Development of a spatiotemporal data model for monitoring systems of the surrounding space*

Volodymyr Yuzefovych[1,†], Yevheniia Tsybulska[1,*,†] and Nikolai Stoianov[2,†]

[1] *Institute for Information Recording of NAS of Ukraine, Shpaka Str. 2 03113 Kyiv, Ukraine*
[2] *Defence Institute "Professor Tsvetan Lazarov", Prof. Tsvetan Lazarov Blvd. 2 1592 Sofia, Bulgaria*

Abstract

This paper proposes a spatiotemporal data model "object-event-process" for the surrounding space monitoring systems. It consists of: object models with geospatial and temporal attributes; models of spatiotemporal events that arise when changing the object's characteristics or the state of the system as a whole; spatiotemporal processes controlled by multilevel factors determined by events. This approach allows us to describe formally the relationships between physical objects, events, space, time, and spatiotemporal domains and, due to increased connectivity of information components, represent various types of geospatial objects of various types, multi-level observational data, multi-factor events, and different time scales and representations.

Keywords

surrounding space monitoring system, spatiotemporal data model, model "object-event-process"

1. Introduction

Monitoring systems that use geoinformation technologies are widely used to observe and track various objects, their current state, movement (or other types of dynamics) in time and space, as well as for data analysis in such areas as logistics, security and defense, ecology, agriculture, etc. [1-3].

A key feature of such systems is the integration of geospatial data with the data obtained from the system's own sensors and other information sources to display them against the background of geographic maps and analyze their behavior over a certain time. In the general case, dynamic changes in the topology, geometry, and semantic attributes of monitoring objects are possible. It leads to different data usage scenarios and, accordingly, formation of different data models for their representation and further processing. Therefore, a monitoring system must model, provide access, combine, process, analyze, and visualize spatiotemporal information.

Analysis of spatiotemporal data can be useful, in particular, for predicting consequences of natural disasters such as floods, fires, and earthquakes. Evaluating historical data also helps to assess the risk of certain events in the future. Environmental science can widely apply such analysis to monitor regional use of various resources (e. g. water resources), assess the effects of climate change, etc. [1,2]. Spatiotemporal data analysis has great potential for better understanding ecological trends and the impact of changes in the natural and urban environment.

CEUR-WS.org/Vol-4337/paper2.pdf

*ITS-2025: Information Technologies and Security, December 11, 2025, Kyiv, Ukraine
* Corresponding author.
† These authors contributed equally.
uzefv71@gmail.com (V. Yuzefovych); evts68@gmail.com (Ye. Tsybulska); n.stoianov@di.mod.bg (N. Stoianov)
0000-0002-6336-9548 (V. Yuzefovych); 0000-0003-3342-4507 (Ye. Tsybulska); 0000-0002-4953-4172 (N. Stoianov)
© 2025 Copyright for this paper by its authors. Use permitted under Creative Commons License Attribution 4.0 International (CC BY 4.0).

CEUR Workshop Proceedings ceur-ws.org ISSN 1613-0073
published 2026-11-26

2. Background and related works

Formal algebras and data models to represent spatiotemporal data

A large amount of research in the field of data models and algebras for spatiotemporal objects has been done in the last few decades. [4-13]. In [4], a space-time ontology based on the RCC mereotopology and Allen time algebra is proposed. The authors formulate a set of axioms for the space-time domain and relations between time and space primitives. This approach provides a formalization of relationships between events, spatial, temporal, and spatiotemporal domains. In [5], a wide range of variants for integrating temporal and spatial objects into spatiotemporal objects in relational databases is proposed. The authors provide different modeling options for spatiotemporal databases and explore the relative expressive capabilities of the models for assessing their relationships. The works of Ferreira et al. [6,7] specify an algebra for spatiotemporal objects, which includes time series, coverages, and trajectories. On the basis of these abstractions, data types "objects" and "events" are described.

A separate area of research is development the representation of moving objects' trajectories. In [8,9], the authors propose a fundamental structure for representing moving objects and introduce an algebraic spatiotemporal data type for storing trajectory data. Based on these works, Zheny et al. in [10] introduce a semantic model of a moving object and a trajectory manipulation language, Bornholdt et al. in [11] propose a spatiotemporal predicate logic with spatiotemporal selection, spatiotemporal framing, and join operators that provide powerful and flexible similarity-based trajectory processing.

Theoretical developments have been implemented in the form of conceptual models for representing and processing spatiotemporal data in GIS and database systems [12]. The most applicable of them are:

- The Snapshots Model. Temporal information is included in this model in the form of time layers, which are a collection of the same type of spatial objects at different points in time. This model does not support the description of geometric changes of objects. This model is quite effective for systems where comparative analysis over time is not required.
- Use Time Series Model. This model stores the baseline state of objects and their changes at irregular intervals (unlike the snapshot model).
- Event-Oriented Model. In previous models, it is impossible (or very difficult) to separate individual changes or events in a dataset. One way to solve this problem is to store events explicitly. In this model, all changes are recorded in a data transaction log, which stores information for the spatiotemporal system. The database stores the current state of objects and uses transaction log rollback to track change history.
- The History Graph Model. The main characteristic of the History Graph Model is detection and reflection of all types of changes in objects over time and management of both objects and events. Objects are divided into three categories: objects that are constantly changing, objects that are static most of the time but can change as a result of events that have some duration, objects that are always static and can change only due to an unforeseen event. The graph labels are used to visualize spatial and other information about an object over time. Each version of an object is defined by a pair of values that specify a time interval during which the object does not change.
- Moving Object Data Model [13]. In this model, spatiotemporal data is viewed as a collection of moving objects – points or polygons. Time is an integral part of a spatial object whose attributes change (time can be both discrete and continuous). Also, changes can occur not only to the topology (location), but also to the geometry of the object. To describe moving points and polygons, which are considered as 3D entities (2D space + time), the model introduces corresponding abstract data types with a set of operations.

Systems and software

Recently, traditional GIS tools have been extended to work with spatiotemporal data. The papers [12, 14] describe the GIS TGRASS, which is based on the open source Geographic Resources Analysis Support System (GRASS). This system operates with the changes in spatial fields or coverages over time, where a spatial field (coverage) is a mapping of spatial locations onto values, which can be any user-defined data structures. The Time Manager plugin, which provides tools for animating vector and raster layers based on time attributes and processing image series, was developed for QuantumGIS [15]. The Tracking Analyst module, which allows us to add temporal data to spatial objects, dynamically visualize and process them as object trajectories, has been developed as part of the ArcGIS software. [14, 16]. Also there is a web tool STempo – a geovisual analytics system designed to support the discovery and analysis of patterns in spatiotemporal events, dynamic visualization, and exploration of spatial data in four dimensions of space and time [16].

Spatiotemporal data is supported by DBMSs such as PostgreSQL+PostGIS, MySQL, SpatiaLite, Oracle Spatial, and others [14, 16]. In addition, there are a number of non-relational (noSQL) DBMSs that are capable of storing and operating on spatial (geographic) data. According to the supported data models, they are divided into document-oriented (MongoDB), graph (Neo4j), columnar (Cassandra), a type of "key-value" (Redis) [17, 18]. Systems such as SECONDO and MobilityDB (a PostGIS extension that supports data on moving objects) [12] have been developed to efficiently store and process trajectory data. However, they do not implement their own data model, but rather view spatiotemporal data as extensions superimposed on the existing data model. For example, MobilityDB stores trajectories in relational tables and implements trajectory-specific query functions on this basis model.

As a result, there are currently many proposals for conceptual models for representing and processing spatiotemporal data in GIS and database systems. However, the use of custom extensions based on existing data models leads to the following drawbacks:

- Data storage redundancy is increased.
- Only special data structures can be spatial or temporal when adding additional attributes and properties.
- When the structure changes, the basic data model grows, contains outdated attributes and relationships, and accumulates difficulties in displaying current data.
- Continuous phenomena are stored as discrete states, which can lead to data loss.
- Software for working with spatial and temporal data is implemented separately, which leads to semantic gaps in the representation of phenomena and processes.

Thus, a full-scale and comprehensive "temporal" GIS, as well as a spatiotemporal DBMS, does not yet exist. Most existing spatiotemporal information processing technologies are either still in the research stage or are specific to a particular application area.

3. Purpose of this research

The goal of the work is to build a unified infrastructure that integrates semantics, space, and time in the surrounding space monitoring systems, systematically describes objects, phenomena, and processes, and is extensible for various applications.

4. Front matter

A spatiotemporal data model is proposed for the surrounding space monitoring systems, which consists of:

- Spatiotemporal objects model with spatial and temporal attributes.
- Spatiotemporal events model with spatial and temporal attributes, that arise when the characteristics of objects or the state of the system as a whole are changed.
- Model of spatiotemporal processes managed by multilevel factors, which are defined by events.

4.1. Spatiotemporal object model

Spatiotemporal objects are models of real-world (physical) objects and models of phenomena. They have semantic attributes, relationships, time of existence, geometry, and spatial location. Figure 1 shows the structure of a data model for representing a spatiotemporal object.

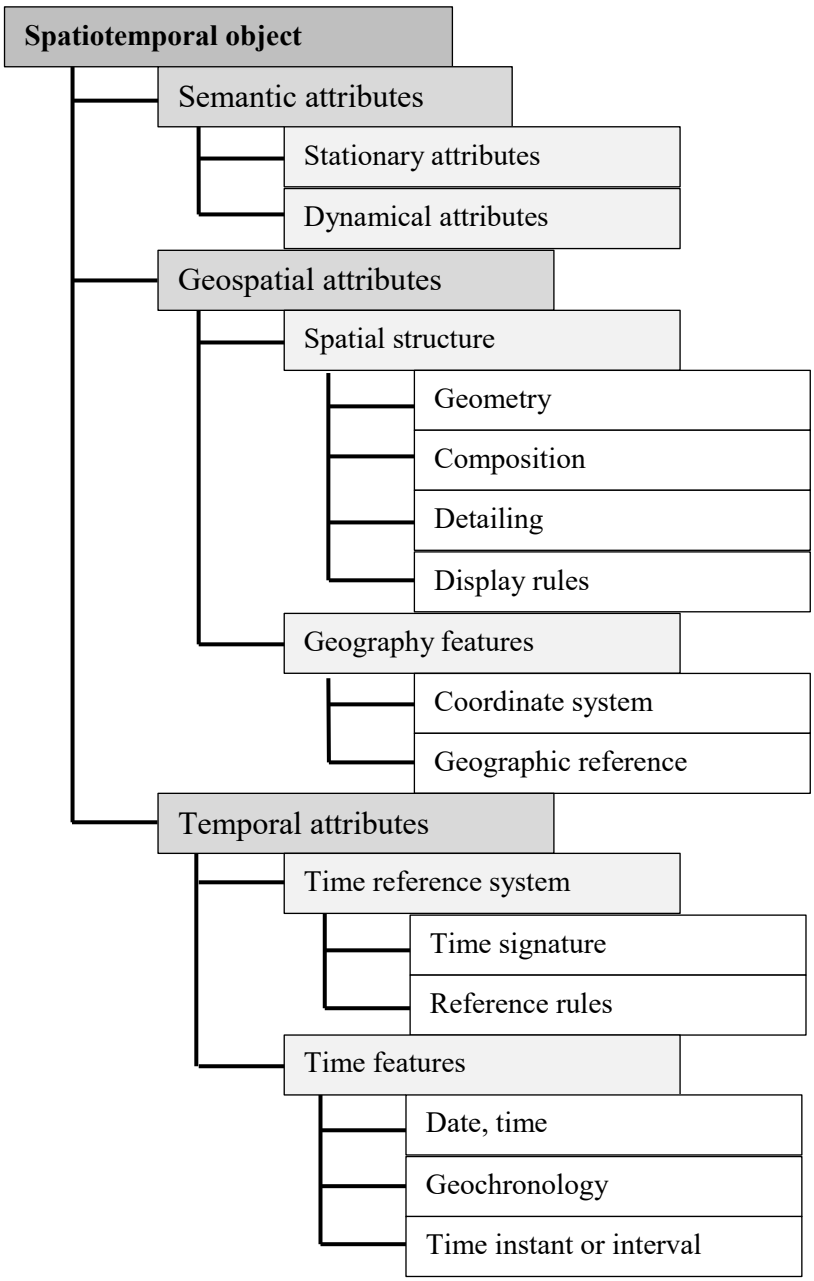


Figure 1: Data model to represent a spatiotemporal object.

According to this model, a spatiotemporal object is a class that contains semantic, geospatial, and temporal attributes. Geospatial attributes contain geospatial structure and geographic features. The former describes geometry, display rules, composition, and multi-level detailing. The latter defines the geospatial reference system and geographic reference. Time attributes contain time signatures and a time reference system. The former consists of time, date, geochronology, time instant, or interval. The latter defines the time scale and rules of reference.

4.2. Spatiotemporal event model

A spatiotemporal event is a change in the state of a monitoring object, which may relate to semantic, temporal features, geometry, spatial location, and connections with other objects.

The data model for a spatiotemporal event is represented by a class that contains semantic, geospatial, and temporal attributes. Semantic attributes define an object or a group of objects that are being monitored. They define monitored attributes for these objects, their values, an event indicator, and boundary conditions that trigger the event (Fig. 2). Monitored attributes and event indicators can either coincide or differ. Geospatial and temporal attributes are represented similarly to the spatiotemporal object model.

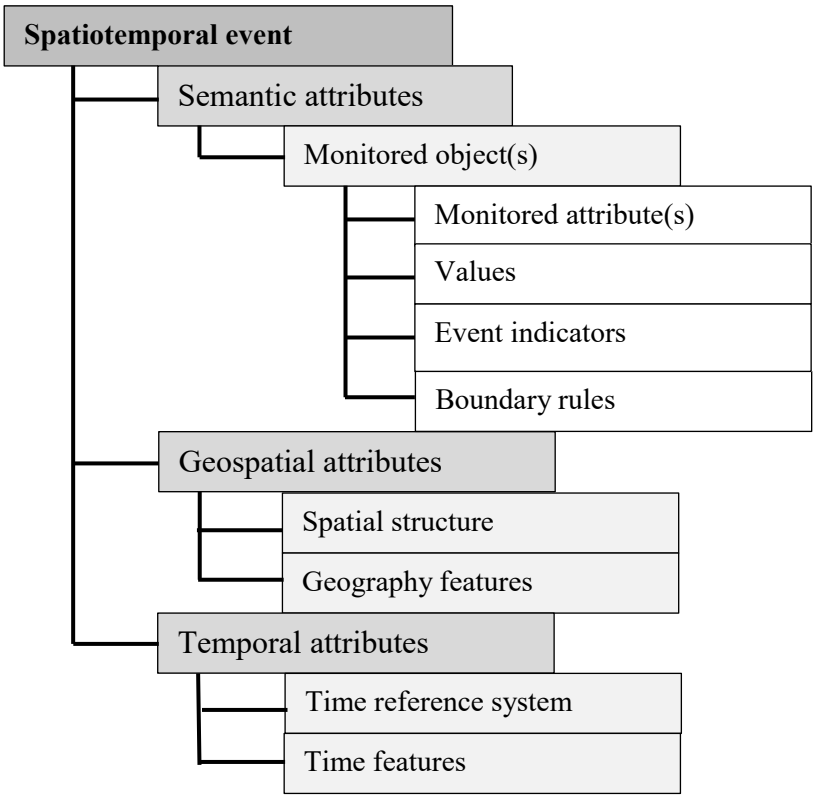


Figure 2: Data model to represent a spatiotemporal event.

An event is initiated as follows. Let $S=\{s_k|k=1,n\}$ - object whose characteristics are subject to monitoring; I – a set of indicators that define events. Indicators can be attributes of the monitored object or attributes of other (related) objects, calculated values, or external influences. When the system is operating, a set of I_V new values is selected from the set of indicators I. A set of new values can be formalized as a predicate:

$$I_V : \forall i \, I_V(iv) \rightarrow (i, iv) \in I \times I_V \quad (1)$$

where i – an indicator belonging to I, and $iv \in I_V$ - a new value obtained for the indicator i.

After extracting new indicator values, the next step is to analyze and evaluate them. A value iv of some indicator is compared with a given set of limit values. Formally, the set of Z_V indicators belonging to the range given by the limit values can be written as:

$$Z_V : \forall i, iv \; Z_V(i) \rightarrow ((iv \leq D_l(i)) \vee (iv \geq D_u(i))) \quad (2)$$

where i – indicator included in I;

iv – value obtained for the indicator i;

D_l – function: $D_l : I \rightarrow L_t$, which returns the lower threshold l_t ($l_t \in L_t$ - set of lower thresholds for an indicator from I);

D_u – function: $D_u : I \rightarrow U_t$, which returns the upper threshold u_t ($u_t \in U_t$ - set of upper thresholds for an indicator from I).

If the indicator value is found to be within a specified range, i.e. $Z_V \neq \emptyset$, then an event is triggered.

4.3. Spatiotemporal process model

A chain of spatiotemporal events, united by the same set of objects and/or one geospatial location, ordered by temporal features on a defined time scale, constitutes a spatiotemporal process (Fig. 3). Processes defined in this way can be interdependent and interconnected, in the case when there are intersections between the sets of events and objects included in them.

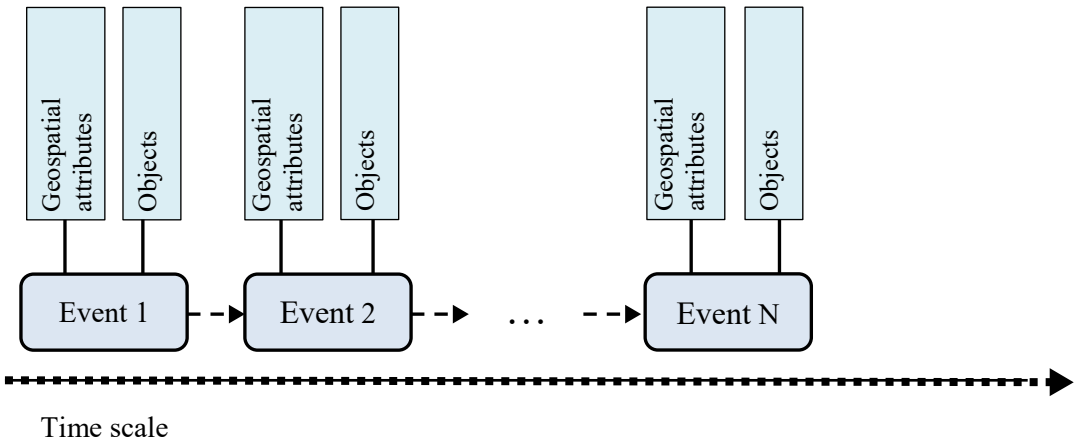


Figure 3: Construction of a spatiotemporal process in the monitoring system of the surrounding space.

A spatiotemporal process is described by a class, which, like previous models, contains semantic, geospatial, and temporal attributes. Semantic attributes represent references to events (start, intermediate, finish), their relationships, and relationship rules (Fig. 4). The geospatial and temporal attributes of the process are defined similarly to the models of spatiotemporal objects and events.

If we consider a spatiotemporal process as a whole, its geospatial characteristics are the combination of the geospatial characteristics of all the events that make it up, and the temporal characteristics are the period between the starting and finishing events. However, at each fixed

moment or time interval (depending on the scale and rules of timekeeping), the spatial and temporal characteristics of the process are determined by the corresponding event.

It should be noted that time modeling in monitoring systems is a separate, quite complex task. For each event, the model time (time of occurrence in a given reference system) and transaction time (time of writing to the database) are stored. The time scale can be continuous, discrete, or interval, which affects the construction of time processes. [5,12,13]. Also, to implement forecasting tasks, it is necessary to provide the possibility of branching the time scale.

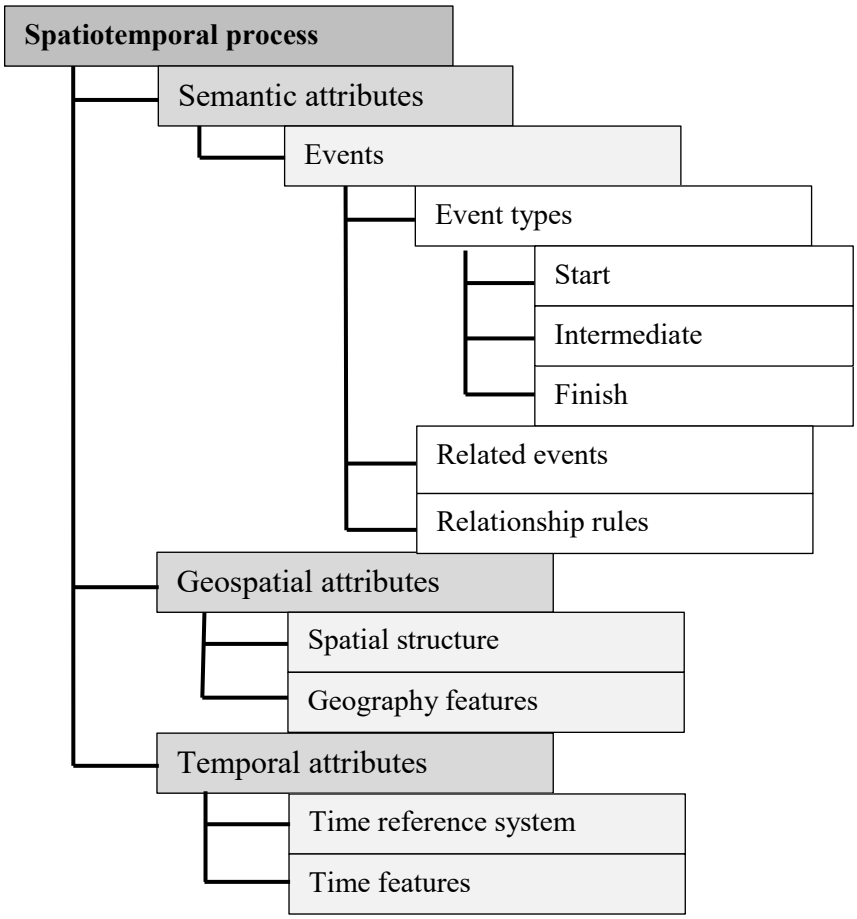


Figure 4: Data model to represent a spatiotemporal process.

5. Modeling of the monitoring system of the surrounding space based on the proposed data model

A monitoring process occurs as follows: at certain points in time, sensors record a change in the state of physical objects or phenomena, which generates an event. The event handler performs multi-factor change processing, which can lead to the generation of higher-level events. A complex of events united by a group of objects, the same space, and/or the same time interval constitutes a spatiotemporal process. A set of spatiotemporal processes determines the evolution of the environment to be monitored.

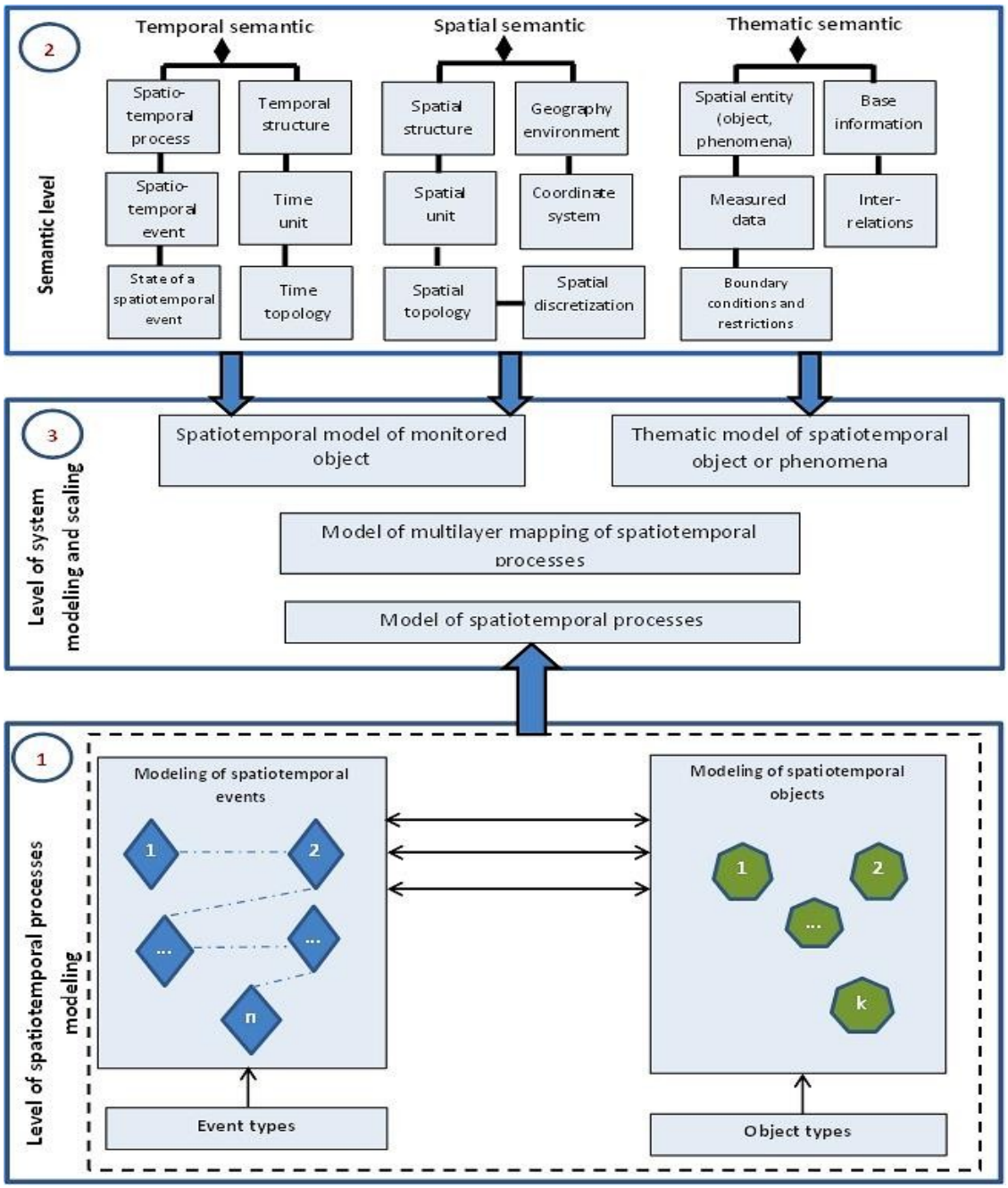


Figure 5: Conceptual model of a surrounding space monitoring system based on a three-level data model "object-event-process".

Here Figure 5 shows a conceptual model of a GIS-based monitoring system. This model consists of three levels:

1. The level of spatiotemporal processes modeling. The main information components are spatiotemporal objects and spatiotemporal events. Processes are built as time chains of events associated with a set of objects
2. Semantic level. Represents the basic, temporal, spatial, and geographical features of the entities of the monitoring object
3. The level of system modeling and scaling. Based on the previous levels, a spatiotemporal geographic model of the monitoring object is built

These layers are coordinated with each other and can support multi-scale geospatial features, multi-level observational data, multi-factor events, and different time scales and representations.

Thus, the proposed data model allows us to see the "holistic picture" of the monitored environment faster and more fully, since by increasing the connectivity of information support, it simplifies the performance of such operations as, for example: list:

- From a request about objects, get related events and processes
- Select processes occurring in a certain territory during a certain period of time and obtain dangerous objects related to them
- Conduct a re-simulation of the process development based on historical data to work out countermeasure options
- Model the possible development of spatiotemporal processes based on previous data
- Assess the effectiveness of implemented measures by comparing new data sets with previous ones

6. Conclusions

A three-level spatiotemporal data model "object-event-process" is proposed for the surrounding space monitoring systems. It consists of: object models with geospatial and temporal attributes; models of spatiotemporal events that arise when changing the object's characteristics or the state of the system as a whole; spatiotemporal processes controlled by multilevel factors determined by events. This approach allows us to describe formally the relationships between physical objects, events, space, time, and spatiotemporal domains. In addition to complex spatial relationships, it is also capable of modeling linear/branched/cyclic temporal order, various spatial changes, and complex temporal relationships.

Considering events and processes as separate entities allows us to organize the moments of change in the states of objects and territories over time and implement their convenient storage in a relational database. Temporal logic, in which events are separate entities, provides the means for the adaptive construction of spatiotemporal processes, where the flow of events can have both uniform and non-uniform discretization in time, which is determined by the real rhythm of changing circumstances. The combination of model components, both by the method of sequential construction (chain) and in the form of network or tree-like structures, allows solving the tasks of monitoring objects and phenomena of varying complexity, target orientation, and hierarchical level.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

References

[1] B. Calka, M. Szostak, GIS-Based Environmental Monitoring and Analysis, Appl. Sci. 15.3155 (2025): 2-6. doi:10.3390/app15063155.

[2] O. Zalyubovska, Landscape research: from paradigm through GIS technology to monitoring (on the example of the territory of the "Slobozhansky National Park"), Bulletin of V. N. Karazin Kharkiv National University, series "Geology. Geography. Ecology" 59 (2023) 110–124. doi:10.26565/2410-7360-2023-59-09.

[3] Ezra Chipatiso. Application of Geographic Information Systems and Remote Sensing in Military Operations: A Systematic Review. URL:

https://www.techrxiv.org/users/641441/articles/705593-application-of-geographic-information-systems-and-remote-sensing-in-military-operations-a-systematic-review.
[4] Yunpiao Bai, Michael Grüninger, Spatiotemporal = Spatial × Temporal, in: CEUR Workshop Proceedings, volume 3249, 2022. URL: https://ceur-ws.org/Vol-3249/paper2-FOUST.pdf .
[5] Martin Erwig, Markus Schneider & Ralf Hartmut Güting, Temporal and Spatio-Temporal Data Models and Their Expressive Power. URL: https://www.researchgate.net/publication/2422280_Temporal_and_Spatio-Temporal_Data_Models_and_Their_Expressive_Power.
[6] K. R. Ferreira, G. Camara, A. M. V. Monteiro, An algebra for spatiotemporal data: From observations to events, Transactions in GIS 18.2 (2014) 253-269. doi:10.1111/tgis.12030.
[7] IK. R. Ferreira, A. G. de Oliveira, A. M. V. Monteiro, D. B. de Almeida, Temporal GIS and spatiotemporal data sources, Brazilian Journal of Cartography 68.6 (2016) 1191-1202. URL: https://www.researchgate.net/publication/311734311_Temporal_GIS_and_Spatiotemporal_Data_Sources.
[8] R. H. Güting, M. H. Böhlen, M. Erwig, C. S. Jensen, N. A. Lorentzos, M. Schneider, M. Vazirgiannis, A foundation for representing and querying moving objects, ACM TODS 25.1 (2000) 1–42. URL: https://files.ifi.uzh.ch/boehlen/Papers/GBE+00.pdf.
[9] A. Z. Spector, Achieving application requirements, in: S. Mullender (Ed.), Distributed Systems, 2nd. ed., ACM Press, New York, NY, 1990, pp. 19–33. doi:10.1145/90417. 90738.
[10] D. Zheni, A. Frihida, H. B. Ghezala, C. Claramunt, A semantic approach for the modeling of trajectories in space and time, in: Proceedings of the ER 2009 Workshops "Advances in Conceptual Modeling - Challenging Perspectives", 2009, pp. 347–356. doi:10.1007/978-3-642-04947-7_41.
[11] Johann Bornholdt, Theodoros Chondrogiannis, Michael Grossniklaus, Trajectory data management: A data model and predicate logic with operators for spatio-temporal query processing, Information Systems 135 (2026): 102595. doi:10.1016/j.is.2025.102595.
[12] K. Jitkajornwanich, N. Pant, M. Fouladgar & R. Elmasri, A survey on spatial, temporal, and spatio-temporal database research and an original example of relevant applications using SQL ecosystem and deep learning, Journal of Information and Telecommunication 4.4 (2020) 524-559. doi:10.1080/24751839.2020.1774153.
[13] Markus Schneider, Moving Objects in Databases and GIS: State-of the-Art and Open Problems, in: Gerhard Navratil (Ed.), Research Trends in Geographic Information Science, Springer Science & Business Media, 2009, pp. 169-187. doi:10.1007/978-3-540-88244-2_12.
[14] R. Keller, Ch. Baru, Geoinformatics: Cyberinfrastructure for the Solid Earth Sciences, Cambridge: University Press, 2011.
[15] E. Bocher, M. Neteler, Geospatial free and open source software in the 21st Century, in: Proceedings of the first Open Source Geospatial Research Symposium, Massachusetts Institute of Technology, Cambridge, 2009.
[16] Spatiotemporal Data. URL: https://www.sciencedirect.com/topics/computer-science/spatiotemporal-data.
[17] K. Wisal, A. Ejaz, S. Waseem, Predictive Performance Comparison Analysis of Relational & NoSQL Graph Databases, International Journal of Advanced Computer Science and Applications (IJACSA) 8.5 (2017). doi:10.14569/IJACSA.2017.080564.
[18] D. Guo, E. Onstein, State-of-the-Art Geospatial Information Processing in NoSQL Databases, ISPRS International Journal of Geo-Information 9.5 (2020): 331. doi:10.3390/ijgi9050331.