Spatio-temporal database support for long-period scientific data

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Objective: Database support for long-period scientific data, like used in geological applications

Balanced restoration of structural basin evolution

Three time steps of the basin modeling in the Lower Rhine Basin:
view from the southern part to north-east with the Oligocene bases and the antithetic faults
Conceptual model of continuously changing spatial data
Change in geometry and topology

Example for the change of the topology and geometry:
part of the Oligocene of the Lower Rhine Basin about 28 million years ago
Conceptual model
-- Design objectives

- Enabling **change in discretization**

- Separate meshes from vertices
  - Building several meshes from one set of vertices
  - **Automatic consistency** w.r.t. vertices

- **Spatio-temporal data structures**
  - Dynamic: *Insert, Delete, Update* operations on 4D geometries

- **Extending existing 3D data types with time**
  - Reuse of spatial functionality
3D conceptual model extended by time
-- database type *MovingVertex*

- *Time* isomorphic to the reals
  - Location and shape of geometries is a **function of time**
- Vertices move on their *trajectories*

\[
\text{ traj}(v) = \{ \text{loc}_v(t) \mid t \in \text{def}(\text{loc}_v) \} 
\]

- **Properties of the model:**
  - Trajectory **piecewise linear**
  - **Change in direction** => Snapshot
  - Linear interpolation also w.r.t. time
    => *const velocity/no acceleration*
  - **Change in velocity** => Snapshot
-- Database type **TemporalSimplex**

- Assemble **complex geometries** from moving vertices
  - Separates meshes from vertices

- A **moving simplex** comprises:
  - References to its moving vertices
  - Temporal interval of validity

- A **moving complex** comprises:
  - Set of moving simplexes
  - Temporal interval of validity

- **Integrity constraints!**
-- Database type *TemporalComplex*

- Given by a pair of:
  - Temporal interval of validity
  - List containing references to moving vertices

- Temporal interval of validity facilitates:
  - Remaining within the type system, e.g., after snapshot queries
  - Updates of snapshots
Representing time-dependent simplicial complexes applying key-frame interpolation

- Points at different times: \( t_0, p_0 \) to \( p_N \).
- Stored value at \( t_0 \) and \( t_1 \).
- Interpolated object at \( t_1 \), \( t \), and \( t_2 \).
- Representation of moving 3D points.

**Key Frame Interpolation:**
- "post" \( t_0 \) and "pre" \( t_1 \) indicate transitions between frames.
- Different data with same discretisation.
- Same data with different discretisation.
- Added and deleted triangles at specific times.

**Interpolated Values:**
- Interpolated value at \( t_1 \) and \( t_2 \).
- Representation of moving 3D points at intermediate times.
Within this scenario:
- Let proven concepts like geometric filter carry over from pure spatial setting
- Support, e.g., through access methods
Examples for spatio-temporal operations:

Base operations on *temporal simplexes*

- Operations on a per-timestep basis not sufficient

- Geometric base operations
  - Analogues in the pure-spatial setting: e.g. segment/triangle Euclidean distance
  - O(1)-operations

- Operations involve two consecutive timesteps on the merged timeline of the two objects
Base operations in the scope of this work

*Minimum Euclidean distance operation*

- Operands:
  - Spatial or spatio-temporal objects
- Types of operations:
  - Scalar function *min-dist*
  - Temporal function *when-min-dist*

*Intersection-operations*

- Operand:
  - Plane or
  - Halfspace or
  - Bounding box
- Types of operations:
  - Boolean predicate *intersects*
  - Temporal function *when-intersects*
  - Object-generating function *intersection*
Base operations on temporal simplexes
-- Implementing minimum Euclidean distance

- Definition: Minimum Euclidean distance

\[
\min_{t \in T} \sqrt{\sum_{i=1}^{3} |x_i - y_i|^2}
\]

- Solution by:
  - Parameterization of the simplex movement (shared time parameter)
    
    \[
    v(t) = v_0(t) + \sum_{j=1}^{d} \lambda_j (v_j(t) - v_0(t))
    \]
    
    \[
    w(t) = w_0(t) + \sum_{j=1}^{d} \kappa_j (w_j(t) - w_0(t))
    \]
  
  - Substitution into Euclidean distance formula
    
    \[
    \text{dist} = \sqrt{\sum_{i=1}^{3} |v(t, \lambda_1, \ldots, \lambda_{d_1}) - w(t, \kappa_1, \ldots, \kappa_{d_2})|^2}
    \]
  
  - Analytical search of minimum
    
    \[
    \frac{\partial \text{dist}}{\partial t} = 0, \frac{\partial \text{dist}}{\partial \lambda_1} = 0, \ldots, \frac{\partial \text{dist}}{\partial \lambda_p} = 0
    \]
Base operations on *temporal Simplexes*  
-- Example *intersection*

- Model is not closed under *intersection*
- Contrast to purely spatial model: Approximation must be performed by query system
System architecture: Extending GeoToolKit

GeoToolKit
object-oriented API
(3D and 4D types)

GeoToolKitObject (GTO)
- methods:
  - clone(GTO):GTO
  - dimension():INT

SpatioTemporalObject (STO)
- methods:
  - time():INTERVAL
  - at(INSTANT):SO
  - distance(STO):REAL
  - when-intersects(SO):TE

SpatialObject(SO)
- methods:
  - contains(SO):BOOL
  - intersection(SO):SO

GeoToolKitObject Class Hierarchy

SpatioTemporalObject Class Hierarchy

0D+T 1D+T 2D+T 3D+T

Moving Point

TempSegm
TempTriang
TempTetra

TempPolyLine
TempTriangNet
TempTetraNet

inheritance
1:1 relationship
1:n relationship
representational data type
Examination with geological and artificial datasets

3D model “Bergheim”
(visualized by the 3D modelling tool gOcad®)

Automatical generation of artificial landform data
Result of a temporal database query from the Bergheim model

(visualized in the VRML browser Cortona™ ®).
Summary and future work

● Conclusions
  ◆ Need for spatio-temporal database types and operations
  ◆ Spatio-temporal operations
    ⇨ metric queries (minimum Euclidean distance)
    ⇨ intersection-queries
  ◆ Applications

● Future Work
  ◆ Enhance existing operations through geometric filters and index support
  ◆ Extend conceptual model: more operations on spatio-temporal types
  ◆ New applications (kinematics of landform)
Sponsors and contact information

- **Sponsor: German Research Foundation (DFG)**
  - Graduate Research Centre 437 “Landform”
  - [http://slide.giub.uni-bonn.de/Kolleg/welcome.html](http://slide.giub.uni-bonn.de/Kolleg/welcome.html)

- Examples taken from joint research between 1994-2001 with Agemar Siehl’s group (Geological Institute) within the Collaborative Research Centre SFB 350
  - [http://www.sfb350.uni-bonn.de](http://www.sfb350.uni-bonn.de)
  - [http://www.geo.informatik.uni-bonn.de/software/geotoolkit](http://www.geo.informatik.uni-bonn.de/software/geotoolkit)

- DFG joint project “Interoperable GIS” (IOGIS)

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