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A Scheme and Application of a Digital Twin-based Road Pavement Management System

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Abstract

It is necessary to conduct efficient repairs on road pavements by extending the service life of pavements and reducing life cycle costs (LCC). On the other hand, many small and medium-sized local governments and construction enterprises (SMEs) are responsible for road maintenance work, and the sophistication of ICT (information and communication technology)-based maintenance management technology has not yet progressed. The authors applied digital measurement technology and constructed a pavement management system based on digital twin technology, assuming that (SMEs) can use it. The maintenance cycle of road pavement can be expressed as follows: inspection, diagnosis, action, record, and next inspection. The authors use a digitalized virtual model (digital twin) as the core, acquire (sensing or monitoring) information and inspection results from the actual model existing in the physical space, and store and accumulate them in the virtual model, which becomes the digital twin. We defined a cycle model that accurately predicts the future by analyzing and simulating the data using a mathematical model and aimed to construct a system to realize this model. In this study, we developed a system based on a spatial information infrastructure. The system can display point cloud data generated from images taken by a simple in-vehicle stereo camera, road surface property data from simple laser measurement, and other data in conjunction with spatial information, and its usefulness has been evaluated. The system was developed using the GIS software "QGIS", which is freeware, to make it easy for SMEs to use. In the future, it is necessary to consider introducing a system that can be shared on the cloud for easier use.

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1 Introduction

While infrastructure development is steadily progressing, countermeasures against the aging of the infrastructure that has been built up to date have also become a significant issue, and there is growing recognition of the need for appropriate maintenance and management. The "Pavement Inspection Guideline" (Road Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Japan, 2016) was established in Japan in 2016, and inspections based on this guideline have been conducted since 2017. However, due to issues such as costs and burdens related to inspections, the Guidelines also set a guideline for inspection frequency of at least once every five years, even for roads with heavy traffic, and routine inspections are left to daily inspections. In addition, efforts are being made to introduce performance regulations and long-term warranty systems for pavement construction, which require an accurate and frequent understanding of pavement surface properties.

Against this background, this study discusses measures for the use of digital twin in road management, based on examples of the application of management technology using digital technology, assuming that it can be used by small and medium-sized local governments and construction enterprises (SMEs) that are responsible for road maintenance work, with the aim of advancing pavement maintenance technology.

2 Digital Twin and Spatiotemporal Information Systems

With the evolution of information and communication technology in recent years, various sensors in physical space have been connected to digital networks, creating an environment in which information can be simultaneously obtained even in remote locations. By consolidating such information, it is possible to virtually reproduce the same environment in a virtual space as in a physical space. In other words, it can be regarded as a digital twin to the physical space, which has recently been called a "digital twin” (Saddik, 2018). In this study, we define “digital twin” as a virtual digital model that can reproduce a space-time equivalent to the real world by acquiring and storing various measurement information obtained from the real world.

With the rapid and dramatic progress of the Internet and mobile wireless communications, an environment in which various terminals are connected to the Internet was realized in the 2000s, which was described as "ubiquitous computing" at the time. The development of IPv6, which dramatically increased the number of terminal addresses on the Internet, and the spread of sensors and control devices combined with card-sized CPU boards and LPWA (low-power wireless communication) attracted attention to the concept of IoT (Internet of Things), in which all things are connected to the Internet. The IoT is a concept that connects all things to the Internet. The system that fuses cyberspace and physical space formed by these IoT devices connected to the Internet and aggregating the digital data transmitted from them is called Cyber-Physical Systems (CPS) (National Institute of Standards and Technology, 2013), which is the core of Society 5.0 in Japan (Ministry of Internal Affairs and Communication, Japan, 2019), the keyword of the Japanese government's information policy.

In the CPS concept, digital data acquired from physical space is aggregated and reconstructed as a digital twin in a space similar to physical space. However, the representation of the aggregated information is not limited to a three-dimensional space identical to the physical space; only the necessary information can be extracted and represented as required, regardless of the dimension. For example, temperature information is obtained through sensors, but it is represented in visual forms such as maps (contour plots, etc.), tables, graphs, etc., and is not directly reproduced as gas temperatures that can be experienced.

An essential characteristic of the digital twin is the ability to store digital data acquired in time series. Events that occur in physical space are sequential and cannot be replayed. However, the past can be reproduced based on the data stored in the digital twin. In other words, past events that could not be reproduced in physical space can be reproduced in digital space. Furthermore, as time passes, digital data accumulates and forms big data. This big data records many of the events that occurred in the physical space in the past. Analysis of the vast amount of accumulated data improves the accuracy of predictions of future events. Furthermore, by comparing the results of predictions with sequentially acquired data and feeding the errors back into the prediction model, it is possible to improve the accuracy of predictions further. If such a system can be realized, a time machine can be constructed as a spatiotemporal information system that allows humans to freely move through time within the digital twin.

We consider the application of the concept of a spatiotemporal information system based on the digital twin to the infrastructure lifecycle. Planning and designing infrastructures in the initial stages are carried out in a virtual space, incorporating information from physical space (e.g., topography and geology) through surveys and investigations. Recently, this virtual space can be called an information space or cyberspace because it is constructed as digital information based on CAD and GIS. As the design process progresses, the virtual models (Building and Construction Information Modeling and Management: BIM/CIM) built in the virtual space become more detailed, and the amount of information increases. Once the design is completed, the design information is transferred to the construction contractor, who plans the construction process and more detailed construction design while construction proceeds in the physical space. When the construction of the target infrastructure is completed, the virtual model and the physical model are in perfect agreement, and the process then moves on to the facility operation and maintenance phase.

A physical model placed in the real world will deteriorate due to external influences such as vibration and weather caused by facility operation and may also be damaged due to disasters and accidents. On the other hand, the virtual model does not deteriorate; however, a mathematical prediction model can be applied to predict future deterioration conditions by understanding the deterioration and operational conditions obtained from the physical space. This enables the formulation of a systematic repair plan, which can be fed back as repair and improvement of facilities in the physical space. The realization of this process enables efficient maintenance management and reliable repair and improvement of infrastructure and is expected to extend the service life of the infrastructure itself.

3 Significance of Digital Twin Application to Road Maintenance and Management

3.1 Objectives for Improvement on Road Maintenance and Management

In Japan, the development of modern infrastructure has been steadily progressing since the Meiji period (1868-1912), and especially in the postwar period, infrastructure was developed in line with rapid economic growth. On the other hand, problems with aging infrastructure have become apparent in Europe and the United States, where infrastructure had been developed ahead of Japan. In response, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and others have been studying appropriate maintenance and management processes, and in 2016, the "Pavement Inspection Guidelines" were established for road pavements with the aim of carrying out efficient repairs to extend pavement life and reduce life cycle costs (LCC), and since the following year, 2017, inspections have been carried out based on these guidelines. The following year, in 2017, inspections based on this guideline began to be carried out.

On the other hand, due to the cost and burden of actual inspections, the inspection frequency in the same guidelines is set at once every five years or more for roads with rapid damage progression, and routine inspections are left to routine inspections. On the other hand, efforts are being made to introduce performance specifications and long-term warranty systems for pavement construction, and there is a need for accurate and frequent monitoring of pavement surface properties. Against this background, the objective of this project is to improve road maintenance and management by applying digital measurement techniques and utilizing digital twin technology.

Objective: To advance road maintenance and management technology by the application of measurement technology based on digital technology.

- Improve inspection frequency (real-time) and accuracy by various time-series data acquired by automatic inspection systems.
- Accurately predict the future based on measurement data and support the development of management plans.
- Achieve information management within the time and space of the digital twin.
- It should be possible for SMEs involved in road management in rural areas to introduce the system.

In recent years, research has been conducted to apply the information stored in digital twins to maintain and manage infrastructures. In the field of road pavement, for example, research has been conducted mainly on the advancement of prediction technology, such as tunnel pavement maintenance by Yu et al. (2020), and the development of a cognitive digital twin for pavement infrastructure by Sierra et al. (2022). Talaghat et al.(2024) also described that road pavement DT research is still scarce and that there are only a few use cases in pavement reactive maintenance in their latest review paper about digital twin technology for road pavement. This research is unique in that it attempts to build a system that can be easily used by SMEs.

3.2 Application of Digital Twin in Road Maintenance Management

In road maintenance and management, the inspection includes not only the detection of abnormalities through daily inspections but also the identification of road surface conditions and underground cavities through periodic diagnoses. The pavement inspection guideline [1] mentioned above lists the following three indices as management criteria: (1) cracking rate, (2) rutting amount, and (3) International Roughness Index (IRI). The degree of progression of deterioration should be determined through soundness diagnosis based on the measured values of these indices, leading to systematic repair and maintenance.

The maintenance cycle can be expressed as the cycle of inspection, diagnosis, action, record, and next inspection. Through this cycle, it is necessary to create and enhance longevity plans and other measures to maintain the appropriate performance required of facilities for more extended periods of time and to promote efficient and effective maintenance management of structures. The process of applying the digital twin to this maintenance cycle is shown in Figure 1.

Information such as sensors, various measurement results, and inspection results are acquired (sensing and monitoring) from the physical model in the physical space and stored and accumulated in the virtual model, which becomes the digital twin. Based on the accumulated data, accurate predictions of the future are made through analysis and simulation using a mathematical model. Based on these predictions, the road administrator can design a repair or management plan, and the information in the digital twin supports decision-making for that purpose. Based on the decision-making, repair, and improvement are carried out as feedback to reality, and the data obtained in the construction phase is stored in the digital twin as the repair history. In this way, the digital twin functions as the core of the maintenance cycle.

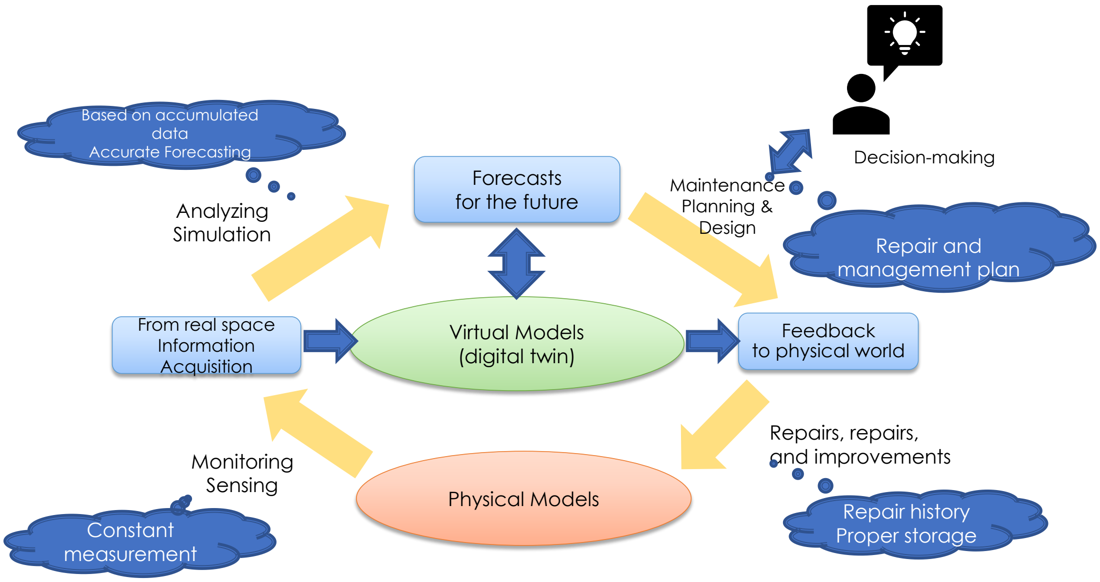


Figure 1: Road maintenance information cycle based on digital twin

4 Development of a Digital Twin System for Road Maintenance and Management

4.1 A Scheme of Digital Twin System Based on Spatial Information Infrastructure

A conceptual diagram of the maintenance management system to achieve road maintenance management is shown in Figure 2. Three-dimensional measurement data acquired during periodic inspections and maintenance work are stored as time series data in the management information database. In addition, IRI data, which is an index of longitudinal unevenness of the road surface, and human body measurement data (pulse, EEG, etc.), which evaluates driving comfort, are also stored as time-series data. Maintenance information, such as the discovery of abnormalities through daily inspections and associated repair work, is also stored in this data. Based on the information accumulated in this way, simulations using artificial intelligence (AI) and mathematical models are used to accurately predict the future and support the formulation of management plans. The information in the management information database can be expressed in various media (2D: drawings, 3D: perspective drawings, 4D: process expressions, reports, forms, etc.) as needed (Figure 2).

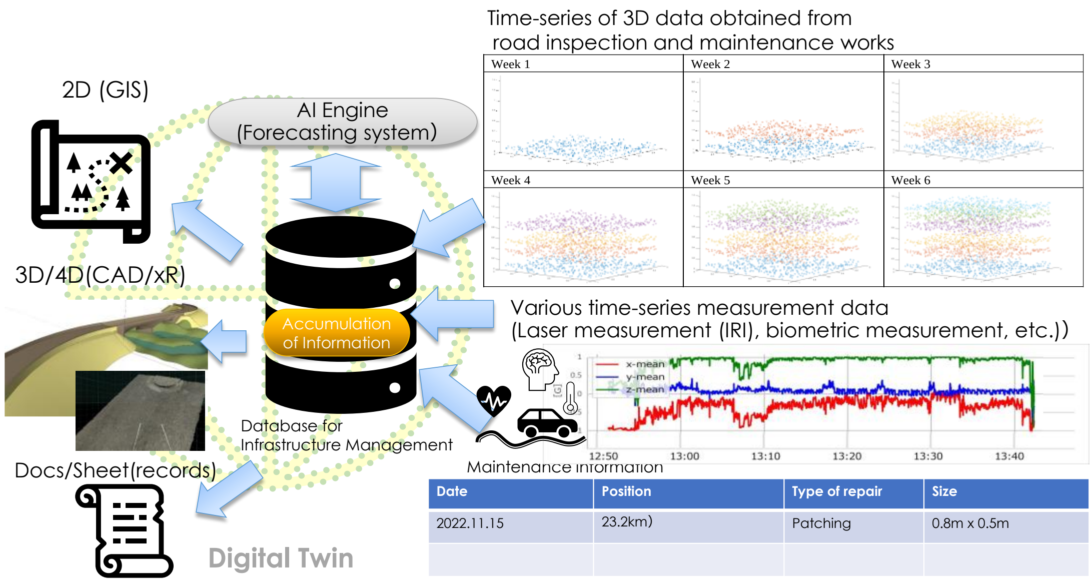


Figure 2: Conceptual diagram of road maintenance system

Spatial information infrastructure plays a significant role in managing large-scale spatial and infrastructure information that exists on national land. In actual system construction, spatial information systems (geographic information systems: GIS) that excel in handling spatial information infrastructures are used as a base. For example, the digital twin platform Plateau of the Urban Planning Bureau of the Ministry of Land, Infrastructure, Transport and Tourism is being developed based on Cesium, a 3D Web-GIS.

The scheme of system to realize the digital twin is shown in Figure 3. The spatial information system exchanges information with the spatial information infrastructure (spatial data), and various data with location information that are input as medical records are linked and stored on the spatial information infrastructure through dedicated applications.

Through spatial information systems, information can be presented in various forms, such as drawings, perspectives (3D), VR, forms, and reports, depending on the situation, and in some cases, new information can be added by humans and stored on the spatial information infrastructure. In addition, data that can be deployed in 3D can be helpful for ICT construction and control of robots, and so on, at construction sites.

4.2 Advanced Forecasting Technology Through Linkage With BIM/CIM Model

Digitization is essential to improve the efficiency of maintenance management, and BIM/CIM models that show the ideal shape and target values of structures are indispensable to promote the advancement of information and communications systems (ICT) . Constructing BIM/CIM models of existing structures is a significant issue. This project devised a simple method to build a 3D model that can be used as a substitute for BIM/CIM based on measurement data at construction time, without using 3D CAD, and is now being tested in practice (Figure 4).

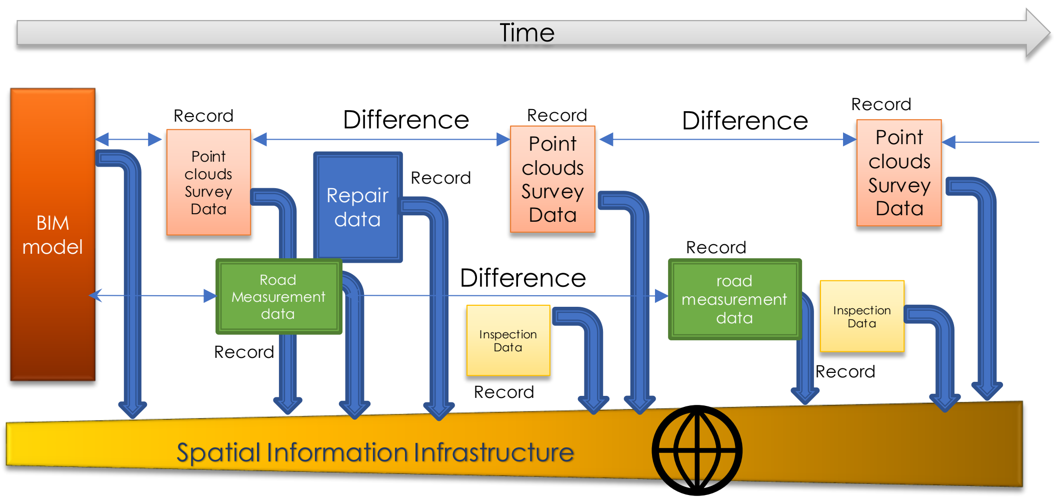


Figure 3: A scheme of an information system for a digital twin

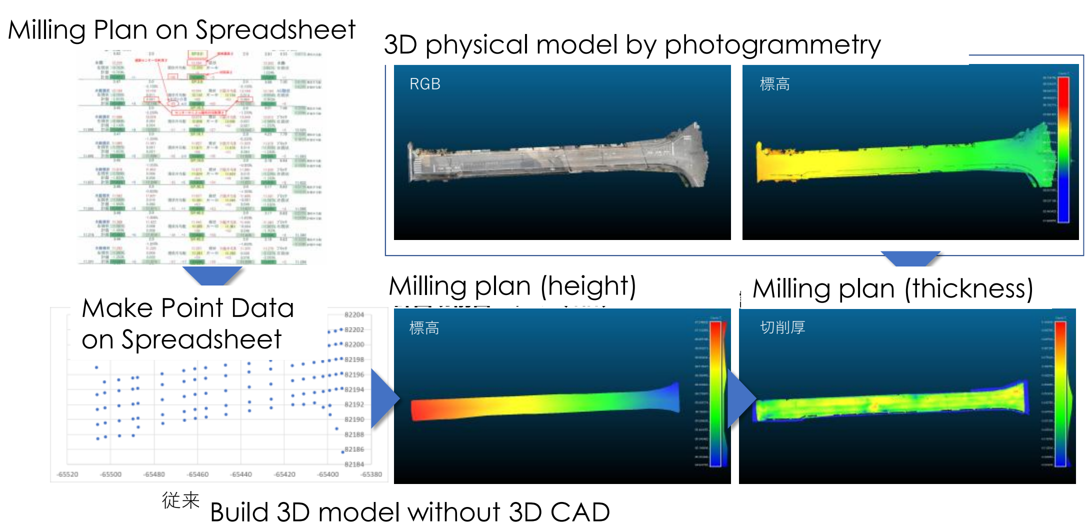


Figure 4: 3D pavement models by photogrammetry

The construction of a BIM/CIM model (or an alternative 3D model) will enable precise as-built shapes in 3D at the construction stage, which will lead to automated construction in the future, as well as the clear presentation of initial (ideal) values of geometry at the maintenance and management stage, which will facilitate comparison with the current status. Although this project's scope is limited to short-term 3D measurement, a long-term 3D measurement history can be accumulated through periodic measurement work in the future (Figure 5).

Accumulation of 3D measurement data and intercomparison of BIM/CIM models will improve the prediction accuracy of mathematical models for predicting deterioration and enable the formulation of management plans based on such models, thereby realizing appropriate maintenance management.

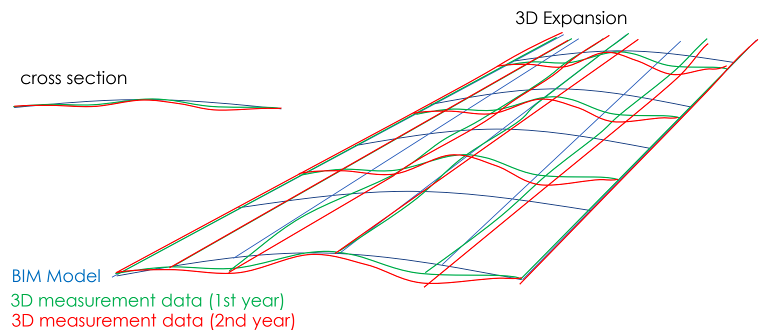
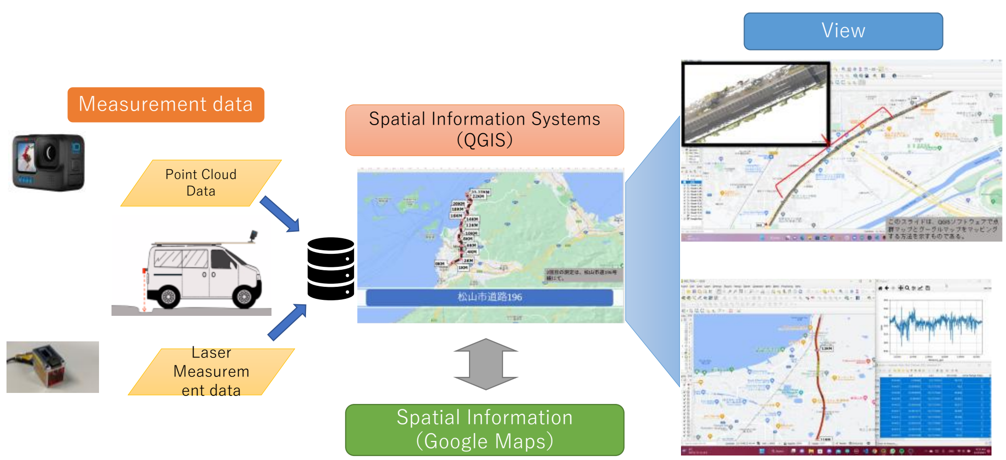


Figure 5: Comparison of CIM models and time-series 3D measurement data

5 Development of Road Pavement Management System on Digital Twin

The previous sections have described the systems, information acquisition methods, and linkage with BIM/CIM models necessary for applying digital twins in road maintenance management. One of the challenges in this study is to be possible for SMEs involved in road management in rural areas to introduce the system. The GIS software "QGIS", which is relatively easy to operate and freeware, is applied to the basis of the geographical information system (Figure 6).



The 3D model acquired from the vehicle-mounted camera and laser and the road surface property

Figure 6: Measurement data management on QGIS

data from the laser measurement is connected to the spatial information infrastructure and managed as a database, and it is shown that problem areas can be extracted by comparing both types of information. Although no comparison data is available at this time because of the short period of time required for the trial, we believe that the system will be able to support quick and reliable decision-making on road management by viewing this information once the data is accumulated and compared in the future.

The objective of this project was to advance pavement maintenance and management technology through the use of digital measurement technology and the digital twin and to construct a database that stores the three-dimensional shape of road surfaces and various measurement data acquired from physical space on a spatial information system, and to construct a system to support planned maintenance and management. The database is used to support the planned maintenance and management of roads. The issues to be addressed for future operation and development are as follows.

(1) Improvement of forecasting accuracy through data accumulation and measurement technology effects

The prototype system, which can store data from measurement, was constructed. It is expected that storing various measurement data and inspection/repair records through continuous operation will improve the prediction accuracy of deterioration and will be helpful for more accurate repair planning. For more accurate prediction, further advancement of measurement technology, such as 3D point cloud data representing road surface geometry, creation of road surface profiles, crack detection, and so on, is desirable. It is desirable to create a system that improves the prediction accuracy of deterioration along the entire route by using these values, such as vehicle detection and shape detection using LiDAR and radar installed on the road surface, and constant measurement of deflection, actual load, and vibration using strain sensors and optical fibers embedded in the road surface (Figure 7).

(2) Increased versatility through cloud computing

The 3D model acquired from the vehicle-mounted camera and laser and the road surface property data from the laser measurement is connected to the spatial information infrastructure and managed as a database, and it is shown that problem areas can be extracted by comparing both types of

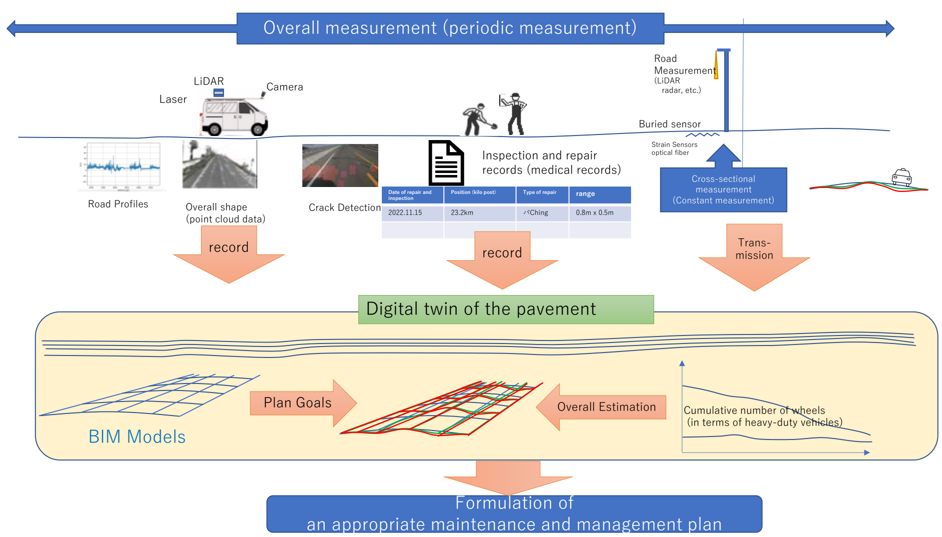


Figure 7: Maintenance management by combining overall measurement (periodic measurement) and cross-sectional measurement

information. Although no comparison data is available at this time because of the short period of time required for the trial, we believe that the system will be able to support quick and reliable decision-making on road management by viewing this information once the data is accumulated and compared in the future.

6 Conclusions

In this study, for the purpose of applying digital twin to road maintenance projects, we developed a database that stores 3D shapes of road surfaces and various measurement data acquired from physical space on a spatial information system and constructed a system to support planned maintenance management using digital twin.

The database is expected to improve the accuracy of prediction of deterioration and other problems as various measurement data, inspection and repair records, etc., are accumulated through continuous operation in the future and to be helpful in the formulation of more accurate repair plans. The system was developed using QGIS, which is freeware, to make it easy for SMEs to use. However, there are some problems, such as preparing equipment individually. In the future, it is necessary to consider introducing a system that can be shared on the cloud for easier use.

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