Guidelines for Installation of Sensors in Smart Sensing Platforms in Underground Spaces

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Abstract: The purpose of this study is to propose guidelines for sensor installation in different types of underground space smart sensing platforms. Firstly, we classify the underground space, analyze the scene requirements according to the classification of underground space, and sort out the requirements for sensors in various types of underground space. Secondly, according to the requirements of underground space scenes for sensors, the types of sensors and corresponding parameters are clarified. After that, the system design and sensor installation guidelines of the underground space smart sensing platform are proposed by sorting out the data acquired by the sensor.

Keywords: sensing system design; sensor parameters; underground space classification; data flow; design phase; construction phase; smart scenario

1. Introduction

This paper clarifies the sensor types and corresponding parameters for smart sensing scenes by analyzing the needs of different types of underground space scenes. Based on the sensor parameters and acquired data required by the underground space smart sensing platform system, the sensor installation guidelines are formed accordingly.

This study needs to clarify types of underground spaces, and we can refer to the laws and regulations of underground spaces in each country. Japan has a perfect legal and management mechanism for underground spaces [1–4], such as the “Act on Special Measures concerning Public Use of Deep Underground”, which clarifies the specific problems and technical measures for underground space utilization. Meanwhile, for different types of underground spaces, there are different technical standards and construction regulations [5], such as “Standard Specification for Tunneling” and so on. The “State Lands Act” and “Land Acquisition Act” clarify the classification basis and ownership of underground spaces, and the “Common Services Tunnels Act” and others have introduced new technical requirements for different underground spaces. There are also different technical standards and construction procedures in different underground space classifications such as “Railway applications Fixed installations Electric traction overhead contact lines”. In the United States, there is also a relatively complete legal and management mechanism for underground space [6], and state laws such as “Laws of Minnesota for 1985 Mined Underground Space” and “Oklahoma Statutes Property” have clarified the technical measures in the development and use of underground space according to the characteristics of each state. There are also different technical standards and construction procedures in
different underground space types, such as “Underground Electric Distribution Standards Manual” and “Underground Construction (Tunneling)”. Similar to the United States, the United Kingdom also has a comprehensive legal and regulatory mechanism [6], such as the “London Underground Act 1992”, which proposes measures to deal with various problems in different areas of London’s underground space. The United Kingdom also has different technical standards and construction regulations in different underground space types, such as “The Road Tunnel Safety (Amendment) Regulations”. Through these laws and regulations, the classification of underground space can be clarified [7,8].

From the location of the underground space, it requires arterial energy from facilities such as water, electricity, transportation and data flow [9–13], and waste water and waste disposal through veins [13–17], while the underground space contains the infrastructure that ensures the function and operation of urban infrastructure and is the “lifeline” that combines the arteries and veins of the city [16–22] in addition to the services and facilities that bring benefits and taxes from commercial operations and provide commercial value to the city [23,24]. Therefore, the planning of underground spaces also emphasizes the actual equipment [25], and smart sensing of underground spaces can improve the responsiveness of equipment and thus the efficiency of the city’s arteries and veins [26,27]. As a basic component of smart construction, the installation of sensors (including model selection, location selection, combination mode, etc.) is an important part of smart work [28–32].

Based on the existing design guidelines in Japan, such as “Facility Construction Safety Construction Technical Guidelines” and “Civil Engineering Work Safety Construction Technical Guidelines”, it is clear in Table 1 that the requirements for equipment in underground spaces under the traditional Japanese design guidelines are mainly reflected in the types of equipment, the general location of equipment and the occasions of use of equipment. The existing regulations and guidelines basically do not involve smart devices, sensors and other new equipment content. This problem is common in the design guidelines for underground spaces in all countries. From the devices used in the current underground space in Japan, we can also see in Table 1 that these devices consume more energy and have a lower degree of smartness, and most of them are universal and do not select devices for the characteristics of different types of underground spaces.

In summary, countries have more complete laws and regulations for the infrastructure construction of underground space [33], but there is a lack of design guidelines for setting up smart sensing devices in the whole underground space [33]. Therefore, this study starts from the design phase of underground space, and after clarifying the classification of underground space, according to the functional requirements of different scenes for sensors in underground space, the type parameters of sensors in each scene are clarified. According to the type and parameters of sensors, the attributes of the collected data are clarified. Finally, based on the classification of underground space, the basic framework of underground space intelligent sensing system design, the properties of sensors, and the properties of data, we propose the guidelines of sensor installation for smart scenes in underground space.
Table 1. Summary of the requirements of the existing guidelines for underground space devices and the devices commonly used in the current underground space.

| The Types of Equipment Mentioned in the Guidelines | Rules for Equipment Requirements Mentioned in the Guidelines | Current Use of the Devices |
|---------------------------------------------------|-------------------------------------------------------------|-----------------------------|
| **Lighting Equipment**                            | 1. Requirements on the installation of lighting equipment in three cases: a. Lighting equipment renewal (completely renewed, mixed old and new); b. Lighting equipment operation next to the air exchange fan. 2. Precautions for wiring installation of lighting equipment. 3. Precautions for installation of lighting equipment itself. | LED tunnel light |
| **Air Ventilation Equipment**                     | 1. The air exchange equipment is mainly tunnel fans. 2. The location of the anchor for the fan is determined and installation precautions. 3. Precautions for installation of the fan itself. 4. Post-installation testing precautions. | Tunnel jet fan |
| **Dust Countermeasure Equipment**                 | 1. Application of air ventilation equipment in the dust response phase. 2. Specific content of dust concentration measurement. 3. Precautions for the use of respiratory protective equipment in emergency situations. | Tunnel jet fan, dust concentration detector |
| **Noxious Gas Response Equipment**                | 1. Requirements for exhaust devices. 2. Requirements for alarm devices (including implementation of monitoring equipment). 3. Response when the critical value is reached (automatic power cut). 4. Requirements for evacuation equipment. | Tunnel jet fans, alarms or emergency bells, Automatic fixed combustible gas alarms, Automatic power cut-off devices |
| **Alarm & Rescue Equipment**                      | 1. Clarify the investigation content of the prior investigation. 2. The use of rescue equipment. 3. The use of alarm equipment. | Alarm or emergency bell, automatic fixed combustible gas alarm, smoke detector |
| **Disaster Response Equipment**                   | To deal with rain, wind, snow, lightning, earthquakes and other natural disasters | Alarm or emergency bell, automatic fixed combustible gas alarm, automatic power cut-off device |
| **Structure Monitoring Equipment**                | Mainly construction auxiliary equipment. | Earth pressure meter (vibrating string type earth pressure meter), pore water pressure meter, static level, displacement meter, in-clinometer, pillar pressure meter, reinforcement meter/anchor force gauge, concrete strain gauge |
| **Environmental Monitoring Equipment**            | 1. Measures for places with poor ventilation conditions. 2. Measures to deal with the cramped environment during mechanical construction. 3. Measurement required for operating environment. | Automatic fixed combustible gas alarm, smoke detector, thermometer, hygrometer, dust concentration detector |

Source: compiled based on Facility Construction Safety Construction Technical Guidelines and Civil Engineering Work Safety Construction Technical Guidelines.
2. Theoretical Concept and Methodology

To meet the monitoring and early warning needs of maintenance management, this study considers that the guidelines for setting up sensors in underground spaces need to clarify the classification of underground spaces and also the properties of sensors such as communication methods, the properties of data and the basic framework of the sensing system, thus taking the following research steps to propose guidelines for setting up sensors for smart scenes in underground spaces:

1. Classify the underground space according to the classification standard of Japanese underground space and the functional characteristics of each type of underground space, and by clarifying the functional requirements of each type of underground space for sensors on the basis of the classification of underground space;
2. Based on the above-mentioned requirements for sensors in the underground space, the sensors are screened on the basis of the temperature and humidity applicable to the underground space, and the sensor types and parameters are selected to meet the smart scene and functional requirements of the underground space;
3. Based on the functional requirements met by the above sensors as well as the sensor types and parameters, the types of data acquired by each type of sensor and the data attributes are clarified;
4. Based on the classification of underground space, sensor attributes and data attributes in I, II and III above, clarify the data transmission methods and data flow between sensors of various types of data, propose the basic framework of smart sensing system in underground space and form the guidelines for setting up sensors for smart scenes in underground space.

3. Underground Space Classification and Scene Requirements Analysis

Various types of underground spaces have different needs for sensors. Since the planning and construction of underground spaces in Japan is at an advanced level internationally, this study refers to the Japanese classification standard for underground space, which distinguishes between civilian land and public land, and classifies underground spaces according to the depth of various underground facilities in Figure 1.

![Figure 1. Classification of underground space in Japan.](image-url)
Based on the Japanese classification standard for underground space, underground space can be divided into six types of underground infrastructure: rail transit, underground functional places (underground stores, parking lots, subway stations, etc.), elevated bridges, underground tunnels, underground municipal pipelines, and underground heat source heat pumps in Table 2.

**Table 2. Classification of underground space and monitoring priorities.**

| Scene Type                | Maintenance and Management | Control-Warning                                                                 |
|---------------------------|---------------------------|--------------------------------------------------------------------------------|
|                           | Daily Maintenance         | Disaster Prevention                                                            |
|                          |                           |                                                                                |
|                          |                           |                                                                                |
| Rail transit              | Personal safety-fall,     | Flooding disaster, fire evacuation, earthquake disaster                         |
|                          | Personal safety-attention |                                                                                |
|                          | wake-up, obstacle         |                                                                                |
|                          | monitoring, track status  |                                                                                |
|                          | monitoring                |                                                                                |
| Elevated bridge           | Structural security       | smart construction monitoring, disaster response (fire, flooding, earthquake, gas |
|                          | monitoring                | leak, tilt, subsidence, deformation)                                           |
| Underground tunnel        | Structural security       | Tube sheet disease, tunnel flooding disaster, fire evacuation, earthquake       |
|                          | monitoring                | disaster                                                                        |
| Underground municipal     | Pipeline structure        | Pipeline leaks (liquid/gas), underground voids                                 |
| pipeline                  | monitoring,               |                                                                                |
|                          | pipe chamber environmental monitoring |                                                                                |
| Underground functional    | Underground space         | Underground space flooding disaster, fire evacuation, earthquake disaster        |
| place                     | environmental monitoring  |                                                                                |
| Underground heat source   | Underground heat source   |                                                                                |
| heat pump                 | pollution monitoring      |                                                                                |
| Geological ontology       | Surface monitoring,       | Geological tilt, subsidence, deformation                                        |
|                          | in-ground monitoring      |                                                                                |
| Ground water              | Groundwater level daily   | Groundwater contamination monitoring                                            |
|                          | monitoring                | Groundwater level, water temperature, water quality abnormalities               |
|                          |                           |                                                                                |

Source: compiled based on Act on Special Measures Concerning Public Use of Deep Underground.

Different functions of the underground space are monitored differently during maintenance. Therefore, there are also differences in the requirements for sensors. In order to meet the operational requirements (Figure 2), the discussion needs to be based on the classification of the underground space in question.

![Figure 2. Cont.](image-url)
Underground spaces have different requirements for various types of sensors in different types of spaces, which are organized according to the Table 3 below.

**Table 3. Summary of underground space requirements.**

| Smart Scene Type                  | Requirements                                      | Purpose                                                                 |
|----------------------------------|---------------------------------------------------|-------------------------------------------------------------------------|
| Basic scenes (generic scenes)    | Monitoring of natural and man-made disasters      | Response before and after disasters, mainly natural disasters (flooding, earthquakes, extreme weather (extreme cold and heat, thunderstorms)) and man-made disasters (fire, equipment failure, construction personnel health) |
|                                  | Monitor construction and operational environments  | Monitoring and adjusting the air environment, sound environment, geotechnical environment, and light environment to make people feel comfortable |
|                                  | Obtaining staff health information                 | Prevention of various types of emergencies in the underground space when affecting the health of staff, timely response |
|                                  | Obtain equipment movement information               | Prevent the loss of equipment in the underground space or loss of contact with the host |
| Rail transit                     | Obtain information on falling objects on the tracks| Prevent people from falling onto the track or objects from falling onto the track and affecting train operation |
|                                  | Monitoring of platform doors for objects caught in them | Prevent damage to people or objects when platform doors are closed |
|                                  | Emergency stop of trains                           | To guide trains to an emergency stop after an emergency situation to reduce damage |
|                                  | Obtain track structure information                  | Prevent damage to the track structure from affecting operation |
| Underground functional place      | Obtain operating environment data and make timely adjustments | To make the environment comfortable and convenient for various functions |
| Elevated bridge                  | Obtain bridge structure information                 | Reducing damage to bridge structures that may affect operations |
|                                  | Obtain information on pillar structure              | Prevention of collapse due to damage to the column structure |
Table 3. Cont.

| Smart Scene Type                    | Requirements                                | Purpose                                                                 |
|-------------------------------------|---------------------------------------------|-------------------------------------------------------------------------|
| Underground tunnel                  | Obtain support structure information        | Reduce the collapse potential caused by damage such as support cracks, and deal with cracks that have a greater impact in a timely manner |
| Underground municipal pipeline      | Real-time monitoring of pipeline structure  | Prevent the occurrence of liquid leakage and air leakage, and respond to liquid leakage and air leakage in a timely manner |
|                                    | Obtain information on pipeline structure    | Prevent fluid leaks and respond to them in a timely manner              |
| Underground heat source heat pump   | Obtain information on the structure of the exchange well | Reduce collapse hazards caused by cracks in exchange wells, etc., and promptly respond to cracks that have a large impact |
|                                    | Monitor the fluid in the well               | Liquid temperature and water level should meet the specific requirements of the heat source heat pump and reduce the influence of the liquid itself on the efficiency of the heat source heat pump |
|                                    | Obtain information on surrounding groundwater | Reduce the pollution of the surrounding groundwater by the liquid in the exchange well |

Source: Compiled based on documents related to underground space issued by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT).

4. Underground Space Sensor Sorting

Based on the classification of the underground space, and the requirements of sensors for different underground space scenarios, the sensors on the market are screened on the basis of the temperature and humidity applicable to underground space, and the types of sensors and the corresponding parameters of sensors that can meet the needs of the scenario are obtained in Table 4.

Table 4. Summary of underground space sensors.

| Smart Scene Type | Sensor Type                   | Detection Principle (Component Equipment)                                                                 | Data Monitoring Scope | Long-Term/Regular Monitoring |
|------------------|------------------------------|----------------------------------------------------------------------------------------------------------|-----------------------|------------------------------|
| Basic scenes (generic scenes) | Infrared smoke sensor  | Infrared 2 wavelength type, fluctuation type, CO₂ resonance radiation type                            | Exposure to smoke YES/NO | Long-term monitoring |
|                   | Gas sensors                  | Hot-wire type semiconductor type, contact combustion type, gas heat conduction type                      | 0~100% LEL            | Long-term monitoring |
|                   | Hydrogen sulfide sensor      |                                                                                                         | 0~50 ppm              | Long-term monitoring |
|                   | Carbon monoxide sensor       | Constant potential electrolytic type, diaphragm plus Varney cell type                                   | 0~250 ppm             | Long-term monitoring |
|                   | Oxygen sensor                | Constant potential electrolytic type, diaphragm plus Varney cell type                                   | 0~25 vol%             | Long-term monitoring |
|                   | Noise detector1              | Condenser electric microphone                                                                         | 28~141 dB             | Long-term monitoring |
| Smart Scene Type                          | Sensor Type                          | Detection Principle (Component Equipment)                     | Data Monitoring Scope                      | Long-Term/Regular Monitoring |
|------------------------------------------|--------------------------------------|-------------------------------------------------------------|--------------------------------------------|-------------------------------|
| Flood sensor                             | Water contact sensor                 | Exposure to water YES/NO                                    | Long-term monitoring                       |
| Temperature and humidity sensor          | Capacities temperature and humidity sensitive sensor | Temperature: –40~80 °C Humidity: 0~100%Rh                       | Long-term monitoring                       |
| Mobile environmental monitoring sensor    | Constant potential electrolytic type, diaphragm plus Varney cell type | Oxygen concentration: 0~25 vol%                             | Long-term monitoring                       |
| Laser distance sensor                    | Light reflection principle           | 0.05~100 m                                                  | Long-term monitoring                       |
| RFID readers/tags                        | Light reflection principle           | 3~5 m                                                       | Long-term monitoring                       |
| Dust sensor                              | Light scattering relative density meter | Exposure to dust YES/NO                                     | Long-term monitoring                       |
| Wind speed sensor                        | Rotor rotation speed                 | 0~114 m/s                                                   | Long-term monitoring                       |
| Gas sensors                              | Hot-wire type semiconductor type, contact combustion type, gas heat conduction type, constant potential electrolytic type, diaphragm plus Varney cell type | 0~100% LEL                                                  | Long-term monitoring                       |
| Hydrogen sulfide sensor                  |                                      | 0~50 ppm                                                    | Long-term monitoring                       |
| Carbon monoxide sensor                   |                                      | 0~250 ppm                                                   | Long-term monitoring                       |
| Oxygen sensor                            | Light reflection principle           | 0~25 vol%                                                   | Long-term monitoring                       |
| Construction monitoring radar            | Light reflection principle           | Collapse occurs YES/NO                                      | Long-term monitoring                       |
| Roll-off detection mat                   | Environment resistance obturation sensor, Drop test camera | Perceived pressure YES/NO                                 | Long-term monitoring                       |
| New-type PSD                             | Residual detection sensors (3D sensors, photoelectric sensors), proximity detection sensors (photoelectric sensors) | Perceived pressure YES/NO                                 | Long-term monitoring                       |
| Track material monitoring device         | Configuration camera (distance image capture device) | Material Breakage YES/NO                                  | Regular monitoring                         |
| Orbit displacement monitoring device     | Linear sensor camera (Intense and faint image photography device) | Orbital displacement YES/NO                                | Regular monitoring                         |
| Image displacement measurement system    | Laser displacement meter             | Orbital displacement YES/NO                                 | Regular monitoring                         |
| Line equipment monitoring device         | Digital camera, displacement meter, in-clinometer | Equipment breakage YES/NO                                 | Regular monitoring                         |
| Underground functional place             | Dust sensor                         | Light scattering relative density meter                     | Exposure to dust YES/NO                    | Long-term monitoring          |
Table 4. Cont.

| Smart Scene Type          | Sensor Type                  | Detection Principle (Component Equipment) | Data Monitoring Scope | Long-Term/Regular Monitoring |
|---------------------------|------------------------------|------------------------------------------|-----------------------|-------------------------------|
| Elevated bridge           | Extensometer                 | Displacement sensor                       | 6.5 ± 1 mm            | Long-term monitoring          |
|                           | Horizontally tiltometer     | Tiltmeter                                 | 0–500 mm              | Long-term monitoring          |
|                           | Crack gauge                  | Crack gauge                              | 5–40%                 | Long-term monitoring          |
|                           | Light strain sensor          | Light strain sensor, Strain gauge, Fiber optic measuring instrument | Sensing to strain YES/NO | Long-term monitoring          |
|                           | Nature frequency gage        | Nature frequency gage                     | 50 kHz                | Regular monitoring            |
| Underground tunnel        | Gas sensors                  | Hot-wire type semiconductor type, contact combustion type, gas heat conduction type, constant potential electrolytic type, diaphragm plus Varney cell type | 0–100% LEL            | Long-term monitoring          |
|                           | Hydrogen sulfide sensor      |                                         | 0–50 ppm              | Long-term monitoring          |
|                           | Carbon monoxide sensor       |                                         | 0–250 ppm             | Long-term monitoring          |
|                           | Oxygen sensor                |                                         | 0–25 vol%             | Long-term monitoring          |
|                           | Construction monitoring radar | Light reflection principle               | Collapse occurs YES/NO | Long-term monitoring          |
|                           | Crack displacement meter     | Crack displacement meter, remote wireless unit | 5–40%                 | Long-term monitoring          |
|                           | Fiber optic crack detection sensor | Crack detection accelerometer, crack detection adapter, data recorder TDS-530 | 5–40% | Long-term monitoring          |
|                           | Fiber optic sensor           | Fiber optic sensor                       | Cracking occurs YES/NO | Long-term monitoring          |
| Underground municipal pipeline | Water leak detection service | Water leak detection sensor               | Water leakage occurs YES/NO | Long-term monitoring          |
|                           | Remote water leak monitoring system | Water leak detection sensor               | Water leakage occurs YES/NO | Long-term monitoring          |
|                           | Installation of tube lumen survey machine | Electromagnetic pulse radar, television cameras | Tube lumen breakage YES/NO | Regular monitoring            |
| Underground heat source heat pump | Pressure type water gauge | Induction of hydro-static pressure in water bodies | 0.05% FS              | Long-term monitoring          |
|                           | Clinograph                   | Tilt sensor, electrolyte and conductive contacts | ±330 micro-radius | Long-term monitoring          |
|                           | Multipurpose water quality gauge | Voltage conductivity                     | PH value              | Long-term monitoring          |
|                           | Water leak detection sensor  | Laser hydrostatic principle              | 0–50 m                | Long-term monitoring          |

Source: Compiled based on the public information of the company: Tokyo Measuring Instruments Lab. (Kiryu Factory, Kiryu, Japan); SAKATA DENKI Co., Ltd. (Head Office & Factory, Tokyo, Japan); New Cosmos Electric Co., Ltd. (Cosmos sensor Center, Hyogo, Japan; Tokyo Factory, Tokyo, Japan); AIREC ENGINEERING Corporation (Head Office & Factory, Tokyo, Japan); TOBISHIMA Corporation, Keyence Co., Ltd. (Head Office & Factory, Tokyo, Japan); Kyosan Electric Mfg. Co., Ltd. (Head Office & Factory, Yokohama, Japan; Zama Factory, Kanagawa, Japan); Japan Railway Track Consultants Co., Ltd. (Head Office & Factory, Tokyo, Japan); Kyowa Electronic Instruments Co., Ltd. (Kofu Kyowa Dengyo Co., Ltd., Yamanashi, Japan; Yamaqata Kyowa Dengyo Co., Ltd., Yamagata, Japan) where each type of sensor is located.
5. Underground Space Data Sorting

Based on the functional requirements of the underground space for sensors, sensor types and parameters, the attributes of the data acquired by various types of sensors are clarified, including data transmission methods and data monitoring scopes. The final results will be classified based on data types and attributes to form a data summary table (Table 5).

**Table 5.** Sensor-based data summarization in underground spaces.

| Smart Scene Type                  | Sensor Type                     | Data Monitoring Scope                  | Monitoring Indicator                        | Data Transmission Method   |
|-----------------------------------|---------------------------------|----------------------------------------|---------------------------------------------|-----------------------------|
| Basic scenes (generic scenes)     | Infrared smoke sensor          | Exposure to smoke YES/NO               | Smoke, thermal infrared                     | ZigBee/Bluetooth            |
|                                   | Gas sensors                    | 0~100% LEL                             | Hydrogen concentration, sulfur dioxide gas concentration, carbon dioxide gas concentration | ZigBee/Bluetooth            |
|                                   | Hydrogen sulfide sensor        | 0~50 ppm                               | Hydrogen sulfide gas concentration         | ZigBee/Bluetooth            |
|                                   | Carbon monoxide sensor         | 0~250 ppm                              | Carbon monoxide gas concentration          | ZigBee/Bluetooth            |
|                                   | Oxygen sensor                  | 0~25 vol%                              | Oxygen concentration                       | ZigBee/Bluetooth            |
|                                   | Noise detector                 | 28~141 dB                              | Noise intensity                            | WiFi/Bluetooth              |
|                                   | Flood sensor                   | Exposure to water YES/NO               | Flooding depth                             | WiFi/Bluetooth              |
|                                   | Temperature and humidity sensor| Temperature: −40~80 °C Humidity: 0~100% Rh | Temperature & Humidity                     | WiFi/Bluetooth              |
|                                   | Mobile environmental monitoring sensor | Oxygen concentration: 0~25 vol% | Oxygen concentration, Carbon monoxide gas concentration | WiFi/Repeater/Bluetooth |
|                                   |                                 | Carbon monoxide concentration: 0~300 ppm |                                              |                             |
|                                   | Laser distance sensor          | 0.05~100 m                             | Distance of mobile devices from the perimeter | Repeater-Bluetooth         |
|                                   | RFID readers/tags              | 3~5 m                                  | Location, trajectory                       | WiFi/Bluetooth/USB          |
|                                   | Dust sensor                    | Exposure to dust YES/NO                | Dust concentration (PM2.5 mainly)          | WiFi/Repeater/Bluetooth     |
|                                   | Dust sensor                    | Exposure to dust YES/NO                | Dust concentration                         | WiFi/Repeater/Bluetooth     |
|                                   | Wind speed sensor              | 0~114 m/s                              | Wind speed                                 | WiFi/Repeater/Bluetooth     |
Table 5. Cont.

| Smart Scene Type         | Sensor Type                | Data Monitoring Scope | Monitoring Indicator                                      | Data Transmission Method |
|--------------------------|----------------------------|-----------------------|------------------------------------------------------------|--------------------------|
| Rail transit             | Gas sensors                | 0~100% LEL            | Hydrogen concentration, sulfur dioxide gas concentration, carbon dioxide gas concentration | WiFi/Bluetooth            |
|                          | Hydrogen sulfide sensor    | 0~50 ppm              | Hydrogen sulfide gas concentration                         |                          |
|                          | Carbon monoxide sensor     | 0~250 ppm             | Carbon monoxide gas concentration                          |                          |
|                          | Oxygen sensor              | 0~25 vol%             | Oxygen concentration                                       |                          |
|                          | Construction monitoring radar | Collapse occurs YES/NO | Construction safety (construction environment)             | Repeater-Bluetooth       |
|                          | Roll-off detection mat     | Perceived pressure YES/NO | Orbital drop                                               | Fiber optic              |
|                          | New-type PSD               | Perceived pressure YES/NO | Rail platform gap                                          | Fiber optic              |
|                          | Track material monitoring device | Material Breakage YES/NO | Track material                                             | Repeater                  |
|                          | Orbit displacement monitoring device | Orbital displacement YES/NO | Orbital displacement distance                             | Repeater                  |
|                          | Image displacement measurement system | Orbital displacement YES/NO | Orbital displacement distance                             | Repeater                  |
|                          | Line equipment monitoring device | Equipment breakage YES/NO | Wires on the track                                         | Repeater                  |
| Underground functional place | Dust sensor               | Exposure to dust YES/NO | Dust concentration                                         | WiFi/Repeater/Bluetooth   |
|                          | Extensometer               | 6.5 ± 1 mm            | Bridge support displacement distance                       | Repeater-WiFi            |
|                          | Horizontally tiltometer   | 0~500 mm              | Inclined amount of bridge                                  | Repeater-WiFi            |
| Elevated bridge          | Crack gauge                | 5~40%                 | Crack width of bridge body                                | Repeater-WiFi            |
|                          | Light strain sensor        | Sensing to strain YES/NO | Bridge strain variables                                   | Repeater-WiFi            |
|                          | Nature frequency gage      | 50 kHz                | Vibration characteristics of the bridge                   | Repeater-WiFi            |
| Smart Scene Type             | Sensor Type                        | Data Monitoring Scope | Monitoring Indicator                                      | Data Transmission Method |
|------------------------------|------------------------------------|-----------------------|----------------------------------------------------------|--------------------------|
| **Underground tunnel**       | Gas sensors                        | 0~100% LEL            | Hydrogen concentration, sulfur dioxide gas concentration, carbon dioxide gas concentration | WiFi/Bluetooth           |
|                              | Hydrogen sulfide sensor            | 0~50 ppm              | Hydrogen sulfide gas concentration                       |                          |
|                              | Carbon monoxide sensor             | 0~250 ppm             | Carbon monoxide gas concentration                        |                          |
|                              | Oxygen sensor                      | 0~25 vol%             | Oxygen concentration                                     |                          |
|                              | Construction monitoring radar       | Collapse occurs YES/NO | Construction safety (construction environment)           | Repeater-Bluetooth       |
|                              | Crack displacement meter           | 5~40%                 | Tunnel support cracks                                    | Repeater-WiFi            |
|                              | Fiber optic crack detection sensor | 5~40%                 | Tunnel support cracks                                    | Repeater-WiFi            |
|                              | Fiber optic sensor                 | Cracking occurs YES/NO | Tunnel support strain variables                          | Repeater-WiFi            |
| **Underground municipal pipeline** | Water leak detection service | Water leakage occurs YES/NO | Pipeline liquid leakage                                  | Repeater-WiFi            |
|                              | Remote water leak monitoring system | Water leakage occurs YES/NO | Pipeline liquid leakage                                  | Repeater-WiFi            |
|                              | Installation of tube lumen survey machine | Tube lumen breakage YES/NO | Pipeline structure                                       | Repeater-WiFi            |
| **Underground heat source heat pump** | Pressure type water gauge       | 0.05% F.S             | Heat source heat pump feed well water level, water temperature | Repeater-WiFi            |
|                              | Clinograph                         | ±330 micro-radius     | Sliding surface depth, sliding direction and movement of heat source heat pump feeder wells | Repeater-WiFi            |
|                              | Multipurpose water quality gauge   | PH value               | Water quality changes in heat source heat pump drainage wells | Repeater-WiFi            |
|                              | Water leak detection sensor        | 0~50 m                 | Location and flow conditions of groundwater fluidized bed of heat source heat pump | Repeater-WiFi            |

Source: Compiled based on the public information of the company: Tokyo Measuring Instruments Lab. (Kiryu Factory, Kiryu, Japan); SAKATA DENKI Co., Ltd. (Head Office & Factory, Tokyo, Japan); New Cosmos Electric Co., Ltd. (Cosmos sensor Center, Hyogo, Japan; Tokyo Factory, Tokyo, Japan); AIREC ENGINEERING Corporation (Head Office & Factory, Tokyo, Japan); TOBISHIMA Corporation, Keyence Co., Ltd. (Head Office & Factory, Tokyo, Japan); Kyosan Electric Mfg. Co., Ltd. (Head Office & Factory, Yokohama, Japan; Zama Factory, Kanagawa, Japan); Japan Railway Track Consultants Co., Ltd. (Head Office & Factory, Tokyo, Japan); Kyowa Electronic Instruments Co., Ltd. (Kofu Kyowa Dengyo Co., Ltd., Yamanashi, Japan; Yamagata Kyowa Dengyo Co., Ltd., Yamagata, Japan) where each type of sensor is located.
6. Basic Framework of Underground Space Smart Sensing Platform

Based on the analysis of underground space classification and scene requirements, sensor attributes and data attributes, the framework of underground space smart sensing platform (smart sensing system control) is proposed in Figure 3.

![Figure 3. Basic framework of underground space smart sensing platform.](image)

Based on the data transmission methods and data flow between sensors in the underground space, the data flow of the sensing platform is clarified in Figure 4: smart monitoring devices (sensors) acquire data. Multiple sensors are combined to form smart scenarios. The data acquired by each sensor is integrated as task (or the data acquired by each scene as Ambience), through the central processor and the database data for comparison, through the network transport module to the database module (update data without problems) or data report generation visualization real-time management module (problem data for feedback) feedback to smart monitoring equipment (alarm device) through forecast and early warning module with problematic data.
7. Production of Sensor Installation Guidelines for Underground Space

In this paper, we make a summary analysis of the requirements of different underground space types to clarify the types of underground space sensor requirements as well as the parameters of the sensors and the monitoring data of the underground space to form the sensor installation guidelines in the underground space smart sensing platform. To facilitate the designers to carry out the design work related to the underground space smart, we will finally form the sensor design and installation guidelines table (Table 6) and the installation location schematic according to the characteristics of the sensors used in different scenarios (Figures 5–16).
### Table 6. Sensor installation guidelines.

| Smart Scene Type                  | Smart Scene Function                                                                 | Sensor Type                  | Suitable Installation Location                                                                 | Installation Method                                      | Testing Requirements                                                                 |
|-----------------------------------|--------------------------------------------------------------------------------------|------------------------------|-------------------------------------------------------------------------------------------------|----------------------------------------------------------|--------------------------------------------------------------------------------------|
| Basic scenes (generic scenes)     | Real-time monitoring of the operating and construction environment                    | Gas sensors                 | Support left and right wall, place left and right wall/column                                    |                                                          | Earth calculation after excavation in construction (excavation volume, discharge and excavation volume, construction progress (excavation depth)); Excavation: the amount of excavated soil and the amount of soil transportation (earth calculation) need to be clarified; Retaining support construction: thoroughly check excavation depth, soil quality, groundwater level, working soil pressure, etc., including installation of measuring equipment. |
|                                   | Real-time monitoring of the operating and construction environment                    | Hydrogen sulfide sensor     | Support left and right wall, place left and right wall/column                                    |                                                          | Earth calculation after excavation in construction (excavation volume, discharge and excavation volume, construction progress (excavation depth)); Excavation: the amount of excavated soil and the amount of soil transportation (earth calculation) need to be clarified; Retaining support construction: thoroughly check excavation depth, soil quality, groundwater level, working soil pressure, etc., including installation of measuring equipment. |
|                                   | Real-time monitoring of the operating and construction environment                    | Carbon monoxide sensor      | Support left and right wall, place left and right wall/column                                    |                                                          | Earth calculation after excavation in construction (excavation volume, discharge and excavation volume, construction progress (excavation depth)); Excavation: the amount of excavated soil and the amount of soil transportation (earth calculation) need to be clarified; Retaining support construction: thoroughly check excavation depth, soil quality, groundwater level, working soil pressure, etc., including installation of measuring equipment. |
|                                   | Real-time monitoring of the operating and construction environment                    | Oxygen sensor               | Support left and right wall, place left and right wall/column                                    |                                                          | Earth calculation after excavation in construction (excavation volume, discharge and excavation volume, construction progress (excavation depth)); Excavation: the amount of excavated soil and the amount of soil transportation (earth calculation) need to be clarified; Retaining support construction: thoroughly check excavation depth, soil quality, groundwater level, working soil pressure, etc., including installation of measuring equipment. |
|                                   | Real-time monitoring of the operating and construction environment                    | Noise detector              | Support left and right wall, place left and right wall/column                                    |                                                          | Earth calculation after excavation in construction (excavation volume, discharge and excavation volume, construction progress (excavation depth)); Excavation: the amount of excavated soil and the amount of soil transportation (earth calculation) need to be clarified; Retaining support construction: thoroughly check excavation depth, soil quality, groundwater level, working soil pressure, etc., including installation of measuring equipment. |
|                                   | Real-time monitoring of the operating and construction environment                    | Temperature and humidity sensor | Support left and right wall, place left and right wall/column                                    |                                                          | Earth calculation after excavation in construction (excavation volume, discharge and excavation volume, construction progress (excavation depth)); Excavation: the amount of excavated soil and the amount of soil transportation (earth calculation) need to be clarified; Retaining support construction: thoroughly check excavation depth, soil quality, groundwater level, working soil pressure, etc., including installation of measuring equipment. |
|                                   | Real-time monitoring of the operating and construction environment                    | Mobile environmental monitoring sensor | Staff members wear them everywhere                                                            |                                                          | Earth calculation after excavation in construction (excavation volume, discharge and excavation volume, construction progress (excavation depth)); Excavation: the amount of excavated soil and the amount of soil transportation (earth calculation) need to be clarified; Retaining support construction: thoroughly check excavation depth, soil quality, groundwater level, working soil pressure, etc., including installation of measuring equipment. |
|                                   | Real-time monitoring of the operating and construction environment                    | Dust sensor                 | Support left and right wall, place left and right wall/column, construction site floor          |                                                          | Earth calculation after excavation in construction (excavation volume, discharge and excavation volume, construction progress (excavation depth)); Excavation: the amount of excavated soil and the amount of soil transportation (earth calculation) need to be clarified; Retaining support construction: thoroughly check excavation depth, soil quality, groundwater level, working soil pressure, etc., including installation of measuring equipment. |
|                                   | Real-time monitoring of the operating and construction environment                    | Wind speed sensor           | Support left and right wall, place left and right wall/column                                    |                                                          | Earth calculation after excavation in construction (excavation volume, discharge and excavation volume, construction progress (excavation depth)); Excavation: the amount of excavated soil and the amount of soil transportation (earth calculation) need to be clarified; Retaining support construction: thoroughly check excavation depth, soil quality, groundwater level, working soil pressure, etc., including installation of measuring equipment. |
| Monitor all kinds of emergencies   | Flood sensor                                                                         | Vertical safety distance of support/side wall from the ground |                                                          |                                                          | Earth calculation after excavation in construction (excavation volume, discharge and excavation volume, construction progress (excavation depth)); Excavation: the amount of excavated soil and the amount of soil transportation (earth calculation) need to be clarified; Retaining support construction: thoroughly check excavation depth, soil quality, groundwater level, working soil pressure, etc., including installation of measuring equipment. |
|                                   | Infrared smoke sensor                                                                 | Top of support, top of place safety distance of support/side wall from the ground |                                                          |                                                          | Earth calculation after excavation in construction (excavation volume, discharge and excavation volume, construction progress (excavation depth)); Excavation: the amount of excavated soil and the amount of soil transportation (earth calculation) need to be clarified; Retaining support construction: thoroughly check excavation depth, soil quality, groundwater level, working soil pressure, etc., including installation of measuring equipment. |
| Get device movement information   | Laser distance sensor                                                                 | Placement with mobile devices |                                                          |                                                          | Earth calculation after excavation in construction (excavation volume, discharge and excavation volume, construction progress (excavation depth)); Excavation: the amount of excavated soil and the amount of soil transportation (earth calculation) need to be clarified; Retaining support construction: thoroughly check excavation depth, soil quality, groundwater level, working soil pressure, etc., including installation of measuring equipment. |
|                                   | RFID readers/tags                                                                    | Readers: Placement with mobile devices; Tags: Top of support/place |                                                          |                                                          | Earth calculation after excavation in construction (excavation volume, discharge and excavation volume, construction progress (excavation depth)); Excavation: the amount of excavated soil and the amount of soil transportation (earth calculation) need to be clarified; Retaining support construction: thoroughly check excavation depth, soil quality, groundwater level, working soil pressure, etc., including installation of measuring equipment. |
| Smart Scene Type | Smart Scene Function | Sensor Type | Suitable Installation Location | Installation Method | Testing Requirements |
|------------------|----------------------|-------------|--------------------------------|--------------------|---------------------|
| Rail transit     | Real-time construction monitoring | Construction monitoring radar | Ground (near construction site) | Underground diaphragm wall method: prevention of excavation wall collapse, attention to the construction environment geotechnical structure. Weathervane work method: after the structure confirms the foundation support by foundation endurance test, it fills the concrete filled in the working chamber in a dry environment. Shield construction method: excavation is carried out using an excavator, and then a block called a section is installed on the wall to construct a tunnel, and the excavation and discharge of sand and soil is carried out continuously. | 1. Electricity test after the dentsu project (electric communication security); 2. Track commissioning test. |
|                  | Response to falling rail accidents | Roll-off detection mat | Both sides of the track | Same as basic scenes |
|                  |                      | Drop test camera | Top of the wall directly above the platform door | |
|                  | Response to platform door accidents | New-type PSD | Both sides of the platform near the train | Same as basic scenes |
|                  |                      | Track material monitoring device | Mounted with the bottom of the train | |
|                  |                      | Orbit displacement monitoring device | Mounted with the bottom of the train | |
|                  |                      | Image displacement measurement system | Mounted with the bottom of the train | |
|                  |                      | Line equipment monitoring device | Mounted with the bottom of the train | |
| Underground functional place | Obtain and adjust operational environment data | Dust sensor | The left and right walls/columns of the place, the ground of the personnel gathering area can be placed separately | Same as basic scenes |
| Elevated bridge  | Obtain bridge structure information | Extensometer | Contact part between column and bridge body | Ground drilling method: mainly soft foundation. As a general local piling construction method is the auger construction method; Shell method: mainly hard foundation. Swing and press into the outer cover hose within the full length of the pile. Mainly need to prevent the foundation from collapse. | Same as basic scenes |
|                  |                      | Horizontally tiltometer | Mounted on the column | |
|                  |                      | Crack gauge | Vulnerable points on columns/bridge deck | |
|                  |                      | Light strain sensor | Bridge side (side wall) | |
|                  |                      | Nature frequency gage | Contact part between column and bridge body | |
| Smart Scene Type            | Smart Scene Function                  | Sensor Type                          | Suitable Installation Location          | Installation Method                                                                 | Testing Requirements                                                                                     |
|----------------------------|--------------------------------------|--------------------------------------|----------------------------------------|-------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Underground tunnel          | Real-time construction monitoring     | Construction monitoring radar         | Ground (near construction site)        | Shield construction method: continuous excavation and discharge of sand and soil is required; Earth cutting: to prevent subsidence, groundwater protrusion and inflow of soil and sand into the end well, reinforcement and improvement of the soil around the cavern ring are required; Soil cutting volume: the cutting soil and sand must be discharged exactly in line with the amount of excavation; 4. Equipment: the shield machine has the feature that it can only enter but not retreat, so pay attention to the construction status of the shield machine. | Same as basic scenes                                                                                       |
|                            | Obtain information on support structures | Crack displacement meter             | Support sidewalls (near sidewall lines) | Same as basic scenes                                                                 |                                                                                                           |
|                            |                                      | Fiber optic crack detection sensor    | Support sidewalls (near sidewall lines) | Same as basic scenes                                                                 |                                                                                                           |
|                            |                                      | Fiber optic sensor                   | Support sidewalls (near sidewall lines) | Same as basic scenes                                                                 |                                                                                                           |
| Underground municipal pipeline | Real-time monitoring of pipeline structures | Water leak detection service       | Liquid pipeline vulnerability point (turning point) | There are various tests such as PC grouting temperature measurement, chloride ion content, compressive strength, archeology test, etc. | Same as basic scenes                                                                                       |
|                            |                                      | Remote water leak monitoring system   | Liquid pipeline vulnerability point (turning point) | Same as basic scenes                                                                 |                                                                                                           |
|                            |                                      | Installation of tube lumen survey machine | Inside the liquid pipeline | Same as basic scenes                                                                 |                                                                                                           |
| Underground heat source heat pump | Obtain information about the structure in the exchange well | Clinograph                           | Exchange well interior side wall        | Trial run: thermal response test, pipe wall temperature test, exchange well temperature and humidity test, flow test, power test, water pressure test | Same as basic scenes                                                                                       |
|                            | Monitoring of fluid in exchange wells | Multipurpose water quality gauge     | Liquid in the well                      | Same as basic scenes                                                                 |                                                                                                           |
|                            |                                      | Pressure type water gauge            | Liquid in the well                      | Same as basic scenes                                                                 |                                                                                                           |
|                            | Real-time monitoring of pipeline structures | Water leak detection service       | Liquid pipeline vulnerability point (turning point) | Same as basic scenes                                                                 |                                                                                                           |
|                            |                                      | Get information on surrounding groundwater | Water leak detection sensor | Same as basic scenes                                                                 |                                                                                                           |
|                            |                                      |                                      | Groundwater after borehole             | Same as basic scenes                                                                 |                                                                                                           |

Self-painted by the author.
Underground heat source heat pump the structure in the exchange well

① Confirmation of pipeline paths for misconnection.
② Checking the depth of buried pipeline;
③ Implementing water pressure test.
④ Laying of buried marker plate.
⑤ Setting buried markers on the ground surface.
⑥ Confirming the construction around the header.

2. Heat exchange well section.
① Capture geological information Record in excavation.
② Simultaneous setting confirmation of water tension in the underground heat exchanger, proper reloading, and thermometer setting at insertion.

Wall temperature test, exchange well temperature and humidity test, flow test, power test, water pressure test

Monitoring of fluid in exchange wells

Multipurpose water quality gauge

Liquid in the well Pressure type water gauge Liquid in the well

Real-time monitoring of pipeline structures

Water leak detection service

Liquid pipeline vulnerability point (turning point)

Get information on surrounding groundwater

Water leak detection sensor

Groundwater after borehole

Self-painted by the author.

Figure 5. Rail transit sensor installation schematic.

Figure 6. Smart interaction function for rail transit. (a): Various types of devices in smart interaction scenarios. Including environmental monitoring devices and accident response devices. (b): User access to the detection range of new-type PSD. (c): The door opens automatically after entering the detection range of new-type PSD, after which drop test camera opens and the user enters the detection range of drop test camera. (d): When the user falls off the track, environment resistance obturation sensor will sound an alarm. He or she will remain in the detection range of drop test camera. At this time, drop test camera will determine the location of the fall accident and upload it.
Figure 6. Smart interaction function for rail transit. (a): Various types of devices in smart interaction scenarios. Including environmental monitoring devices and accident response devices. (b): User access to the detection range of new-type PSD. (c): The door opens automatically after entering the detection range of new-type PSD, after which drop test camera opens and the user enters the detection range of drop test camera. (d): When the user falls off the track, environment resistance obturation sensor will sound an alarm. He or she will remain in the detection range of drop test camera. At this time, drop test camera will determine the location of the fall accident and upload it.

Figure 7. Underground functional place sensor installation schematic.

Figure 8. Smart interaction function for underground functional place. (a): Various types of devices in smart interaction scenarios. Environmental monitoring equipment is the main focus. Users can read basic environmental information at temperature and humidity sensor. (b): When a user is detected to be in the monitoring range, the devices mainly in HD camera are automatically turned on.

Figure 9. Elevated bridge sensor installation schematic.
Figure 10. Smart interaction function for elevated bridge. (a): The monitoring devices are mainly column structure monitoring devices. (b): The various devices are linked by optical fibers, and when cracks appear/structure damage, electrical signals are conducted from measurement sensors/horizontally tiltometer to 3-axis accelerometer system and uploaded by 3-axis accelerometer system via optical fibers. (c): Bridge structure monitoring equipment is the main focus. (d): The user captures the location of multiple fenster target’s by sampled model camera and determines if the bridge is deformed by comparing it to the indicator.

Figure 11. Underground tunnel sensor installation schematic.
Figure 12. Smart interaction function for underground tunnel. (a): The smart devices are mainly tunnel support structure monitoring devices. (b): Various devices are linked by fiber optics. When a crack/structure breakage occurs in the support, the electrical signal from the sensor is stored to data recorder via optical fiber and uploaded by data recorder.

Figure 13. Underground municipal pipeline sensor installation schematic.

Figure 14. Smart interaction function for underground municipal pipeline. (a): The smart devices are divided into environmental monitoring devices and pipe corridor structure monitoring devices. Users can read basic environmental information from temperature and humidity sensor on the walls of the corridor. (b): The monitoring range of environmental monitoring devices covers the entire corridor space.
The study of requirements in this paper focuses largely on maintenance management. In this paper, we analyze the requirements of different types of underground space scenes and clearly establish the sensor types and corresponding parameters for smart sensing scenes. Based on the sensor parameters and the acquired data, we propose a system design for smart sensing platform in underground space and form the sensor installation guidelines accordingly. The guidelines are mainly divided into two parts: installation guideline table and installation schematic, and the purpose of setting the guidelines is to guide the work related to the construction of smart scenes in underground space.

The study of requirements in this paper focuses largely on maintenance management. The next step will be to refine the process of developing and constructing smart scenes in underground spaces, and to propose different development proposals and guidelines at different phases according to the refined process.

8. Conclusions

In this paper, we analyze the requirements of different types of underground space scenes and clearly establish the sensor types and corresponding parameters for smart sensing scenes. Based on the sensor parameters and the acquired data, we propose a system design for smart sensing platform in underground space and form the sensor installation guidelines accordingly. The guidelines are mainly divided into two parts: installation guideline table and installation schematic, and the purpose of setting the guidelines is to guide the work related to the construction of smart scenes in underground space.

The study of requirements in this paper focuses largely on maintenance management. The next step will be to refine the process of developing and constructing smart scenes in underground spaces, and to propose different development proposals and guidelines at different phases according to the refined process.
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