Underground Facility Monitoring Services for Detecting Road Subsidence

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***Abstract*—This paper presents underground facility monitoring services to detect road subsidence. Each service includes a wireless sensor network, middleware, an analyzer, and a visualizer. The network, equipped with many sensor nodes and an underground safety-access point (UGS-AP), acquires sensing values on the physical condition of underground facilities and transmits them. The middleware manages, stores, and provides the values to the analyzer and the visualizer. The analyzer evaluates the status of the facilities by using the sensing values and generates a subsidence risk index (SRI) in a certain area, which indicates the risk level. The SRI is the result of the aggregation of the statuses generated from all underground facilities included in the area. Each SRI is classified in a category (low, medium, and high risk level). The visualizer displays the SRI with geometric objects and imagery data. This service will enhance the ability to increase public safety by monitoring the underground space and help explain the causes of the road subsidence by analyzing the sensing values.**

Keywords–Underground safety; Subsidence risk index; Underground facility.

I. INTRODUCTION

The industrial revolution brought about many changes in the social life of people. One of the most important things was an excessive population shift from rural to urban areas. Rapid population movement changed a rural society where most people lived on farms to an urban society where most people lived in cities. According to a report published by the Economist, about 64 % of the developing regions and 86 % of the developed regions will be urban areas by 2050 [1]. Consequently, 66 % of the world's population will dwell in urbanized areas by 2050. The rapid growth of urban population developed infrastructure to increase health and to support a comfortable life for the city dwellers. The infrastructure contained everything from water supply and sewer systems to road, power, and rail networks. Many different types of infrastructures were installed underground. Water pipes and sewer pipes are primarily underground and out of sight. There are several reasons that human beings use and develop underground space.

- The lack of surface place leads to use the underground space.
- Underground space is used not to spoil the aesthetic feature of city.
- Underground space is used to provide natural protection for whatever is placed in it.
- Underground space is used to protect the surface environment.

However, it is no doubt that the infrastructure of many big cities around the world is aging and failing. The current outdated and aging infrastructure is creating many problems. Each year, many water pipes broke and sewer pipes cracked in big cities. For example, water pipes of New York City were constructed more than 100 years ago [2]. The aged pipes resulted in frequent and disruptive breaks. Since 1998, more than 400 water pipe breaks all over the city have happened every year. Also, road subsidence caused by the breaks and cracks of underground infrastructures has emerged in downtown areas in Korean cities. This situation is considered as a very serious social problem because some people fell into the holes created by the subsidence. According to a report published by Seoul, road subsidence appeared in 3,328 locations from 2010 to 2014 [3]. Its occurrence trend is shown in Figure 1. We can clearly see that road subsidence had happened more than 400 times every year. Figure 2 shows the heatmap that highlights the occurrence of the road subsidence in a certain region. We can clearly see that road subsidence occurs across Seoul. The heatmap is based on dividing the entire area into 50m $\times$ 50m grids. The metric is the sum of the number of road subsidence occurrences in each grid. The red indicates that many road subsidence occurred in the grid. By several investigation reports on the road subsidence, the road subsidence in downtown areas is formed by empty space in the underground. Breaks in water supply pipes, cracks in sewer pipes, and poor backfilling are identified as the main causes of the empty space. In addition, the subsidence appeared in other cities such as Busan, Incheon, Daejeon, Gwangju, Jeonju, Suwon, Suncheon, Yongin, Andong, etc.

Unfortunately, the failures of the underground infrastructures are not predictable as well as the failure detection is very difficult. There are several reasons that make the failure detection difficult.

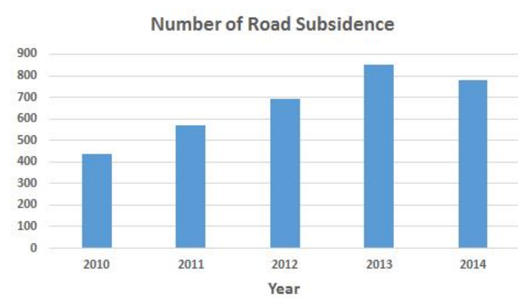

Figure 1. Number of road subsidence by year in Seoul (Source: Seoul City).

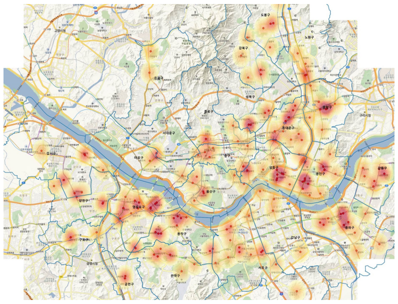

Figure 2. Road subsidence in Seoul shown as heatmap on Google map (Data source: Seoul City).

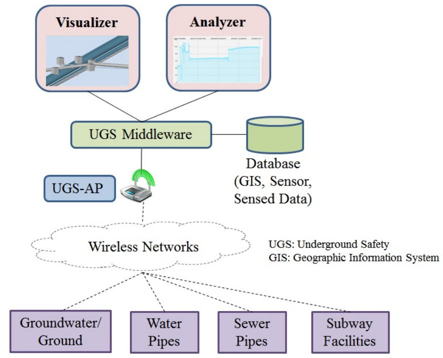

Figure 3. Architecture of underground facility monitoring service.

- The underground space and infrastructure in it are invisible.
- The failures suddenly happen without early warning signs.
- We do not even know where the infrastructure is below ground.
- It is not easy to explain what exactly leads to the failures.

Although the road subsidence raises the public safety concerns in Korea, investigators are struggling to find out the cause of the failures because there is no evidence to explain the process of the failures. We have developed an underground monitoring system to recognize when a risk suddenly happens in the underground area and to provide the evidence. To achieve this goal, this system collects and monitors the state changes of various kinds of underground facilities and utilities including water pipes, sewer pipes, metro lines, metro stations, ground, and groundwater levels [3], [4]. The monitoring system monitors the current state of the underground infrastructure and also records the history of its state change. The development of novel methods for non-destructive evaluation of underground infrastructure is one of the interesting research areas. Figure 3 shows the architecture of the underground facility monitoring service which consists of underground facilities, wireless networks, UGS-AP (Access Point), UGS (Underground Safety) middleware, database, and visualizer [3]. To acquire sensing data related to the state changes, various types of sensing devices are attached to those underground facilities and their sensing values are sent to the visualizer through the UGS-AP and the UGS middleware. The UGS-AP provides various communication methods including Ethernet, long term evolution (LTE), and WiFi. The UGS middleware is responsible for collecting, storing, and managing sensing data. The visualizer displays the sensing values, sensor nodes, and appearances of all underground facilities. This module uses GIS technology to similarly represent the appearance of the individual facility based on the actual shape.

The rest of this paper is structured as follows. Section II introduces wireless sensor networks that capture the states of each facility and transmit them. Section III introduces the UGS middleware that collects, stores, and manages sensed data and GIS data. Section IV introduces the analyzer which evaluates the status of each underground facility. Section V introduces the visualizer which displays risk indexes, sensing data, and geographic data. Finally, Section VI concludes this paper.

II. Wireless Sensor Networks

A wireless sensor network (WSN) is used to collect the state changes of underground infrastructures. The network includes two kinds of devices: an UGS-AP and sensor nodes.

These devices communicate with each other wirelessly and form a star topology to transfer data fast without collisions. This data transmission scheme gives the network better performance. An UGS-AP interconnecting a WSN and an IP-based network includes various communication schemes such as Ethernet, WiFi, and long term evolution (LTE). A sensor node involves one or more sensors which collect the states of underground utilities. Sensor nodes are attached to water pipes, sewer pipes, and subway lines and installed in tube wells. Each sensor node transmits its sensing values to the UGS-AP which it connects to.

Underground facilities produce various types of sensing values according to their properties. A sewer pipe produces still images and videos which show its internal state like a crack. Those values are captured by a sewer inspection camera attached to a sewer robot. A water pipe produces leak noise and motion changes such as pitch (lateral axis) and roll (longitudinal). The noise and motion are captured by a acoustic sensor and a gyroscope, respectively. A subway line and station produce videos, still images, stress, acceleration, and the amount of influent water. Videos and still images are captured by a tunnel inspection camera. The acceleration and stress are captured by a strain gage and an optical fiber-based sensor. The amount of water is captured by a flowmeter. A tube well produces water level, water temperature, water conductivity, water turbidity, soil temperature, soil conductivity, and soil moisture. The water level is captured by a water level sensor. The temperatures are captured by temperature sensors. The conductivities are captured by conductivity sensors. The moisture is captured by a moisture sensor. All sensors are installed in one sensor node. Most of the sensing values are sent to the database through the UGS middleware and the WSN; however, still images and videos are uploaded into the storage through the Internet.

III. UGS Middleware

UGS Middleware (UGS-M) is located between some applications including the visualizer and the UGS-AP which receives sensing values from a large number of sensor nodes. UGS-M plays a role in collecting data from the UGS-AP, validating them, transmitting them to the applications, storing them to the database, providing access control to sensing devices, and providing an abstraction on various specifications of communication protocols and sensing devices. The abstraction enables an application to reduce the heterogeneity of different devices and to use them effortlessly. UGS-M provides two data formats, binary and XML, to exchange data with the UGS-AP. To achieve this goal, we classify the required functions of UGS-M in six functional components. They are a communication manager, resource manager, monitoring manager, data translator, sensing data manager, and a service interface [3]. UGS-M uses a RESTful interface as a service interface for applications.

We use Kairos [5] as a data storage and manager. Kairos is a spatial database management system (DBMS) which manages geometry data types as well as typical data types such as various numeric and character types at the same time. As Kairos is a main memory based DBMS, it shows high performance on spatial and typical query processing. It provides the typical database functions such as storage management, indexing, query processor, user management, etc. It also provides GIS engine including spatial data types, spatial operations,spatial indexing, spatial analysis, etc. Kairos stores geometric objects such as water pipes and sewer pipes, their attributes such as diameters and materials, and sensing values.

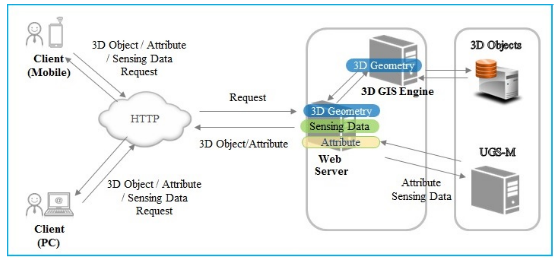

Figure 4. Data flow among components in visualizer.

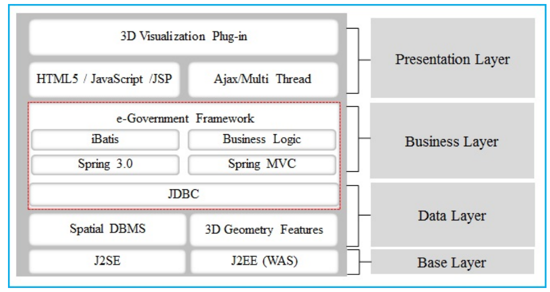

Figure 5. Architecture of visualizer.

IV. ANALYZER

An analyzer evaluates the status of the facilities by using the sensing values and generates a SRI in a certain area, which indicates the risk level. The SRI is the result of the aggregation of the statuses generated from all underground facilities included in the area. The SRI is represented as a numerical value as well as graded in a category (low, medium, high risk level). A lot of properties of each underground utility are used to estimate its status value. We use four status values generated from water pipes, sewer pipes, subway lines, and ground, one value from one utility. The evaluation of the status values related to underground utilities must be performed with different methods, according to their properties.

V. VISUALIZER

A visualizer is implemented as a client-server application for a Web-based service. In this model, graphical user interface (GUI), forms, and business logics are included in a client application and GIS engine for 2D/3D objects, data query and processing, and user management are included in a server application. Figure 4 shows the data flow in the visualization service. The Web server is accessed with a Web browser on a client and can be used by a lot of clients. The client application is running on both a personal computer and a mobile device based on Android. Each client requests 3D geometry objects, their attributes, and sensing data to the Web server. The Web server separates the requests into two groups. One is for a 3D geometry and its attribute; the other is for sensing data, 2D geometry, and its attribute. The former is processed in the Web server; the later is sent to UGS-M.

A. Architecture of Visualizer

The visualizer is designed and implemented to provide a Web-based service using Java technologies. Its architecture is shown in Figure 5. This visualizer is implemented based on e-government framework. The visualizer consists of the presentation, business, data, and base layer which has its own functionality. Each layer is implemented by Java technologies to ensure portability and flexibility of the service.

1) e-Government Framework: The e-Government framework provides a standard operating environment for developing Java-based information systems. The Korean government has developed this framework to increase the quality of governmental services. As it also is open to the public sector, the framework is widely used to increase the efficiency of the development of information systems in the sector and to shorten the development period. The framework has several advantages such as reuse common features, increase interoperability, standardization, and openness. Its core technology is the integration of Spring and iBatis. Spring is a framework of various frameworks; iBatis provides automatic connectivity between databases and Java objects. We used this framework in the business layer and data layer to increase the efficiency of the data connection and the data processing flow.

2) Presentation Layer: The presentation layer displays 2D/3D geometry objects, their attributes, SRI values, and sensing data. To display this data, this layer provides the GUI of this application and involves a series of forms for client interaction.

3) Business Layer: The business layer implements the business logics and policies of this application. This layer represents the business rules that control the data flow concerned with the retrieval, processing, transformation, and management of application data. This layer also ensures data consistency and validity.

4) Data Layer: The data layer provides access to 3D feature files and spatial databases. This layer consists of the definitions of database schemata, tables, and columns. This layer also includes the program logic which is needed to navigate the database. This layer enforces rules regarding the database and access of data. The Java Database Connectivity

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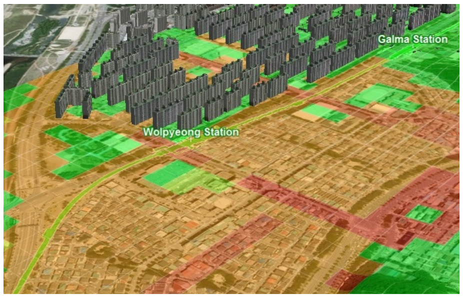

Figure 6. SRI grids.

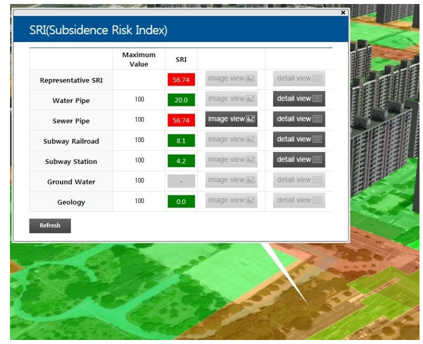

Figure 7. A grid cell and its status values.

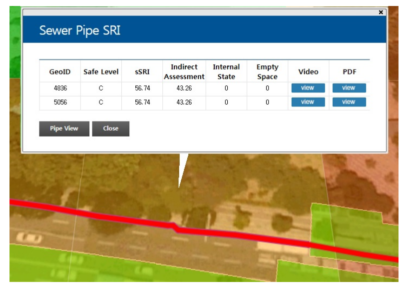

Figure 8. Representation of sewer pipes.

(JDBC) is used as a data access object.

5) Base Layer: The base layer provides the runtime environment to create this Web application. The Apache Tomcat is used as a Web application server which exposes business logic to client applications through HTTP.

B. Implementation Result

One of the most important objectives of the visualizer is to show the subsidence risk index (SRI) which represents the risk level of a certain region. The risk index is expressed with GIS data and imagery data provided by Daejeon Metropolitan City and V-World. Figure 6 shows the SRI grids in Seo-gu, Dajeon City where our testbed is installed. We divide the monitoring area into a lot of grid cells with 50m $\times$ 50m size. Each grid cell is colored in red, yellow, and green which indicate low, medium, and high risk, respectively. The SRI of a grid cell represents the highest risk value among the statuses of underground facilities in the grid. A risk values in Figure 6 is assigned to each grid cell by evaluating the state of each underground facility. Figure 7 shows the SRI value and the status values of a grid cell marked in red because the sewer pipe has the red state. These state values are displayed to check the cause of the risk level. The SRI value is rated from 0 to 1 and each status value is rated from 0 to $Maximum$. The SRI value is calculated as $SRI = MAX(S_w, S_s, S_m, S_g)$, where S_w, S_s, S_m, and S_g indicate the status of water pipes, sewer pipes, subway lines, and ground, respectively. The MAX function can be replaced by another such as MIN or SUM. Figure 8 shows the sewer pipes and their states in the grid cell. This space includes the dangerous sewer pipes that are depicted in red. The green object represents the subway station and line. The visualizer handles both two-dimensional geographic objects and three-dimensional objects.

VI. Conclusion

As many big cities have experienced serious social problems such as road subsidence and sinkholes, the evaluation and visualization of the underground facilities is very important to recognize the risk which suddenly occurs underground. This paper describes the characteristics of an underground facility monitoring service to detect the road subsidence. To detect the risk, this system attaches some sensor nodes to underground facilities such as sewer pipes, water pipes, and subway lines. It senses the states of facilities, collects the sensing values, generates risk values based on the statuses of facilities, and visualizes risk values and facilities represented by geographic objects. The risk values are displayed in a SRI grid cell to identify easily the risky areas.

We are planning to design and develop several analysis methods that evaluate the status of each facility and detect its state changes from the sensing values. We will also work to determine an optimal function and model to calculate the SRI value from the statuses of underground facilities. Furthermore, additional underground facilities and structures which affect the road subsidence will be considered to improve the reliability of the evaluation results. In addition, more research is needed because the exact expectation of the road subsidence is very difficult.

Acknowledgment

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