Implementations of Spatio-Temporal Data Structure for Geographic Information System

Kazuaki Iwamura
Information and Telecommunication Systems Company
Hitachi, Ltd.
Tokyo, Japan
e-mail: kazuaki.iwamura.wx@hitachi.com

***Abstract*—A new spatio-temporal data structure for a geographic information system (GIS) is introduced and employed for various applications. First, the concept for the spatio-temporal data structure is established. The effectiveness of the data structure for management and visualization of real-world states is then demonstrated. To outline its effectiveness, real-time map update and level-of-detail representation are described. The data structure is implemented in a new type of GIS platform, denoted as a four-dimensional GIS (4D-GIS). 4D-GIS applications to social infrastructure management and monitoring are also introduced. 4D-GIS is expected to contribute to the solution of real-world problems.**

Keywords-spatio-temporal; data structure; data integration; four-dimensional GIS.

I. INTRODUCTION

Numerous geographical information systems (GISs) have been employed for various applications and used for data management [1]. GIS platforms also have evolved in accordance with developing technology. For example, platforms that can manage 3D data or integrate numerous types of data have made important applications possible. Thus, users are enabled to employ GISs as problem solution tools.

This paper focuses on spatio-temporal and integrative structures to visualize and solve real-world problems. Actually, many real-world problems are concerned with two-dimensional (2D) and three-dimensional (3D) data that include temporally changing elements and aspects, which are recorded in various types of documents such as maps and diagrams. For this purpose, common data structures and integration methods are introduced to solve various problems.

Spatio-temporal data modeling has hitherto been proposed and applied to various fields [2]-[4]. In [2], a three-domain model comprising semantic, temporal, and spatial domains is proposed to realize complex query compositions. In [3], two temporal dimension models are introduced to represent actual and planned events. In [4], a data structure for spatio-temporal queries is proposed. In this paper, a new type of spatio-temporal data structure that can represent 2D, 3D and their time changes and their applications is introduced.

In Section II of this paper, the basic formulation of the proposed spatio-temporal data structure is established. In Section III, real-time map updates and level-of-detail (LOD) representation, which are data visualization control methods, are described to illustrate some spatio-temporal aspects. In Sections IV, V, and VI, the structure is implemented in a new type of GIS platform, denoted as four-dimensional GIS (4D-GIS), and applications to social infrastructure management and monitoring are introduced. In Section VII, the effectiveness of the proposed spatio-temporal data structure is discussed and a conclusion of the work follows.

II. THE SPATIO-TEMPORAL DATA STRUCTURE

In this section, the basic formulation of the proposed spatio-temporal data structure and its extensions to 3D and temporal changes are established.

A. The Structure of Spatio-temporal Shapes

Spatio-temporal shapes are coordinate data whose dimensions are 2D and 3D in addition to temporally correlated changes. An illustrative structure is shown in Fig. 1.

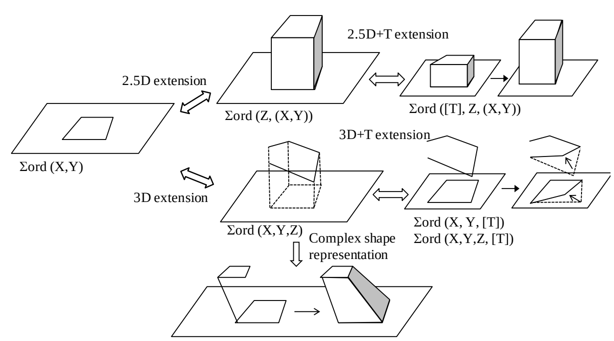

Figure 1. Spatio-temporal data structure

The basic shape of the structure is 2D. The 2D structure is written as follows in (1).

$$\Sigma_{ord}\,(X, Y) \quad . \qquad (1)$$

Here, Σ_{ord} does not imply a summation of numerical values but indicates ordered (X, Y) coordinate sequences. All shape data whose dimensions are greater than 2D are obtained by the expansion of this 2D structure. 3D shapes are extended by inserting a new dimension for height or depth. This extension takes one of the two forms given in (2) and (3).

 ISBN: 978-1-61208-383-4

$$\Sigma_{ord}\ (Z, (X, Y)) \quad , \qquad (2)$$
$$\Sigma_{ord}\ (X, Y, Z) \quad . \qquad (3)$$

Structure (2) represents a 2.5-dimensional (2.5D) structure, where Z is a common height/depth dimension for all (X, Y) coordinates. Using (2), 3D structures such as buildings can be represented. On the other hand, for structure (3), all (X, Y) coordinates include individual Z coordinates. For example, sewer pipes, which are inclined, would be represented by 3D polylines using structure (3).

Spatio-temporal structures are expansions of structures (1), (2), and (3). For structures (1), (2), and (3), time data are attached as follows in (4), (5), and (6), respectively.

$$\Sigma_{ord}\ (X, Y, [T]) \quad , \qquad (4)$$
$$\Sigma_{ord}\ ([T], Z, (X, Y)) \quad , \qquad (5)$$
$$\Sigma_{ord}\ (X, Y, Z, [T]) \quad . \qquad (6)$$

Here, [T] is a time value that is attached only to changing coordinates. Because time is a continuous value, the time attributes are attached as follows.

- creation start time and creation end time,
- elimination start time and elimination end time.

A given start time and end time are paired values.

The 4D-GIS serves as a spatio-temporal data integration platform, and all data structures (2)–(6) can be expanded from the base structure (1) according to dimensions required by a given application. The merits for adopting the above spatio-temporal data structures are as follows.

- Because past data is not deleted, time change sequence data remains available for applications.
- Data with future time change sequence data can be stored for planning applications.
- Because changed structures remain in a coordinate sequence, it is easy to locate the point in time when changes occur.
- Because only coordinate difference data is stored, data storage does not become large.

B. Extension to Complicated Shapes

Real-world object shapes tend to be more complex than those presented above. Shapes that are more complicated can be represented by a combination of structures given by (1)–(6). The equation for combination is as follows in (7).

$$\text{Shape} = F_1\ (S_1\ (t), S_2\ (t), L_1(t)) + F_2\ (S_2\ (t), S_3\ (t), L_2(t)) + \ldots + F_n\ (S_n\ (t), S_{n+1}\ (t), L_n\ (t)) \quad . \qquad (7)$$

Here, S_i is a control surface, L_i is a control line, and t is a parameter. S_i and L_i have the same structures given in (1)–(6), and time varying representations are also possible. Full shape data is created by interpolating between control surfaces S_i and S_{i+1} along a control line L_i. This structure can be denoted as homotopical data. The word homotopy is a mathematical term in topology describing smooth deformation/connection between two shapes.

Two types of homotopical data generation exist.

- Interpolation of a control line by curve fitting, where control surfaces are attached to both ends of a control line and a fit curve is generated among a control line. An example is shown later in Fig. 6.
- Interpolation by model shapes along a control line, where model shapes are generated and connected along a control line successively. An example is shown later in Fig. 3.

C. Spatio-Temporal Attribute Data

Attribute data, which are connected by a position or by map objects, are also managed by the temporal structure. Fig. 2 shows the table structure of attribute data in a relational database.

Latest attribute data table

Start time	End time	Attribute 1	Attribute 2
09/01/2014	20/01/2014	AAAA	BBBB
25/02/2014	10/03/2014	CCCC	DDDD

History data table

Start time	End time	Attribute 1	Attribute 2
09/01/1990	09/01/2014	AAAA	EEEE
15/01/1990	10/03/2014	FFFF	DDDD

Figure 2. Attribute data and their history management

This structure comprises two table types. One is the latest attribute data table and the other is the history data table. The latest attribute data table stores the latest data and the history data table stores records to be changed.

Each record in both data tables includes “start time” and “end time” terms. When the attributes in the record fields in the latest attribute data table are to be changed, data in these records are moved to the history data table and the available periods are attached according to the start time and end time. Then, fields of the latest attribute data table are changed by the newly obtained data. When GIS users want to refer to past attribute data, the corresponding records in the latest data table and the history data table are exchanged. Thus, histories of attribute data are managed and used.

D. Spatio-temporal Linear Feature Data

Linear features are concerned with elongated configurations such as roads and trunk gas/oil pipelines. Data for these facilities in GISs are managed by a distance parameter [5]. Moreover, linear features that change according to time can be denoted as spatio-temporal linear features. For example, defect positions such as pipeline corrosion are managed using distances from a reference point, and corrosion expands gradually with time.

Using the complicated shape representation given by (7), shape data for large-scale social infrastructures can be generated. An example of road shape generation is shown in Fig. 3.

The shape generation steps are as follows.

Step 1: facility parameters are retrieved according to the distance value obtained from the attribute database.

Step 2: templates given as model shapes are generated by referring to facility parameters.

Step 3: model shapes are aligned along a control line and connected. Then, the full shapes are generated.

Merits of this process of shape generation are as follows.

- The linear feature model is generated using attributes, and is therefore a compressed type of data.

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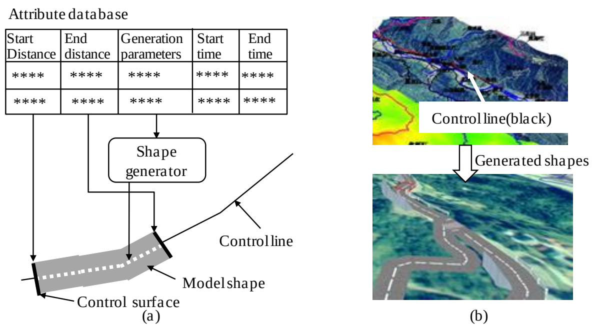


Figure 3. Road shape generation: (a) Principle, (b) Example

- When facilities are changed, it is sufficient to update only the parameters of the facility attribute data because new shapes can be generated using the updated parameters.

As an example, when the method is applied to updating map data for a sound-proof wall of an elevated causeway, the update cost using linear features is about 1/3 that when using full shape data.

III. REAL-TIME MAP UPDATE AND LEVEL-OF-DETAIL CONTROL

In this section, two remarkable uses of the proposed spatio-temporal data structure and the homotopical data structure are presented. One use is in real-time map update and the other is LOD control in shape visualization.

A. *Real-time Map Update*

Map data becomes antiquated immediately after creation because the real world changes rapidly. Therefore, timely updating map data in accordance with real-world changes is preferable. On the other hand, the obtained map data should be authorized by the responsible authorities, and updates of original maps can require considerable time for completion. TABLE I lists the update cycle times of gas and water supply facility maps prepared by a local government of Japan.

TABLE I. UPDATE CYCLES OF FACILITY SCHEMATICS

Drawings/Maps	Scale	Update cycle	Time to update
Gas supply facilities	1/500	3 times/Year	2–5 months
Water supply facilities	1/500	Once/Year	2–5 months
Water facilities' master	1/500	Once/Year	One year
CAD Drawings	1/200	Once/Year	One month

Because infrastructure such as gas pipelines are repaired or exchanged daily, map data in which the latest infrastructural configurations are reflected should be created in a timely manner. Thus, a new method for the real-time map update was developed. The developed system is illustrated in Fig. 4, and an example of map update is shown in Fig. 5.

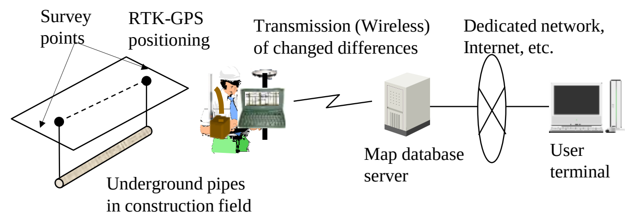


Figure 4. System for real-time map update

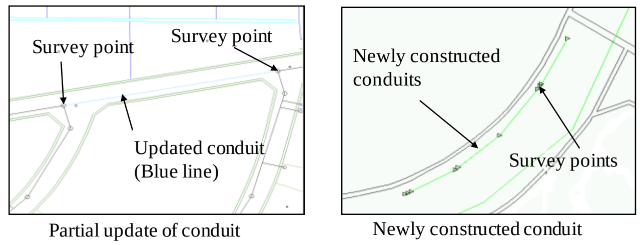


Figure 5. Example of real-time map update

As shown in Fig. 4, real-time kinematic global positioning systems (RTK-GPS) are employed to obtain facility position coordinates such as for pipes, which represent a segment of infrastructure. Then, the configuration coordinates of this segment with time values are transferred to a map database server, and the map data is immediately updated according to the spatio-temporal schema.

At this point, a comment is required. The obtained coordinate data are embedded into the map data. However, the updated maps are not official until authorized. Thus, the updated maps are temporary. To accommodate authorization requirements in the spatio-temporal data format, an authorization tag bit is incorporated. Prior to authorization, this tag bit is switched off. After authorization, the tag bit is switched on, allowing 4D-GIS users to discriminate the status of map elements. This method has important merits whereby current real-world states can be evaluated and 4D-GIS users can employ the latest maps at any time.

B. *Level-of-detail Control*

The LOD establishes design criteria for map visualization control. In this section, two types of LOD design methods that are concerned with accuracy controls are described. One is a 2D case and the other is a 3D case. The LOD control is necessary to visualize maps of different accuracies successively.

1) *Level-of-detail control in 2D visualization*

In this section, the homotopy concept of (7) is applied to curved polyline accuracy controls. When map data is magnified, curved polylines such as contour lines become coarse. However, the resolution of curved polylines should remain consistent even when magnified. One solution to avoid this situation is to prepare a plurality of curved polylines with different levels of accuracy and to select them according to the magnification employed. However, when data are updated, all related data should be updated. Thus, a curve fitting method

 ISBN: 978-1-61208-383-4

based on homotopical data interpolation was developed. The fitting equation based on (7) is as follows in (8).

$$\mathrm{Curve}_i(t) = (1 - t)C_i + tC_{i+1} \quad . \qquad (8)$$

Here, Curve_i is a fitting curve for the line L_i, where $0 \le t \le 1$., and C_i and C_{i+1} are circle arcs. The method is also illustrated in Fig. 6 (a).

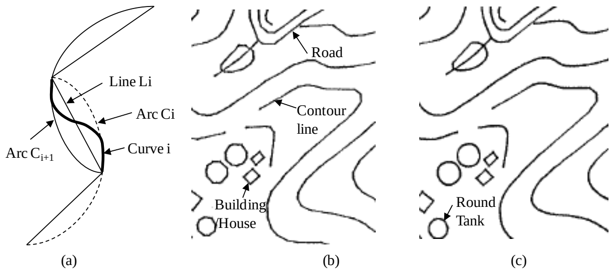


Figure 6. Homotopical LOD control of 2D shapes: (a) fitting principle, (b) shapes before fitting, (c) shapes after fitting.

Polylines might include groups of segments that represent large curvatures. At these segments, curve fitting without controls would result in an unexpected overlap with other shapes. Thus, the four controls listed in TABLE II are imposed.

TABLE II. LOD CONTROL OF 2D SHAPES (CURVE FITTING)

Parameter	Condition	Control
Line length L_i	$TL_{min} \le \lvert Li \rvert$ $TL_{max} \ge \lvert Li \rvert$	$C_i \to L_i$ in (8)
Angles θ of two lines L_i, L_{i+1}	$TA_{min} \le \lvert\theta\rvert$ $TA_{max} \ge \lvert\theta\rvert$	$C_i \to L_i$ in (8)
Maximum deviation d between C_i and L_i	$d \le T_d$	Fitting (8) stops
Ratio r/d (r is radius of C_i)	$r/d \ge T_r$	Fitting (8) stops

Here, T_{Lmin}, T_{Lmax}, T_{Amin}, T_{Amax}, T_d, and T_r are thresholds. T_r is determined uniquely. The consideration wherein squares are not fitted, and therefore, not changed to a circle requires that

$$d = r - \frac{r}{\sqrt{2}} \text{ and } T_d = \frac{r}{d} = \frac{\sqrt{2}}{\sqrt{2}-1} \cong 3.4. \quad . \qquad (9)$$

The result is shown in Figs. 6 (b) and (c).

2) *Level-of-detail control in 3D visualization*

In 3D urban area visualization, 3D shapes far from a given viewpoint are small and details are degenerated. Thus, display of all 3D data including details is needlessly time consuming, making it is necessary to control the visualization accuracy. For example, shapes near a viewpoint are visualized in detail, whereas shapes far from a viewpoint are eliminated or the details are omitted. Using homotopical data structure, LOD controls can be realized effectively. The design criteria of LOD are listed in TABLE III. Here, T_{L1}, T_{L2}, T_{L3}, T_H, and T_S are thresholds.

TABLE III. LEVEL-OF-DETAIL CONTROL OF 3D SHAPES (OBJECTS)

Parameter	Condition	Result
Distance L from a viewpoint to a shape	$L \ge T_{L1}$	Objects whose heights are lower than T_H are deleted.
	$T_{L2} \ge L \ge T_{L3}$ ($T_{L2} \ge T_{L3}$)	Small lines whose lengths are less than T_s are deleted. When an object comprises a group of objects, the group is united into a single average object.

Fig. 7 illustrates the application of these control criteria.

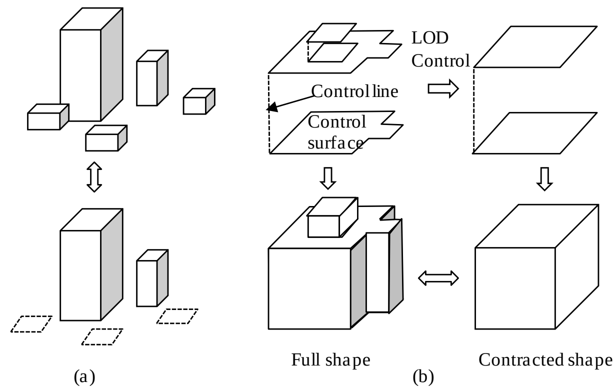


Figure 7. Homotopical level-of-detail (LOD) control of 3D shapes: (a) object control and (b) deformation.

Fig. 7 (a) presents an example of object control, where objects far from a viewpoint are eliminated. Fig. 7 (b) is an example of deformation, where detailed segments of objects are removed because the details fade as objects recede from a viewpoint.

The merits of the homotopical method in LOD controls are as follows.

- The amount of data required to construct models are significantly reduced. For example, using this method to construct a 3D model of the crowded city-center of Tokyo reduces the required data size by 28% on average relative to the use of full shapes.
- By managing only the original homotopical data, any LOD data can be generated by deformation of control surfaces.
- Temporal changes are also represented by attaching time values in control surfaces and control lines.
- Smooth viewpoint changes are also realized.

IV. TRUNK GAS PIPELINE INTEGRITY MONITORING

In Sections IV, V, and VI, applications using spatio-temporal data to trunk gas pipeline integrity monitoring, communication facility management, and power consumption monitoring are introduced. In this section, trunk gas pipeline integrity monitoring is presented.

A. *Pipeline Integrity Data*

For trunk gas pipelines, transport pressures are greater than 4 MPa. Numerous trunk pipelines whose lengths are greater than 1000 km pass through several countries. When pipelines are buried underground and not adequately

 ISBN: 978-1-61208-383-4

maintained, defects such as corrosion appear, and the wall thicknesses of pipes decreases over time. These conditions induce pipeline collapse. Thus, GISs are introduced for maintenance support to protect against pipeline collapse and possible explosions. The requirements for GISs are as follows [6].

- Representation of overall pipeline conditions. Data reflecting the overall pipeline status should be integrated and retrieved by map interfaces.
- Prediction of potential risks. Potential risks such as deterioration of pipes caused by expanding defects should be readily detected.
- Contribution to stable and safe gas transport. The stress concentrations on defects should be calculated.

In TABLE IV, pipeline integrity data necessary to meet the above requirements for pipeline monitoring are listed.

TABLE IV. DATA FOR PIPELINE INTEGRITY MONITORING

Name of data	Contents
Maps	Pipeline configurations based on 3D coordinates
Facility construction records	Construction specifications such as pipe section length, wall thickness, and pipe diameter
Defect inspection data	Corrosion dimension and positions obtained by the autonomous in-line inspection robot called a "pig"
Protection data	Cathode voltage
Gas transport parameters	Transport pressures at discharges and suctions at compressor stations. Parameters can be obtained from a supervisory control and data acquisition (SCADA) system
Survey results	Soil conditions, facility conditions obtained by digging

Pipelines are often laid on undulating terrain. Thus, pipeline configuration data must possess 3D features. Nearly all data are managed by distance parameters. Moreover, according to a given lapse of time, pipelines located on soft soils tend to sink and defects tend to expand in the absence of repair. Thus, nearly all integrity data are managed as spatio-temporal linear features.

B. *Safety Diagnoses*

Corrosion expansion is concerned with not only soil conditions, but also pipeline materials and transport pressures. The number of areas of corrosion in/on pipelines is occasionally greater than 1,000 per 1 km in the absence of maintenance. However, not all incidents of corrosion are dangerous. Estimating the risks associated with corrosion is important. For this purpose, a safety diagnosis function was incorporated with the 4D-GIS.

The corrosion expansion speed is obtained by extracting size differences between two or more corrosion history data points. In the absence of corrosion history data, the corrosion expansion speed V can be determined by (12) as follows.

$$V = V_0\,(1+E\varepsilon_0)\,\exp\{f\,(T, \varepsilon_1, M)\} \quad . \qquad (12)$$

Here, V_0 is the corrosion speed under no stress conditions, E is an environmental parameter, $\varepsilon_0/\varepsilon_1$ is the volumetric/average strain, f is the stress function, T is the fluid temperature, and M is a pipeline material parameter. By comparison with real data, corrosion expansion is found to coincide with measured values within an error to the order of 0.01 mm.

In Fig. 8, a screen image of the 4D-GIS safety diagnosis function is shown.

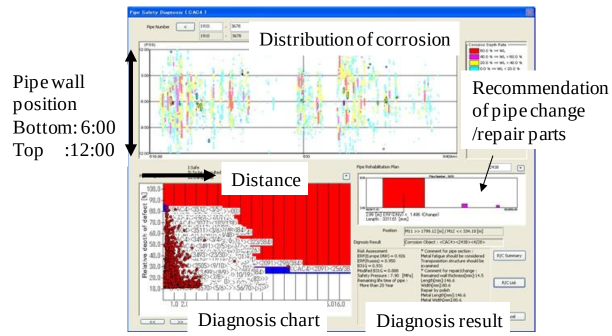


Figure 8. Safety diagnosis

The upper graph in the figure is the corrosion distribution diagram. The bottom left is the corrosion diagnosis chart. The bottom right is the update/repair recommendation and the diagnosis result. In the safety diagnosis, all instances of corrosion in/on the selected pipe sections are projected after the prediction of the current states using past corrosion data or (12). When corrosion is in the red area, exchange or repair of the corroded pipe section is recommended. The blue area represents the warning zone and the white area is the safety zone. Corrosion in the white zone is safe. Moreover, the remaining life time of the selected pipe sections are also predicted using (12).

C. *Analysis of Stress Concentration*

When the wall thickness of a pipeline section thins owing to severe corrosion, stresses caused by transport pressures can induce pipeline failure and potential explosions. Therefore, monitoring of the transport pressure distribution and stress concentrations are highly recommended. An extraction of stress concentration on pipeline sections is shown in Fig. 9.

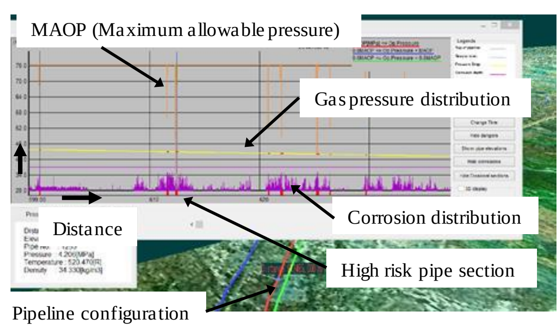


Figure 9. Calculation of pipeline stress concentration

In Fig. 9, red bands means high risk pipe sections. Orange graph means maximum allowable operation pressures (MAOP). Stress concentrations depend on the transport pressure, corrosion size, and pipe dimension. It is convenient to transform stress values to allowable pressure values. Stress values are calculated by the stress-strain equation. An allowable pressure P_{max} is calculated using the following equation (13).

$$P_{max} = 4\sigma\delta/D \quad . \qquad (13)$$

Hear, σ is the axial stress, δ is the modified wall thickness, and D is the modified pipe diameter. When P_{max} /MAOP > α, pipe sections with these Pmax values have high risks. $\alpha = 0.5$ for safety.

When a bypass pipeline, denoted as looping, is utilized, the transport pressure is reduced by an operational method that divides the gas flow into a main pipeline and a looping pipeline.

V. OPTICAL COMMUNICATION FACILITY MANAGEMENT

In this section, an optical communication facility management is introduced. Some local governments in Japan have constructed optical communication networks in sewer underdrains and pipes for data communication among sewage disposal plants. For maintaining communication facilities, engineers refer to numerous types of documents. A listing of these reference documents is given in TABLE V.

TABLE V. DOCUMENTS FOR COMMUNICATION FACILITY MAINTENANCE

Type of document	Content
Map	Communication routes and their locations
Facility diagram	Connections of network equipment
Network diagram	Schematic communication routes
Fiber connection diagram	Routes of fibers cores included in cables
Facility data	Specifications of facilities

Maps, diagrams, and facility data are altered according to network expansion. Moreover, future networks are also input. Thus, spatio-temporal data management was adopted.

In maps, geographical locations of communication routes are presented. However, equipment such as fiber connection boxes is not represented. On the other hand, other diagrams are topological, and connection sequences of network equipment are given. When documents are used, the following problems are encountered.

- When maps and diagrams are separately referenced, facility sequence information cannot be obtained from maps and facility locations cannot be obtained from diagrams.
- Fiber connection diagrams describe the connection routes of fibers. Because the number of fibers in a cable is large, drawing diagrams manually is difficult.

Facility managers and engineers use all types of documents in daily maintenance work, and the 4D-GIS can solve the problems described above by integrating the different types of documents employed.

A. *Categorical Connection among Documents*

The method employed for the integration of maps and diagrams is described. Both types of documents are connected according to category theory [7][8]. Category is a mathematical concept that describes the relations of homomorphic structures.

The connection method among two structures is illustrated in Fig. 10 (a). In the figure, “Map” indicates map objects, “Dgm1” and “Dgm2” indicate two different diagram objects, and “Attr” indicates attributes. Relations among maps and diagrams are illustrated in Fig. 10 (b).

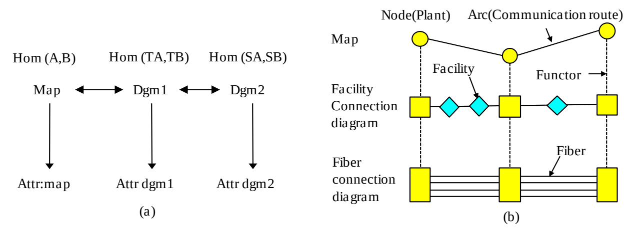


Figure 10. Connection between documents based on categories: (a) connection structure, (b) interconnections among documents.

Nodes represent plants and links between two communication routes. The nodes in maps and diagrams are connected beforehand because the number of nodes is large (about 100). Routes between nodes can be calculated by a path-finding algorithm.

The mappings between nodes and between links can be denoted as functors. Functors are bridges between two structures. A functor τ is a projection of nodes and links as follows in (14).

$$\tau\text{: Hom(A,B)} \rightarrow \text{Hom(TA,TB)} \qquad (14)$$

Here, Hom(A,B) is a projection and corresponds to a route from node A to node B, whereas TA and TB are mapped nodes in the other document that correspond to node A and node B, respectively. In a facility connection diagram, facility connection sequences are described. However, map users cannot retrieve the sequences of facilities and their specifications because these data are not attached to maps but to diagrams. Thus, functors play important roles as connectors among documents.

The outline of steps for retrieving communication routes and facility data by linking between a map and diagram are described below.

Step 1: selection of two nodes on a map.
Step 2: finding corresponding nodes on a diagram by a functor.
Step 3: finding the related route on a diagram, as calculated using a path-finding algorithm.
Step 4: retrieval of facility data on the selected route from the database.

An example of related route finding based on the above steps is shown in Fig. 11.

Following the finding of the route on the map (the red color route in the map), the corresponding route in the facility diagram (the red color route in the facility diagram) is detected.

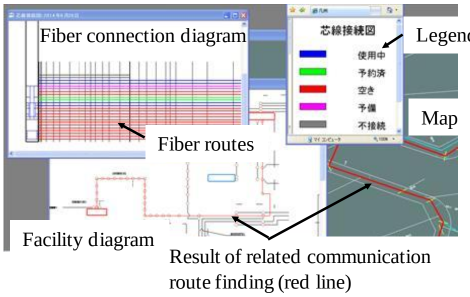


Figure 11. Related route finding and generation of fiber connections diagram

B. *Automatic Fiber Route Diagram Generation and Implicit Data Management*

Presently, fiber connection diagrams are drawn manually. However, drawing fiber connection diagrams is difficult because a great many fiber core lines, occasionally more than 1000, are included in a single cable. Using the functor approach, fiber connection diagrams can be generated automatically. Moreover, a new database method, referred to as implicit data management, is shown to contribute to the retrieval of fiber connection data easily.

Two fiber cores are connected by melting or with connector boxes, and a very great amount of connection data must be managed effectively. However, to input connection data manually is time consuming. Every fiber core has an index such as 1-2, 2-3. The former number represents the cable case number, whereas the latter number represents the fiber core number. Two fiber cores with the same index are ordinarily connected whereas few fibers with different indices are connected exceptionally. Thus, only connection data with different indices is stored in the database and ordinary connection data is not stored. In this manner, when an index pair does not exist in the database, fibers with the same indices are connected. This data registry method is herein denoted as implicit data management. The total data size is thereby reduced by greater than 1/5. A result of fiber connection diagram generation is shown in Fig. 11. The fiber connection diagram that corresponds with the finding route (the red color route in the map) is generated.

VI. BIG DATA PROCESSING IN POWER MONITORING

Recently, numerous smart city projects have been planned and executed. In smart cities, effective monitoring of power supply and consumption is pursued. For this purpose, energy consumption data is collected by equipment such as smart meters and analyzed to determine consumption trends. The data occasionally comprise greater than 10 million individual elements. It is a technical challenge to develop methods to handle such large power consumption data sets, which can be denoted as big data. For this purpose, the 4D-GIS adopted in-memory techniques. In-memory techniques employed in 4D-GIS are shown in Fig. 12 and described as follows.

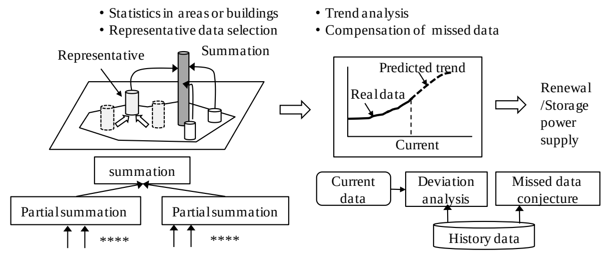
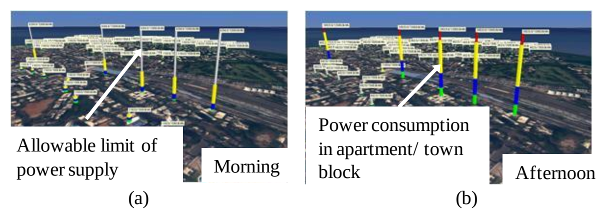


Figure 12. In-memory processing techniques employed in 4D-GIS

- Capture of statistics over areas or for individual buildings obtained from the summation of power consumption values in designated areas or for building objects in maps.
- Representative data selection from, for example, houses that show similar consumption values and patterns. In this example, a representative house is selected and the consumption data of other houses are omitted. Thus, the amount of collected data is greatly reduced.
- Trend analyses using historical data from which future prediction is executed.
- Compensation for missing data. All power consumption data obtained in a specified time interval is managed within the database by spatio-temporal schema. However, when communication facilities fail, some data becomes unavailable, and values of missing data can be extrapolated from the consumption history stored in the database.

The visualization reflecting changing conditions of electricity consumption is shown in Fig. 13.



High Resolution Satellite Image:©Digital Globe and Hitachi Solutions, Ltd.
The screen images were created using flood simulator by Hitachi Power Solutions Co., Ltd.

Figure 13. Visualization of power consumption monitoring: (a) morning, (b) afternoon.

In the figure, green, blue, and yellow segments of the columns represent energy consumption by different equipment in apartments or town blocks. The gray segments of the columns represent the allowable limits of power consumption. In Figure 13 (a), electricity consumption in the early morning is shown and is low because communities are not particularly active. In Figure 13 (b), electricity consumption in the afternoon is shown, where some of the formerly gray columns have changed to red owing to power consumption close to supply limits.

VII. DISCUSSION AND CONCLUSION

The spatio-temporal structure is a reflection of real-world states. Thus, the 4D-GIS in which this structure is implemented becomes a platform to solve real-world problems. The benefits for the 4D-GIS utilization are as follows.

- 3D and temporal changes are represented by a natural extension of the 2D data structure. Thus, 4D-GIS can be readily extended to other application fields.
- By combination with homotopical representation, complicated data can be constructed effectively. Data size is reduced and the visualization effect denoted as LOD can be implemented.

Hitherto, other types of spatial data structure have been authorized as international standards. Data structures such as web map service (WMS) and web feature service (WFS) are notable examples. These formats are used for data exchanges among GISs. The proposed spatio-temporal structure is native to the 4D-GIS platform. The 4D-GIS imports standard format data such as WFS, converts it into the native format, performs operations on this data, and the results can be exported to other GISs after converting into WFS or WMS data structures.

Numerous future challenges are also evident. In the current implementation, the data structure is applied in the representation of only man-made objects. For further applications, representations of soil and atmosphere are also necessary.

In this paper, a new type of spatio-temporal data structure has been introduced and has been implemented using the 4D-GIS integration platform for various applications. The spatio-temporal data structure has demonstrated the following remarkable characteristics.

- Real-world states can be effectively represented, allowing for realistic solutions to real-world problems.
- Data representation is flexible and many applications unavailable to traditional 2D map base GISs can be realized.

Three applications, trunk gas pipeline integrity monitoring, optical communication facility management, and power consumption monitoring, have demonstrated the effectiveness of the proposed spatio-temporal structure.

ACKNOWLEDGMENT

The author would like to thank Enago (www.enago.com) for the English language review.

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