substituted by a discrete summation function showing the discrete rather than continuous nature of change:

$$\vec{O}_j^{t_n} = \sum_0^{t_1} \partial \vec{O}_j \oplus \sum_{t_1}^{t_2} \partial \vec{O}_j \oplus ... \oplus \sum_{t_{n-1}}^{t_n} \partial \vec{O}_j \tag{10}$$

Based on the capturing method and requested accuracy a discrete representation can be considered as continuous (complete).

Here we should note that this aggregator can function at any "horizontal" level of our model. If it is applied at the coarser level, a vector is created since there is only one dimension, at the other levels a matrix-type representation is returned.

If users wish to collapse change over time then some rules have to be defined on how change is summarised. For a metric attribute, this can be straightforward. For example in cases such as a geometric description, a simple vector overlay would be sufficient. In non-metric attributes, however, change summarisation rules would have to be defined based on user needs. Conceptually it would be hard to apply summarisation rules at the two coarser levels and it is beyond the scope of this paper. The most appropriate solution would be to apply it on the most detailed level, obtain the summarised results and then present them incoarser detail following the propagation operator described below.

2.3.2 Multi-resolutional Change Propagation Operator

Information flow in our model would commonly be bottom-up. Detailed change information propagates upwards to update the corresponding indices. In order to do so we introduce a *change propagation operator* $\wr$. If we define as $\partial\vec{O}_j = [\delta O_j^1, \delta O_j^2, ..., \delta O_j^n]$ the change value vector expressing the change of object O_j in n dimensions and we omit the temporal interval of application to simplify the representation and label $\partial\vec{O}_j index$ the change value type vector we have:

$$\partial\vec{O}_j index = \wr\, \partial\vec{O}_j = \wr\, [\delta O_j^1, \delta O_j^2, ..., \delta O_j^n] \tag{11}$$

Since there is a one-to-one relation between the dimensions of the index (value type) and the actual values, we can apply the operator separately in each dimension:

$$\partial\vec{O}_j index = [\wr\, \delta O_j^1,\ \wr\, \delta O_j^2, \ldots,\ \wr\, \delta O_j^n] \tag{12}$$

In the complex case of propagating change to the coarser level of the one-dimensional accumulated change, the problem of grouping dimensions to produce a single result arises. We reserve this for future work within our environment. For now, we provide the general framework to incorporate this in our model.

2.4 Operations

Based on the above change representation we can apply a variety of operations within our model. First we discuss operations that only require access to coarser levels of change representation and then we show how more detailed ones are applied by using actual change values.

2.4.1 Index-based Operations

We begin our discussion by showing how our representation supports fundamental index-based operations as introduced in (Worboys, 1992). These operations (e.g. birth, expansion and death) were later extended by (Hornsby and Egenhofer, 2000). We will show how these queries can be addressed within the content of the coarser two levels of our approach.

- Birth/Death

The creation of an object can be returned directly by querying the coarser level and return the temporal value of the [→] birth pointer. Similar use of the [←] value shows the end of existence.

- Expansion and Reduction

These two operations can be addressed in a qualitative and a quantitative level. If the user requests information about the presence of expansion or reduction the second level would be enough. Value types such as [+, -, $\mp$] and their corresponding temporal pointers can answer this type of query sufficiently.

- Advanced operations

In addition to the above operations that were introduced in the past we also support new, more complex change information retrieval. For example in large geospatial systems, an automated process can be supported to facilitate future information acquisition. Change information gaps can be detected easily by making use of our [*] value type. In other cases, the absence of change might be of importance for some applications such as video compression/summarization. The [$\varnothing$] value can directly point to the unchanged objects within the database for a specified temporal interval. In more advanced scenarios a temporal change pattern match operation can be triggered, for example show me when this dimension changed like that and that dimension like this after time t. Such issues, however, are beyond the scope of this paper, although a general framework of support is provided.

2.4.2 Value-based Operations

- Detailed change retrieval

At this level detailed change, information is available. Change-oriented queries can be applied on single or multiple objects. For example for a single object we support information retrieval such as:

– "Show me Boardman's largest expansion/reduction"
– "Has Boardman ever showed a specific shape of change (e.g. Π-shape)?"
– "Was there an expansion at the North side?"

We can also combine multiple objects and summarise results:

– "In this area (on campus) show me the largest expansion decade"
– "Return the most popular expansion direction (e.g. North)"
– "Has the campus ever changed following this pattern (where pattern might be a combination of spatial/thematic dimensions over time)?"

- Consistency operations

In order to provide the user with valid results, some consistency checks are introduced. In the first category, we can find operations that apply to all dimensions. Such operations might look for validity of a subtraction. The idea is that the system cannot subtract something that does not exist.

Let's assume that a subtraction in dimension w of object O_j takes place at t_k .We perform a one-dimensional aggregation in $[0, t_k]$ through the $\oplus$ operator:

$$\Big|_0^{t_k} \vec{O}_j^w = \int_0^{t_1} \partial O_j^w \oplus \int_{t_1}^{t_2} \partial O_j^w \oplus \ldots \oplus \int_{t_{k-1}}^{t_k} \partial O_j^w \tag{13}$$

The $\Big|_0^{t_k} \vec{O}_j^w$ shows the current state of object Oj in dimension w in time t_k. Assuming $\Big|_{t_k}^{t_{k+1}} \delta O_j^w$ is the one-dimensional change element then

$$\text{is\_ negative}\,(\Big|_{t_k}^{t_{k+1}} \delta O_j^w) = \text{True} \tag{14}$$

If we define consistency unary predicate as *cons_subtraction* and A=$\Big|_0^{t_k} \vec{O}_j^w$, while B=negative descriptor(s) of $\{\Big|_{t_k}^{t_{k+1}} \delta O_j^w\}$ then we have:

$$\textit{cons\_subtraction}\ (\text{A, B}) = \left\{ \begin{array}{l} \text{if } A \cap (-B) = (-B) \text{ then True} \\ \\ \quad \text{else False} \end{array} \right\} \tag{15}$$

In the second category of consistency checks we find validity operations that depend on the dimension. For example if one dimension is the "building outline" then a consistency check might be that it is a closed polygon. Another important operation would be to compare change dimensions with expected behaviour to filter out inconsistencies.

3 Implementation in a Differential Gazetteer

In Agouris et al (2000) we proposed a Spatio-temporal Gazetteer (STG) as an efficient model to store and retrieve spatio-temporal information. We will use this prototype to demonstrate the practical use of the operators introduced in this paper. In the following figures we show the original dataset in the STG that was provided for change detection in Boardman Hall.

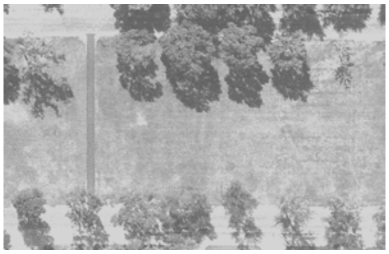


Fig. 3. Boardman Hall in t_1 (1932)

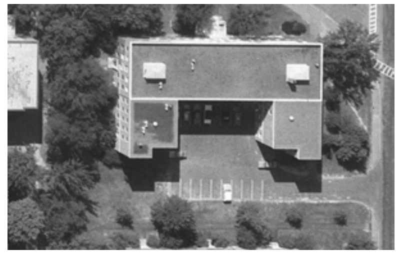


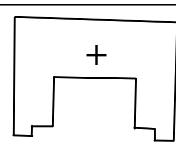
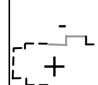
Fig. 4. Boardman Hall in t_2 (1971)

Fig. 5. Boardman Hall in t_3 (1985)

Fig. 6. Boardman Hall in t_4 (1997)

After analysing the above dataset, this is how change information and specifically the building's outline is represented in our model. At the coarser level a general change description is stored. At the second indexing level, the δO_j data types are stored and at the more detailed level the metrics of change are shown.

Table 1. Building's outline change representation example

Accumulated Change Type	$\rightarrow$ +		$\varnothing$	$\mp$
Dimension Change Type	$\varnothing$	+	$\varnothing$	$\mp$
Dimension Change Values	$\varnothing$		$\varnothing$	
Time Line	$0 < t < t_1$	$t_1 < t < t_2$	$t_2 < t < t_3$	$t_3 < t < t_4$

In a different example this is how the building area (using information from complementary datasets like blueprints and maps) would be stored in a state-based structure as opposed to our change-oriented one using the primitives defined before.

Table 2. Building's area state representation example

Time (years)	Building Area (sq. meters)
1925	∅
1932	∅
t_1	∅
t_2	1043
1979	1043
1982	1043
t_3	1043
t_4	1239
2000	1239
2001	1239

Table 3. Building's area change representation example

Accumulated Change Type	→ +		∅	+
Dimension Change Type	∅	+	∅	+
Dimension Change Values	∅	+1043	∅	+196
Time Line	$1925 < t < t_1$	$t_1 < t < t_2$	$t_2 < t < t_3$	$t_3 < t < t_4$

The main points demonstrated by these two examples are that the minimal redundancy and clear expressiveness of the method can be achieved. With this approach, we can ensure *redundancy minimisation* in most cases by reducing a multi-dimensional problem to its minimal modified dimensions. There are however, some cases where a change-oriented approach might require a larger volume of storage (e.g. constantly changing qualitative dimensions). Nevertheless, for common geospatial applications, where we have numerous instances in which a monitored object remains unchanged the gain of a differential model over a state-based one becomes substantial.

Regarding *expressiveness,* it can be easily seen that a differential STG model directly supports numerous types of object and scene queries. They range from object to scene queries, and can address any level of resolution within the model of Fig. 2. This allows for example queries on the index level (e.g. how many times has a building changed over the last 10 years?), the object level (e.g. what is the largest expansion of this building during the last 5 years?), and even the scene level (e.g. which building within this area has expanded the most in the last decade?).

4 Conclusions

In this paper we presented a differential change-oriented model for the storage and communication of spatio-temporal information. We discussed the development of model primitives and operators to support the aggregation of change over time and the propagation of change across resolution. By making use of these primitives the result is a multi-resolutional change model that captures the semantics of change from the coarser level to the most detailed one. Our primitives and operators presented here extend existing qualitative operators to support the management of quantitative and geometric information within a change-oriented spatio-temporal environment. The major advantage of this approach lies in the minimisation of redundancy, and its superb expressiveness in the communication process. A GIS implementation prototype is discussed to reveal the effectiveness of our change model.

Acknowledgements

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