Spatiotemporal graph queries on geographic databases under a conceptual abstraction scale

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Visual queries assist non-expert users to extract information from spatial databases in an intuitive and natural approach, making Geographic information systems comprehensive and efficient for a wide range of applications. A common visual means of querying takes the form of drawings or graphs, under which many spatial ambiguity and translation errors rise. In this study, common query attributes extracted from user graphs such as spatial topology, size, cardinality, and proximity are regarded under a conceptual moderation scheme. Thus, the system/user may concentrate on various conceptual combinations of information. Furthermore, time is incorporated to support spatiotemporal queries for changing scenes and moving objects. Arbitrary, relative, and absolute scaling is possible according to the data-set and application at hand. The theoretic approach is implemented under a prototype user interface system, called ShapeController. Under this prototype, a user may extract scene-based relations in an automatically inferred fashion, or include single object-oriented relations when all possible relations seem redundant. Finally, a natural language description of the query is extracted upon which the user may select the desired query relations. Experimentation on a spatial database demonstrates the concepts of predefined draw objects, scaling relaxation, conceptual abstraction, and scene, object- and textual-oriented transitions that promote query expressiveness and restrain ambiguities.

Keywords: visual queries; spatial topology; spatiotemporal queries; graph and sketch queries; query by example

1. Introduction and related work

Geographic Information Systems (GIS) become a popular problem solving means for an increasing number of users and applications. Their value was undoubtedly established through their dynamic contribution in a wide range of decision-making sectors including geosciences, natural resources, energy, environment, trade, urban planning, natural hazards, etc. reported in local, national, and global scales (1). Nevertheless, they are still considered as an advanced and often rather complex tool, usable only by specialized and trained personnel. The existing gap between the extensive applicability of GIS and handling complexity is a crucial point preventing their further diffusion among various potential user groups.

Some efforts attempt to bridge the above-stated gap towards an effective, intuitive, and natural way of expressing queries by approximating the conceptual and empirical perception of a user (2). Part of these efforts deal with the efficiency of placing queries with the use of examples or visual aids (3). The present study attempts to provide a robust and applicable interactive prototype to address queries posed in spatial databases through the exploitation of user defined graphs incorporating spatiotemporal and conceptually scaled information.

Visual types of user queries have been introduced to GIS environments under the rubric of visual metaphors, sketches, glyphs, and pictures (4–8). Beyond this main functionality enabling a user’s intuitive query posing, visual query implementation involves processes contributing towards various research directions: (a) advanced topological measures, (b) human conceptual understanding and interpretation of space, and (c) data structuring with extends in generalization, summarization, and spatial data vagueness.

The common structural elements that constitute the essential interpretation attributes of a sketch query, include relations of objects in terms of spatial topology, direction through rigid cardinality, spatial proximity between points of interest in the form of points, lines, or polygons. Application examples include queries to find regions with dangerous turns (shape), near schools (proximity), and high speed limit (attribute) characteristics for accident prevention applications. Accordingly, a user might want to retrieve a place he vaguely remembered from his childhood as a hotel in a (spatial topology) small (size) coastal region where we could watch the sunset (cardinality). Obviously, such examples address a specific region of interest since answers may become vast. In Figure 1, two sketches are shown, describing a route (left) and spatial relations between three objects (right).

Various studies experiment on how a series of users perceive a concrete spatial question through the drawing of a corresponding sketch. Then, the common attribute
recordings are classified towards space conceptualization and provide the essential attributes of the sketches. Problems emerge from vagueness in the interpretation of sketches and the transformation of the drawing in a valid unambiguous expression between the drawn objects. On similar terms, every user is influenced by his perceived experience and thus various levels of complexity are evident in user sketches (9).

Errors due to cognition, conceptualization, and schematization simplify and distort space in a different way than classic abstraction and generalization techniques. This transition from rigid map-based concepts to sketch vagueness poses a new way of space comprehension. Along these lines, Ref. (2), showed that four cardinal directions are preferable compared to eight cardinal ones. Furthermore, the order of points of interest along a route is more adequate than cardinality for wayfinding instructions on road networks, proving that sketches have also an application specific dimension. Accordingly, Ref. (10) proposed a spiral web structure for road networks to describe a complex sketch line.

Spatially dependent problems in the interpretation of a query include the definition of topologic measures, the abstraction level the user requires or implies, (e.g. the direction of the overlap between two drawn regions is important or not), scale issues (the different sizes between drawn objects are deliberate or random), and object issues (objects extracted are part of other objects or individual ones). Towards sketch interpretation, object extraction along with conception theory is employed in Ref. (11), to delineate sketch objects. Ref. (5) proposed query by sketch to address spatial topology and conceptual similarity measures under firm and relaxed measures. In addition, in order to restrain perceptive ambiguities, complementary descriptive elements are imported in the sketch via simple typing or voice recognition (12). Ref. (13) proposed topologic, metrical, logical, and structural operations. Ref. (14), through the GeoPQL query language, enriched relations between visual objects through “any” and “alias” operators for explicitly including/excluding topologic measures between objects. Geographical pictorial and sketch-based query languages proposed in Ref. (15), restrain ambiguity by recording user behavior in time during sketching, to identify objects. Approximating query results is demonstrated in Ref. (16). Topological, semantic, and structural similarity graphs are constructed in order to retrieve the most relevant object relations when the exact user defined query relations are absent.

In a different fashion, time is incorporated in the query process to address spatiotemporal databases in a series of studies based mainly on Allen’s temporal logic (17). Ref. (7) formulated the Cicadas language to facilitate spatiotemporal queries with the use of icons. Ref. (4) proposed Lvis language, introducing balloons and anchors identifying thematic, temporal, and logical criteria. Time also proves to be a key component in work concerning moving objects in smart environments (18).

Refs. (19, 20) introduced spatiotemporal relations of objects as they change their spatial attributes over time through the Query-By-Trace visual interface.

The corresponding studies and systems developed can be classified in terms of topology focus, scale dependency, time inclusion, visual types for posing queries, and matching targets (sketch, database). In the present study, our proposed system shares common methodologies with the systems discussed, including incorporation of time in the querying, reduction of sketch ambiguity through predefined shapes and tools, and usage of attribute names from the database to form the textual parts of the query.

The main novelty of this study is the integration of temporal scenes in the user query interface, proposing spatiotemporal graph queries along with conceptual abstraction of the information to be included in the query. Conceptual moderation is adjustable by the users, forming a robust system supporting absolute, relative, and arbitrary attribute metrics. Finally, a query may be based on the whole scene, an object of interest, or any combination of object relations defined by the user.

Several structural practices proposed, contribute towards the limitation of drawing ambiguities and provide novel specifications to aid the competence of visual queries:

- Inference of relations not explicitly expressed by the user.
- Automatic extraction of self calibrating relations.
- Structured conceptual classification of abstraction levels controllable by the user.
- Absolute, relative, and arbitrary relation definitions.
- Object, scene, and “user” oriented query architecture.
- Playback visualization for temporal query structuring.

In the next section the query attributes between objects are theoretically discussed along with the system’s methodological approach. In Section 3 the system implementation is presented under a graphical user interface, while Section 4 includes demonstration and results of spatial and spatiotemporal queries in a geographic
database. The paper concludes with a discussion of the findings and future suggestions.

2. Query attributes
The theoretical aspects of the proposed query system include various attribute manipulation strategies concerning spatial topology, proximity, size, cardinality, and time. These attributes are considered under a non-explicit mode towards an abstracted, relaxed, intuitive query formation.

2.1. Topologic spatial relations
Spatial topology between points, lines, and regions is modeled by various research studies (21–23). Classic relations include general geometric type definitions (MBR, boundary, etc.), logical relations in binary form (equals, disjoint, intersects, crosses, within, relates, etc. as true or false), and measures resulting in a spatial object (intersection, union, difference, etc.). The disjoint operator is the most prominent topologic relation of the defined objects, thus, it is not included in the query formation (9).

2.2. Shape descriptors
Geometric, statistical, least square, histogram-based techniques provide invariant descriptors to represent a shape (24–27). Shape in the context of this work is not of primary concern. Nevertheless, explicit shape change over time and space is important in various applications and will be examined in a future study. In the present system, classic base shapes of points, lines, rectangles, or circles are used to define the query objects. The use of these basic shapes restricts the user to draw a simplified object and serves towards ambiguity resolution. The predefined shapes describe a single object regardless of possible complex intersections. Hence, on top of an object a spatially identical object may reside without any implementation conflicts (topology relation “equals”).

2.3. Distance and size measures
Spatial proximity is measured between objects in a scene as an abstract distance measure which includes a self calibration mode to indicate which objects are close, medium, or far. This relative measure is extracted from averaging the spatial distances between all objects. Since this measure is relevant to the scene at hand, space is automatically divided in proximity regions according to the spatial occupancies of the objects, remaining indifferent of scaling and rotation (28). Of course, absolute values are welcome but this self-inferred measure can prove beneficial when the user implies vaguely proximity relations. As in the case of topologic disjoint, the “far” relation may prove difficult to interpret since it is the usual case for drawn objects of a scene and query-wise is less commonly used than the “close” expression. Thus, it is omitted unless otherwise stated by the user, yet the farthest objects remain useful to define the “close” classification.

In the same fashion, size is relatively or explicitly defined as small, medium, or large. Measures of object sizes in the scene provide a size classification automatically inherited by the objects. Size relation is inferred between lines or polygons given their type similarity. In order to extract a threshold value for the various classifications, simple statistics on the tables of the database are performed to assign proximity and size limits.

2.4. Cardinality, direction, and other geometries
Classic strict cardinal directions such as North, South, East, West (29), and their subdivisions are implemented, yet they may fall short in achieving rotation-indifferent performance. As stated in Ref. (2), an ordinal or object-centered approach may be closer to a user’s perception, according to the application at hand. In case of many objects comprising a scene, cardinal metrics introduce a competitive approach to describe a winning cardinal direction by self rotation towards a state of balance (28). Since scenes may not be populated with many objects, in the present system, both classic- and object-centered directions are welcome along with “up-down-right-left” directions.

2.5. Temporal metrics
Temporal topology is based upon the constructed timeslots where the base scene may change through the movement and alteration of objects. Allen’s temporal logic (17) including expressions before, after, during, starts, stops, meets, overlaps is used to characterize each object’s dynamic behavior. Spatiotemporal description of a single object’s evolution is supported, including descriptions of movement and change. Thus, the types of queries supported include (Figure 2):

- queries based on temporal algebra:
  E.g. “B” happened during “A”, “C” started after “A” and “B” started, “C” stopped with “A”.
- queries based on the evolution of single moving objects:
  E.g. “A” became larger from t3 to t4, “A” moved west from t1 to t2.
- queries based on relations between temporal slices:
  E.g. duration (t1, t2) > duration (t2, t3) introducing relative scale, duration (t1, t2) = 1 year or t2 = 15 March 2012 providing a relative or absolute temporal scale.

2.6. Methodological approach considerations
Scaling is arbitrarily implied through the relative measures of the object properties in the scene. At this
self-calibrating approach where the user does not specify any type of measure. Nevertheless, the ability to define relative thresholds of the attribute classifications (small, large, close, far, etc.) is supported. Finally, scaling is allowed through absolute measures of distances considered as far or close.

On the same terms, time is abstractly referenced through Allen’s temporal algebra, yet relative or absolute differences or timestamps may impose relative or absolute temporal scales. Cardinality on the other hand is considered rigid in terms of NSEW specifications and can become rotation independent through a self-oriented process stating relative direction based on an object.

These arbitrary, relative, and absolute scaling factors tackle many ambiguity concerns through abstraction. Beyond the scaling factor, conceptual errors are restrained through the use of predefined graphical objects that the user can draw, eliminating any misinterpretation in terms of object definition and occlusion.

Another defining characteristic of the proposed system is the conceptual moderation capability, under which the user can choose the attributes to be included in the query. This type of attribute relaxation promotes further information abstraction and renders the results under alternative perspectives. Results may be classified under this conceptual scheme, and provide answers that the user may or may not have perceived before the query formation.

Since cardinality and topology relations may become numerous between the objects of a scene, we may consider only the relations of objects being “close” in proximity. Another query strategy is to consider the scene query under an object-oriented fashion and thus follow the relations of proximity and cardinality only based upon the single object under consideration.

Adding to the conceptual moderation, the user can finalize/choose the relations he/she inferred through a textual representation of his drawing under the perspective of the attributes selected. The query takes the form of natural language sentences broken down to simple, comprehensible object relations, selectable by the user.

3. User interface and query processing prototype

Beyond the theoretical approach, an implemented all inclusive interface is presented herein. This software prototype is intended to demonstrate the expressive possibilities and potential applicability of the system and does not suggest a professionally designed product. Some tasks are deliberately omitted since they are implemented and established research-wise and do not further promote the comprehension of the overall methodology.

The ShapeController is the application implemented for generating descriptions of objects changing over time. It was created using Visual C# 2010 Express and SQL Server Express 2008 R2 with SP1 from Microsoft Corporation. It provides a GUI for automating tasks such as inserting objects in a scene of objects, creating snapshots of the variations of their properties over time, and generating natural language descriptions of the overall observed event.

3.1. Object manipulation

The main program screen as shown in Figure 3 is divided in four distinct parts: (a) the toolbox used to insert various shapes that represent objects in the scene (Figure 3(a)), (b) the scene visualization window (Figure 3(b)), (c) the object list which is used to select the active object (Figure 3(c)), and (d) the properties tab (s), which are used to manipulate an object both spatially and temporally (Figure 3(d)).

There are four available object types: point, line, rectangle, and circle types that all have corresponding representations in the scene window. Each object type has its own distinct set of properties including the context, size, and rotation parameters. Annotation may be inserted through the connection of the system to the database at hand, providing reserved predefined name tags for objects and corresponding attributes. After an object has been inserted in the scene it can be made active from the object list. Other available actions include object deletion and cloning at its initial state. By clicking anywhere on the scene window with the mouse, the object can be moved around the scene. By pressing on tab “Operations,” the object’s size and rotation can be changed. A “Z-order” attribute is also available, for objects that occupy the same space.

Temporal changes can be assigned to each object by using the trajectory tab on the properties part of the GUI (Figure 3(e)). “Time slots” can be used to store sequences of changes in an object’s position, size, and rotation. The playback button displays the sequence of time slots for the currently selected object from the object list.
The fourth tab titled “Relations” (Figure 3(f)) is used to provide information on demand about the status of the objects. The user can ask to see a comparison of the proximity, cardinality, and size metrics using the corresponding buttons. Three additional buttons are available: “Temporal profile,” which describes the current object and how it has changed during the time slots assigned to it, “Trajectory Interaction” which applies temporal algebra to describe the relationships between objects’ evolution, and “Topology” which displays the topological relations between the current object and the rest.

3.2. Object relations
Proximity can be calculated using two methods: in the variable distance limit method, the user inputs a percentage describing his estimation on how much a distance must deviate from the average of all distances between objects to be considered a “medium distance.” If the distance between two objects deviates further than the percentage set, it is considered as either “far away,” if its absolute value is above the average distance, or “nearby” if its’ absolute value is below the average distance.

The second method for characterizing distances between objects is the explicit limit method, where the user inputs two variables; a “meters/pixel” variable determining how many meters correspond to 1 screen pixel and the limit for distinguishing “far away” and “nearby” objects.

Finally the user can select how the temporal elements of the scene will be described. The temporal evolution of a scene can either be described on a “per object” basis, meaning that each object’s evolution through time will be described until completely finished, before moving on to the next object, or on a “per time slot” basis, where all the objects’ interactions are described in a single time step before moving on to the next. Topology, size, and cardinality are implemented as described in Sections 2.1, 2.3, and 2.4. Topology includes the touch, intersect, and equal relations while cardinality is again defined as classic (NSEEW)- or object-oriented (up-down-left-right of …).

The conceptual abstraction option is evident in the menu of Figure 4 under the “attributes to include in the export” selection. Thus, the user may select the types of relations he is interested in including.

3.3. Natural language export
The application facilitates the description of a scene in “natural language.” By using proper syntax and string handling, a scene can be broken down to all the temporal changes and topological relations that are described through objects and time slots. The features that are exported are user selectable and include proximity, cardinality, size, topological relations, trajectory interaction, and temporal profiles of the objects (Figure 4).

The natural language export option from the menu brings up a window containing the description of the scene, so it can be used for further analysis. The simple structure of these sentences makes a “Natural Language to PostGresSQL Parser” easy to implement.
in a structured language (e.g. SQL) or any database or GIS environment can be further automated.

The application offers the option of using a database to save the scenes created with it. Scenes can be retrieved from the database, can be saved in it or they can be permanently deleted. The application supports exporting the current scene in comma separated value and jpeg formats for use in other programs.

4. Experimentation and discussion

To demonstrate the implemented graph query prototype, a spatial database of seismic faults was utilized. Possible queries were drawn and corresponding results are shown under the conceptual arrangement of the attributes used. For data organization PostgreSQL was used, a cross-platform open source object-relational database system, along with PostGIS plug-in for spatial manipulation. GeoServer was further used for data sharing and visualization. The compiled data-sets include major residential areas (square points), seismic faults (lines), earthquakes (triangular flag points), soil type (polygons). Some of the data-sets were provided at no cost, while others were synthetically created. In addition, the full spatial database shown graphically in Figure 3(a) was spatially altered to form a second temporal instance. It is noted that the data-sets and example queries are used for demonstration purposes and do not imply a scientifically sound paradigm.

In this example the desired query includes finding scenes with faults near residential areas and near earthquakes whose length has changed from time slot t1 to time slot t2. The faults also have to intersect with any soil type. This query can be generically expressed by the sketch of Figure 3. Through conceptual arrangement, we acquire the following queries:

- **Query 1:** Spatial topology
  Find scenes of faults, residential areas, soil type areas, and earthquakes with faults intersecting soil type areas and residences are inside soil type areas (Figure 5(b)).

- **Query 2:** Spatial topology and time
  Query 1 + soil types change size (Figure 5(c)).

- **Query 3:** Spatial topology, time, and proximity
  Query 2 + two earthquakes close to faults (Figure 5(d)).

By moving from scene-based to object-based strategy, we base our query upon the fault type and its relations to the rest of the sketched objects. For the same data-set we obtain:

- **Query 4:** Find faults having close earthquakes and residential areas and to their north (Figure 6(a)).

Finally, by selecting relation preferences from the natural language list, queries can designate specific properties upon selected objects (Figure 6(b)):

- **Query 5:** Query 4 + residential areas west and close to earthquakes.
By examining the results, after applying conceptual constraints or additional single relations to the database, the number of results is sequentially reduced, to demonstrate the conceptual relaxation process. Thus, based on an identical query visual formation, inclusion/exclusion of possible relation types provides conceptually associated results.

5. Conclusions and future work

A visual query system for geographic databases based on graphs was presented. The methodological and structural selections of the system contribute towards the reduction of ambiguities. This is initially facilitated through the constrained type of objects and draws available to the user, without a significant discount in expressivity. Thus,
a feature extraction phase prone to errors was fully waived.

The query system covers various attributes (size, proximity, direction, topology, time) and the users may select/modify the ones that suit their inquiry under a conceptual moderation schema. Furthermore, arbitrary relations could become more specific through relative and absolute metrics, whenever the user needs to incorporate existing information. Self-calibrating scene attributes were calculated inferring relations not explicitly defined by the user.

Since dynamic systems and spatiotemporal processes are highly important in an increasing number of applications, time-dependent queries are incorporated within the query framework as a valuable decision support feature. The time slots defined can be reviewed through a video sequence for improved comprehension. Time was considered in relative and object-oriented forms describing both scene and single object’s behaviors. Likewise, the spatiotemporal queries may be posed through scene- or object-oriented basis, excluding unwanted object relations. In other cases, the system may provide alternative answers to a single query, by partially incorporating components of the implemented attributes providing various perspectives for further assessment. Finally, the user may indicate the preferred relations by selecting the object relations in the form of natural language sentences.

In the future, more complex topologic relations, based on history, complexity, grouping, statistics of objects, and conceptual modeling, should be incorporated in the system under the prevailing logic of the present study. That is, it will avoid placing burdens onto the user, but infer relations and attributes through self calibration and abstraction practices.

Another point to be elaborated is the consideration of new objects that emerge from intersected objects in the query. In our proposed query system many improvements may be incorporated including user interaction capabilities with the spatiotemporal depiction of the scene in time. Testing from non-experts could prove essential to fine-tune the interface in order to further limit the sketch ambiguities. Finally, hierarchical relations between objects or topologic measures \( f_0 \) should be constructed so as to define “across” and “top-bottom”…“bottom-up” connections. These hierarchies can prove crucial to organize application specific strategies.

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