Visualizing changes in a dynamic Voronoi data structure via time travel

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ABSTRACT

In recent years there has been rapidly growing interest by the GIS community in new visualization methods for cartographic data. The visualization of map changes is important for several reasons: spatio-temporal analysis, process modelling, and animated maps.

It is now widely recognized that current GIS software has no ability to maintain incremental change of spatio-temporal data, and therefore visualization of such data is limited to series of 'snapshots' of cartographic data (see [Peque94a]).

The growing amount of research on spatio-temporal databases shows that today's world of spatial data handling requires a dynamic and interactive environment for map visualization.

In this paper we will present a conceptual approach for representing cartographic data changing in time and space. The approach emphasizes several research efforts: on the Voronoi spatial data structure, the reversibility of its map construction commands, and their applicability to map visualization and map animation.

INTRODUCTION

The recent research on dynamic spatial data structures based on Voronoi diagrams, and the reversibility of their operations ([Gold95a], [Anton96a], [Roos90a], [Schwa92a]), brings a new approach for dynamic visualization of cartographic data. Visualization can be done dynamically and incrementally, and we will see that this is fully supported by the dynamic spatio-temporal Voronoi data structure.

The Voronoi diagram for a set of map objects (points and line segments) is the tessellation of the space, where each map object is assigned an influence zone (or Voronoi region), that is the set of points closer from that object than any other object (see [Okabe92a]). Within the dynamic Voronoi spatio-temporal data structure developed by [Gold92a], the map objects are stored as nodes of the dual spatial adjacency (topology) graph: the Delaunay triangulation. The algorithm used to construct the Voronoi vertices has been described by [Anton97a]. The changes in this data structure are therefore the changes in the spatial adjacency relationships, that is to say the changes in the Delaunay triangulation. This spatial data structure has a dynamic, incremental, and explicit topology. Within this data structure, user inputs are changing the map interactively and locally, and the map objects and their spatial adjacency relationships are visualized all along the execution (see [Anton95a]). Furthermore, this approach allows real-time dynamic maintenance of this spatial data structure as well as the dynamic sequential processing of events.

In such a spatio-temporal model based on interactive and local updates, the user has capabilities for visualization of map events evolving in space and time. In order to visualize the evolution of a map, we use the term time travel (see [Atwoo96a]). The idea of time travel comes from the scientific visualization community, which describes it as the ability to receive a continuous visualization of spatial data as the map commands execute, coupled with the ability of the user to interactively modify the map at any time during the execution, and immediately see the effects of these changes (see [Atwoo96a]).

In visualization, this results in the ability to display the changes in the maps in both directions in time. In general, two approaches that are used for dynamic visualization are the forward method, and for the reverse time, the backward method (see [Sosic94a]). Visualization of changes in a backward direction on the time line can be done by executing the map commands that are the inverse of ones previously applied (see Fig. 1).

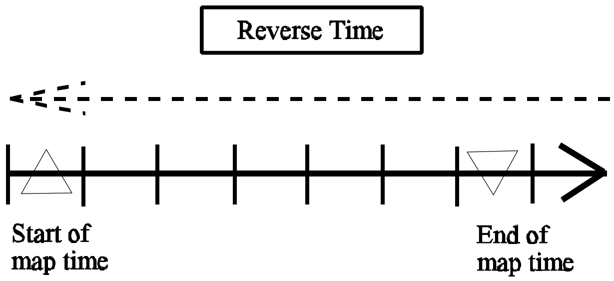

Fig. 1: Forward / Backward visualization on time line.

Reversible execution allows users to navigate backwards in time. Reversibility has been defined as “simply determinism looking backwards in time” by Frank and *al.* [Frank98a]. While different approaches have been used to implement reversibility in operating systems and programming languages, in the GIS world reversibility is still relatively unexploited.

In this paper we will present an approach based on the history of the map construction. We will use this map history in order to visualize changes within the Voronoi data structure via time travel. We start by formalizing the operations available in the dynamic spatio-temporal Voronoi data structure imagined by Gold [Gold91a], by providing the full set of atomic operations (self contained by reversion), and the full set of complex operations obtained by composition of the atomic operations. Then we study their reversibility. We describe the history tree and its spatio-temporal signature. Finally, we show how it is possible to visualize changes within the dynamic spatio-temporal Voronoi data structure via time travel.

THE DYNAMIC SPATIO-TEMPORAL VORONOI DATA STRUCTURE

The Voronoi dynamic spatial data model is based on an Event-Condition-Action paradigm (see [Gold96a]) which seems to provide many advantages over traditional GIS data models. The main advantage of the dynamic Voronoi spatial data model is its dynamic, incremental, and explicit topology, which allows one to automatically keep track of each event and change of map state.

The topology is given by the Delaunay triangulation, that is the dual representation of the Voronoi diagram, and thus stores all the spatial adjacency relationships between map objects. These spatial adjacency relationships are defined by the fact that their Voronoi regions have one Voronoi edge in common (see Fig. 2).

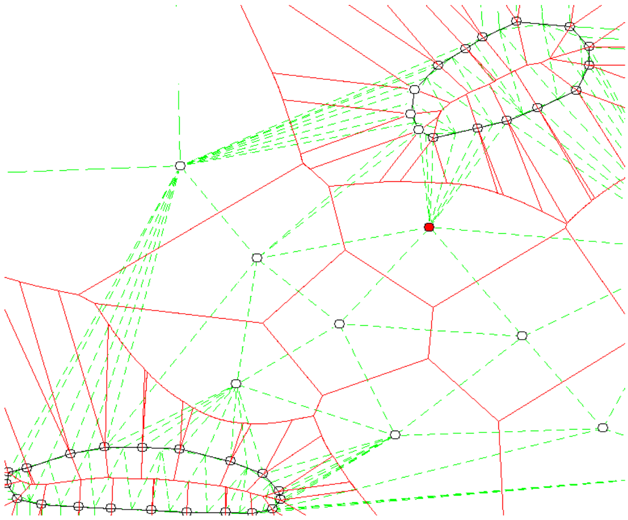

Fig. 2: Spatial adjacency within a line Voronoi diagram.

Therefore, the only map state changes of the dynamic Voronoi data structure produced by events are the changes in the Delaunay triangulation. These events are ruled by the Delaunay triangulation empty circumcircle criterion (see [Teill93a] and Fig. 3).

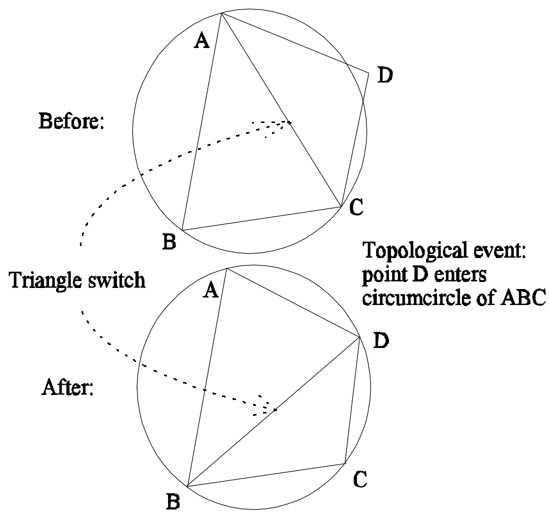

Fig. 3: The Delaunay triangulation empty circumcircle criterion

When a point comes inside a circumcircle or goes out from a circumcircle (we call it a "topological event"), the boundary between the two triangles inscribed in the circumcircle "switches" (see Fig. 2). Within the dynamic Voronoi spatio-temporal data model, all the operations are local and “kinematic”: the addition of a new object is done by splitting the nearest object into two and moving the newly created object to its destination, and the deletion of an existing object is done by moving it to the nearest object and merging them. It is easy to see that the two operations described just before are the reverse of each other: the reverse of a split being a merge and the reverse of a merge being a split. The Split operation splits the selected point, adding a new point in the database. The Merge operation merges the selected point with its nearest neighbour, removing the selected point from the data structure. The Move operation moves the selected point from its current position to a new position. The Link operation occurs after a Split operation, and adds a line segment in between the point selected for splitting and the newly created point. The Unlink operation occurs before the Merge operation, and removes the line segment in between the selected point and its nearest object.

To preserve the temporal ordering inside the data structure the two new operations are introduced. The Order operation which must occur after Split and Link, and exchanges the IDs of the selected line segment and its higher ID end-point. The Reorder operation must occur before Unlink and Merge, and exchanges the IDs of the selected line segment and its higher ID end-point. These operations constitute the set of atomic operations of the dynamic spatio-temporal Voronoi data structure (see [Anton97b] for more details). These atomic operations and their corresponding changes in topology are described in the following table (Table 1).

Operation	Symbol	Changes in topology
Split	S	3 new triangles, 1 dead
Merge	M	1 new triangle (old reinserted), 3 dead
Move	N	2 old adjacent triangles, 2 new adjacent triangles whose common edge has been switched for each topological event
Link	L	6 new triangles inserted, 2 dead
Unlink	U	2 new triangles (old reinserted), 6 dead
Order	O	IDs of the line segment and the end point are exchanged. Order must occur after Split and Link
Reorder	R	IDs of the line segment and the end point are exchanged. Reorder must occur before Unlink and Merge

Table 1: The atomic operations

All the map commands of this dynamic Voronoi spatial data structure are complex operations based on the atomic operations (see Table 2). Due to the local scope of its spatio-temporal topology, all the atomic operations of the dynamic Voronoi spatio-temporal model are reversible. The commands for map construction have been carefully designed in such a way that all of them are invertible. Indeed, each atomic operation has its reverse atomic operation (see Table 3), and therefore the resulting complex operations are reversible.

Map command	Decomposition	Reverse
Move a point	N	Move a point
Add a point	SN	Delete a point
Delete a point	NM	Add a point
Add a line	SNSLN	Delete a line
Delete a line	NUMNM	Add a line
Join 2 points	SLNM	Unjoin 2 points
Unjoin 2 points	SNUM	Join 2 points
Join point+line	SLONSLNM	Unjoin pt+line
Unjoin pt+line	SNUMNRUM	Join pt+line
Join 2 lines	SLONSLONSL NM	Unjoin 2 lines
Unjoin 2 lines	SNUMNRUM NRUM	Join 2 lines

Table 2: The map commands and their decomposition

Reversibility of the operations on the dynamic spatio-temporal Voronoi data structure

Overall reversibility of the Voronoi spatial data structure, as for any system, depends upon the fact that reversible primitives are reversibly composed in order to get complex operations (see [Baker92a]). The reversibility of the addition and deletion of intersecting line segments has been studied by [Anton96a].

Atomic Operation	Inverse Atomic Operation
Split	Merge
Merge	Split
Move	Move (Self-Reversible)
Link	Unlink
Unlink	Link
Order	Reorder
Reorder	Order

Table 3: Reversibility of atomic operations

The result of implementing reversibility rules inside the Voronoi dynamic data structure is that spatial objects can be recognized on the map (actually in the Voronoi spatial data structure) according to the IDs (identity numbers) assigned to atomic spatial objects. This means not only that an object can be generated as the result of a map command, but also that a sequence of map construction operations can be reconstructed from object IDs. This proves in another way that the operations are reversible: the input can be deduced from the output; or, in other words, computation happens without any loss of information (see [Frank98a]).

HISTORY OF THE MAP CONSTRUCTION

The user is constructing a map incrementally by giving the map commands, and at the same time the visualization is performed. This is made possible in the dynamic spatio-temporal Voronoi data structure exploited in this paper by the fact that all operations have local scope and are therefore executable in real-time. Their results are visualizable also in real time. All past map events are permanently stored in a history of the map as sequences composed of basic geometric operations.

In this section we will first define what we consider to be a sequence of map updates. We call the spatio-temporal signature the sequence of atomic operations that have been applied on the spatial data structure. In other words, we can define it as a mapping from the set of atomic operations available on the spatial data structure, to the set of triangulations. A knowledge about occurrences of events in a specific spatial context is encoded in the spatio-temporal signature and stored as the log file of the map. The operations recorded in the spatio-temporal signature (log file), have a direct translation into the spatial topology (dual graph) as the history of the triangulation. The history of the triangulation keeps all past states (triangles) of the map topology.

Each atomic operation from the update sequence corresponds to the addition or inactivation of triangles in the history tree (see Fig. 4 and 5). The data structure encodes the history of map construction at two different levels, as spatial topology, and history relationships.

The data structure has the following specification:

- For each point:
  - a pointer to its coordinates.
- For each line segment:
  - two pointers to its endpoints coordinates.
- For each triangle:
  - three pointers to its vertices (that are points or line segments);
  - three pointers to its adjacent triangles.

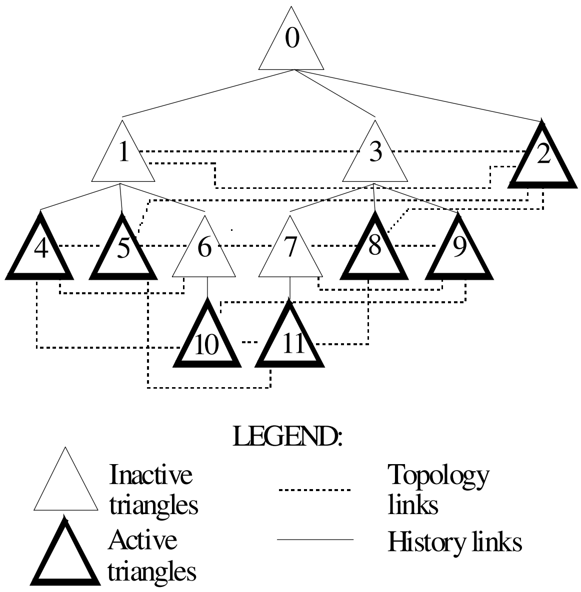

Fig. 4: The history tree.

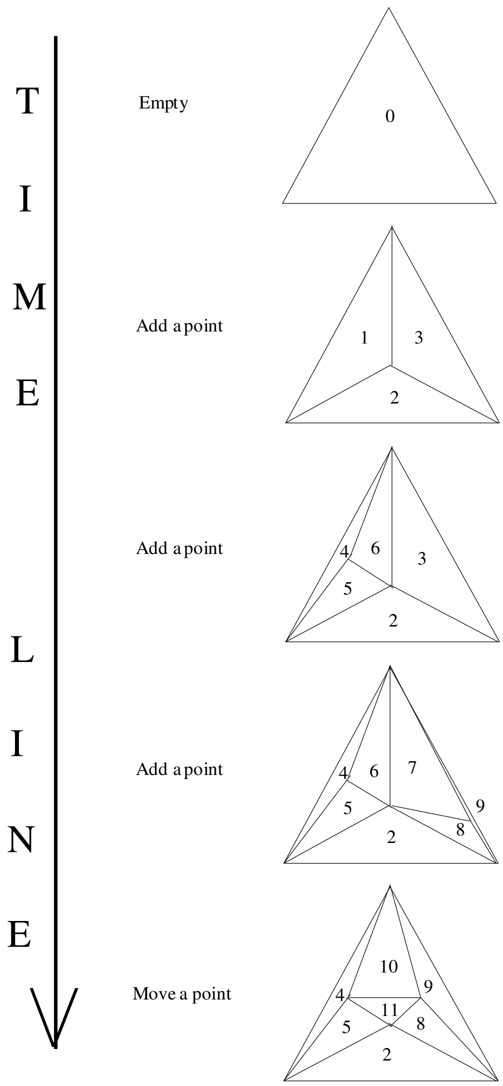

Fig. 5: The evolution of map topology

In addition, the parent-child relationships in the Delaunay triangulations are maintained through history links (see Fig. 4).
Real-time sequencing of user invoked events produces temporal ordering of spatial objects inside this objectoriented Voronoi data structure. The naming conventions
for spatial objects developed by [Anton96a]) preserve the order inside the spatial structure, even after intersections of line segments. The consequences of temporal order preservation have direct implications for the reversibility of the Voronoi data structure.

There are several significant implications of the temporal ordering of map construction events in the Voronoi data structure. The mapping between map construction commands and the history of the Delaunay triangulation (the result of the map events) allows the user to navigate from log file to the past versions of the map (see Fig. 4 and 5). Applying the inverse of the operations that have been applied on spatial objects, it is possible to reconstruct previous map states.

VISUALIZATION VIA TIME TRAVEL

Visualization via time travel has been defined by Atwood and al. ([Atwoo96a]) in the context of visualizing program changes and execution. But, it can be applied to GIS by giving the following definition adapted from [Atwoo96a]: "Users can visualize as they specify, explore, and alter the behavior of a spatial structure while traveling through the map's logical time". Atwood and al. found it essential to have an explicit notion of time and time travel. Here, the term time travel means the ability to return to a previous step of a computation. This approach brings several advantages that we will explore now.

Incremental and dynamic map updates: If the user alters the history of the map, the change is reflected not only in present and future computations, but also in all past computations.

In this dynamic spatio-temporal Voronoi data structure, the user can make changes to the map at any time. Doing so automatically adjusts the past, present and future, so that users can explore to see if the change had the desired effects (see [Atwoo96a]). The visualizations are automatically synchronized with the map construction commands and the dynamic maintenance of this spatio-temporal data structure.

Spatio-temporal reasoning: Today, GIS applications do not support an option for evaluation of the history of a particular site. The Voronoi data model, where all the operations are recorded sequentially, allows us to view the history of spatial objects (see [Gold94a]) .The user can use time travel to explore and visualize causes and effects of events that are part of the map history. This is of particular interest in environmental planning, where reversibility allows one to perform evolution analysis.

Visualization of map scenarios: A map scenario is the reconstruction of a sequence of map commands, which are different from the ones recorded in the Voronoi spatial data structure. It leads to a different map state in the present.

In such a spatio-temporal model based on interactive and local updates the user has capabilities for incremental map visualization and animation of map events through the flow of time (see [Kraak97a]).

The user is given the possibility to explore the now-redefined map history via time travel. It is inherent for the entire history of spatial structure to be redefined according to this change because triangulation histories are defined by their map construction commands (see [Gold96a]). Progressive evaluation (see [Atwoo96a]) is used: as soon as a change is made, all affected histories are automatically redefined, and all affected on-screen values are automatically recomputed and redisplayed.

CURRENT AND FURTHER WORK

Usually, in the map updates, the ordering of map time events corresponds to the ordering of events in real-time. Even though retroactive updates are not a usual map update operation, in some applications such as forestry mapping and cadastral maps, they are needed. Within a current GIS systems retroactive updates are not supported.

The approach of time travel to map history is implemented at the prototype level, for a small number of map updates. We are still not ready to test it on large data sets, due to the fact that we are still working on the line-line collision problems.

Following the experience of Schwarzkopf (see [Schwa92a]) and Clarkson (see [Clark92a]), we expect that the retroactive updates for the large spatial data sets can affect the performance of the spatial database. We do not intend to use the different approaches proposed by Schwarzkopf and Clarkson to improve the performance of the data structure, because in their approaches some history information are discarded.

Instead, we plan to partition the spatial data structure and its history by the VMO tree, the spatial partitioning method for Voronoi data structure proposed by [Yang96a]. This will allow us to work on smaller, partitioned spatial data sets, and the database performance can be improved significantly.

Current research at Laval University on the dynamic spatio-temporal Voronoi data structure and the reversibility of its operations shows that benefits of this method include backup facilities, spatio-temporal queries and updates, and different spatio-temporal analysis methods.

Further research is planned to investigate possibilities for spatio-temporal reasoning and decision making with the Voronoi data structure.

CONCLUSION

This paper presents a new mechanism for the dynamic visualization of spatio-temporal data. Research on dynamic Voronoi spatial data structures offers new possibilities for incremental and dynamic visualization of spatial data.

The spatio-temporal model based on this reversible Voronoi dynamic data structure is based on a set of histories of map construction operations, that are recorded as a history of map (spatio-temporal signature preserved in the "log file"), and the history tree, that stores the history of the Delaunay triangulation.

The benefits of this approach, within this dynamic spatio-temporal data structure, reside in the fact that it is possible to perform reverse execution of the map commands previously applied to the Voronoi spatial data structure, in order to visualize the evolution of the map via time travel.

The visualization of map changes enables fast comprehension of the events and processes that occurred in space and time. Visualization of map changes offers a powerful tool for spatio-temporal reasoning, which is needed in many GIS applications.

The spatio-temporal semantics of the map are preserved and encoded in the history structure. The property of reversibility is very strong, and allows analysis methods to produce deeper information (see [Baker92a]) than it is possible with the traditional map analysis methodology. In this paper, we presented several new methods for scientific visualization of spatio-temporal data.

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