Smart Tunnel Inspection and Assessment using Mobile Inspection Vehicle, Non-Contact Radar and AI

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Abstract –

We have developed a mobile survey vehicle with a high-precision laser scanner measurements for deformation analysis, 20 video cameras for damage assessment on lining surface such as cracks and water leakage, and also a non-contact radar to detect lining thickness and cavity behind lining.

In this paper, we report the development of a non-contact radar survey system mounted on a mobile inspection vehicle to detect inner defects and cavities behind lining concrete, and examination of efficiency of utilizing an integrated diagnosis system to assess the soundness comprehensively as well as value of compiling database of various unsoundness conditions including inner defects by a 3D visualizing technology.

It supports the technical experts to evaluate the diagnosis and the cause of the damage in the tunnel. It contributes to efficient damage detection for tunnel inspection based on AI (Artificial Intelligence) and 3D visualization of various damage conditions, including inner defects.

Keywords –
Tunnel inspection; Mobile survey technology; Non-contact radar; Lining defects and cavity detection; 3D visualization; Artificial Intelligence

1 Introduction

Human visual inspection of road tunnels has been a common practice used in routine maintenance procedure to ensure its safety. It, however, has some problems; it requires traffic restrictions on at least one lane, and it is hard to make a fair judgement in dark and narrow spaces.

We have overcome some of the problems, by developing a mobile survey vehicle with a high-precision laser scanner measurements for deformation analysis, 20 video cameras for damage assessment on lining surface such as cracks and water leakage, as explaining the overview of the inspection vehicle in next section.

Our next challenges are to dispense hammering test of unnecessary normal parts. We introduced non-contact radar to detect lining thickness and cavity behind lining, and developed an inspection technology detecting the inner defects in concrete lining using rapidly scannable non-contact radar as a complement of hammering test. With non-contact radar system, which allows the vehicle to survey at 50km/h, concrete lining thickness and its back cavity has successfully detected.

In addition, in this paper, we examined efficiency of utilizing an integrated diagnosis system to assess the soundness comprehensively as well as value of compiling database of various unsoundness conditions including inner defects by a 3D visualizing technology. With the acquired data, analysis engineers overlay the result on the 3D model and integrate information such as position synchronized images, deformation contours, cavities and inner defects. It is expected to support the technical experts to evaluate the diagnosis and the cause of the deformation in the tunnel. By recording those damages in digital format, progressiveness can be correctly and accurately tracked off. After the first survey measurements, the cause and progress of damage is continuously monitored. It contributes to efficient damage detection for tunnel inspection based on AI (Artificial Intelligence) and 3D visualization of various damage conditions, including inner defects.

2 Overview of Mobile Inspection Vehicle

An overview of this mobile inspection vehicle is shown in Figures 1, 2. The following measurement data and functions are available for the tunnel inspection.

1. Laser Tunnel Surveys and Deformation mode analysis: The high-precision laser scanner with 1 million points/second is used to obtain high-density data, which enables us to objectively determine the

lining shapes and the deformation of the lining (deformation mode, joints, and level differences of cracks).

2. Tunnel Image surveys and Soundness assessment: Image of wall surface taken while travelling at 50-70km/h, the cracks of 0.3 mm or more can be identified. It is possible to draw an objective and accurate damage map, and to identify the progressive of unsoundness conditions and to estimate the causes of damage.
3. Radar Tunnel Surveys Cavity Evaluation: Non-contact radar system to detect lining thickness, back cavities, and inner defects (while travelling at 50km/h). The system aims to quickly detect hazard locations with thin lining and cavities [1]. This is the world's first radar antenna capable of high-speed detection with a separation of about 3 m. The details of the functions and development are indicate in next section.

The results obtained from these results can be used to support efficient close visual inspection and hammering test, and plan detailed inspections and repairs.

3 Development of Mobile Non-contact Radar

3.1 Radar for Inspection of Lining Thickness and Cavities behind Lining Concrete

3.1.1 Principles of radar survey

The principles of subsurface radar survey are those of indirect survey, which applies the physical characteristics of EM waves that reflect at boundaries between different substances.

Due to the damping nature of a substance, when an EM wave propagates through a medium, its energy is absorbed and the amplitude reduced as a result. Because of this, the general characteristics are that the reflected waves coming from deep locations lack adequate strength and thus are undetectable on radar records. This damping effect is closely interrelated with frequency; the greater the frequency the greater the damping effect, and vice versa. Therefore, to have a deeper survey depth, it is necessary to set a lower frequency.

On the other hand, a lower frequency which leads to a lower resolution, making it difficult to identify small configurations. There is thus a conflicting relationship; obtaining a high resolution requires high frequencies, while achieving a larger survey depth requires low frequencies (See Table 1). Because of this

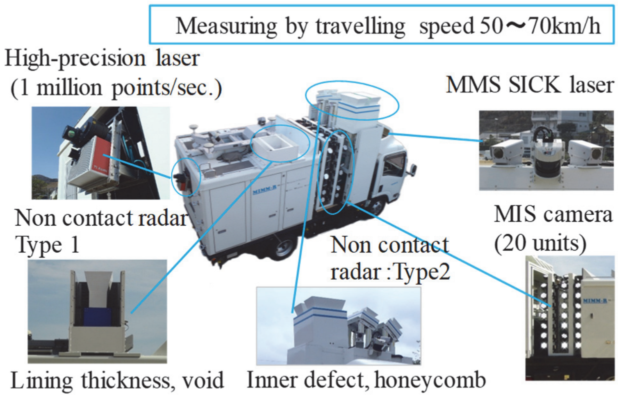


Figure 1. System of MIMM-R

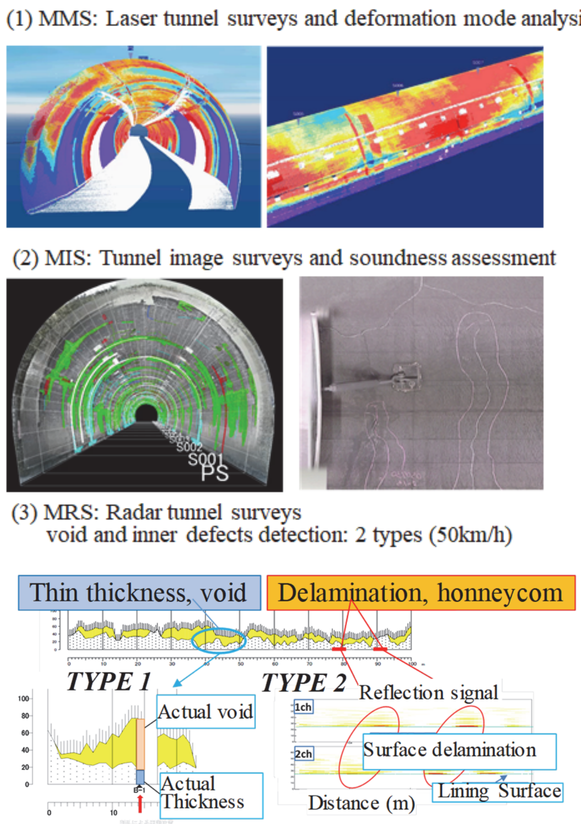


Figure 2. Function of MIMM-R

Table 1. Frequency and resolution

	High frequency	Med frequency	Low frequency
Frequency	1000GHz~	900～300MH	~300GHz
Detectable depth	~0.3m	~1.0m	~1.8m
With rebars	ctc 100mm	ctc 300mm	ctc 500mm
Depth image	Shallow		Deep
Resolution image	Fine		Rough

dependency of EM wave characteristics on frequency, an appropriate frequency should be selected according to the purpose and the target of a survey.

In improving the non-contact radar system to be applicable to tunnels, particular attention was given to the following two issues [2] .

3.1.2 Approx. 3m distance from the target in the non-contact radar system

The non-contact radar system makes it difficult to analyze the patterns of reflected waves further away from the target due to the damping and diffusion of EM waves. Based on the principles analysis that takes into account the polarity and coefficient of EM wave reflection as shown in Figure 3, the team managed to resolve the issue of reduction in detection performance in the non-contact radar system.

In the case of contact antennas, the diffusion characteristics of EM waves also caused difficulties in keeping an adequate distance. The contact-type bow tie antenna has no directionality and low sensitivity, and therefore should be touched with the target. On the other hand, the newly adopted horn antenna has a high directionality and high sensitivity, allowing to set a greater distance of 3m.

3.1.3 Realization of high-speed inspection

Improvement of the controller was necessary to obtain the same amount of data as the contact type while travelling at a speed of 50km/h or faster. To handle the extreme speed of EM waves, a sampler is used to divide a single trace, obtain the divided pieces and then reconstruct the same single trace shape. Data collection at a 50km or faster was made possible by enhancing the sampling speed, and speeding up the analog/digital converter.

3.1.4 Evaluation of Practical Use

To determine the practicability, past adequacy survey results obtained for a tunnel using the contact-type antennas and those by drilling were compared to the data obtained with the non-contact radar system, the differences of which were then analyzed and evaluated.

Regarding Sample shown in Figure 4, Data A and B were obtained with a conventional contact-type radar system and the newly developed non-contact radar system, respectively. The figure shows that they yielded more or less the same results.

The data obtained with the non-contact system were then compared to the actual lengths measured in a boring survey, which proved to have a high correlation as shown in Figure 4. Next, the analytical results for the radar survey were compared to the actual measurements taken by boring. These results show that the accuracy is generally 80-90%, which is sufficient for practical use.

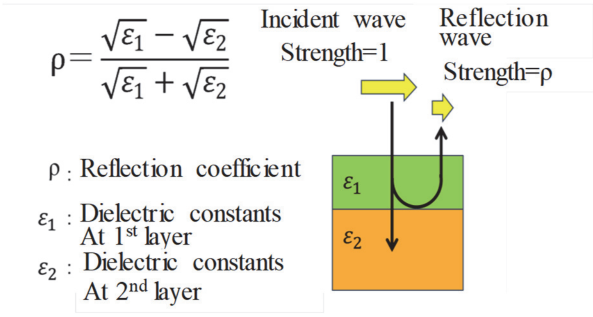


Figure 3. Concept of polarity and coefficient of reflection

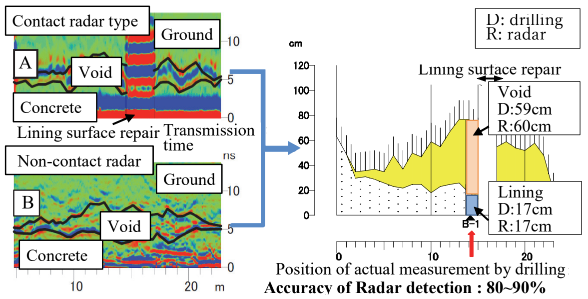


Figure 4. Comparison of results obtained by radar type and comparison with actual drilling

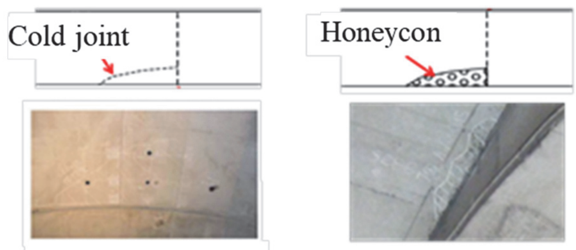
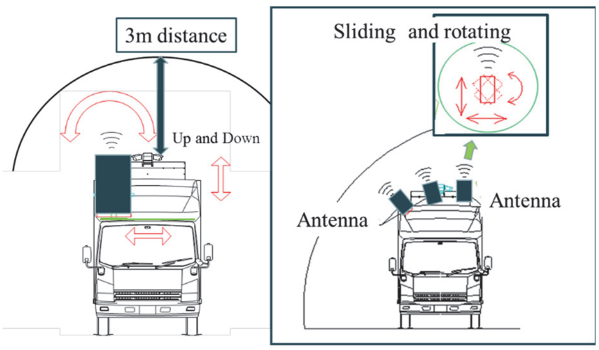


Figure 5. Targets of inner defects



Radar for detecting of lining thickness and cavity behind lining

Radar for detecting of inner defection (New developing radar)

Figure 6. 2 types of radar systems

3.2 Radar for Inner Defects Detection

3.2.1 Development Background and Target

In the field of SIP (Cross-ministerial Strategic Innovation Promotion Program in Japan) infrastructure maintenance, renewal and management technology, we have developed the technology under the theme of "Development of Internal Defect Inspection Technology and Integrated Diagnosis System for Tunnel Lining Using High-Speed Non-contact Radar" (completed in fiscal year 2016), and have achieved good results in the development of radar for internal defects as a support system for percussion inspection [2] [3].

Of various irregularities found in tunnel lining concrete, exfoliation of block pieces is regarded important in tunnel management because it gives direct impacts on users, and the timing of its occurrence is difficult to predict. In particular, certain inner defects including discontinuous joint loosening, honeycombs and poor material quality that do not involve cracking, water leakage or level differences on the surface are extremely difficult to detect unless a proper hammering test is carried out. Survey vehicles could not detect these inner defects if they were of the non-contact type and travelling at a high speed. Such inner defects often occur around and along joints, as shown in Figure 5. Given these, for the radar system designed for inner defects detection, the target size of areas to be surveyed was set at 5cm and 1m in the longitudinal and transversal directions, respectively.

The antennas of five domestic and five overseas companies were investigated prior to the development of the radar antenna. The results of the survey showed that a maximum separation of about 1 m is the limit for the existing antennas to detect defects in concrete. In road tunnels, a separation of about 3 m is required to allow for a driving survey without traffic control, due to constraints caused by clearance limit and obstacles such as signs and jet fans. As a result, this led to the development of an original antenna.

3.2.2 Verification Results

Figure 6 shows the schematic diagrams of the two types of radar systems, figure 7 shows the installation and measurement status of the internal defect radar antenna. The antenna specifications are shown in Table 2, and the verification results of the developed antenna are shown in Figure 8.

The results of the verification are as follows; internal cavities of known size and location were accurately detected in the full-scale test model of New Bridge at Nagoya University. The depth of the search for cavities, surface delamination and honeycomb in the lining concrete is about 20 cm, and the developed

Figure7. Installation and Measurement of Internal Defect Radar Antenna

Table2. Specifications of Internal Defect Radar Antenna

Specifications		Remarks
primary detecting target	Void in lining	Mainly used to detect for void e.g., in the tunnel lining
Maximum detectable distance	4m	The distance to the wall is assumed to be about 3 m
Pitch resolution	0.075m	In concrete: 0.025m
Maximum detecting speed	25m/s	Actual speed: 25[m/s]/Number of antennas used
Radar system	FM-CW	Separate antenna system for transmission and reception
Centre frequency	3Ghz	—
Bandwidth	2Ghz	—
Signal Processing and Display	The received signals can be aggregated in the direction of the vehicle's motion by the synthetic aperture process. Outputs the distance to the wall and reflection intensity. It is possible to evaluate whether the reflected signal is due to a cavity or metal.	

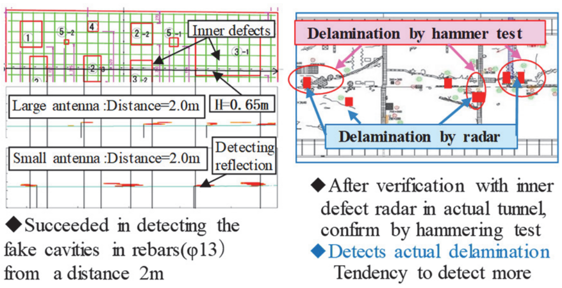


Figure 8. Verification results of radar system

method can support efficient inspection by screening the problem areas before the hammering test.

4 Damage Detection with AI

4.1 Damage Detection Using Deep Learning Based Semantic Segmentation

In the post-processes of measurement, it requires a lot of time and efforts to manually detect damages and record them on a damage map. In order to reduce manual efforts, we have applied deep learning and semantic segmentation models [4] [5]. In particular, it is expected that the semantic segmentation models can be improved to practical detection of degradation [6].

4.1.1 Training dataset

Using 200 spans of tunnel inspection images, annotate three types of damages; water leakage, free lime and cracks. In our previous studies, discrepancies between the damage on the inspection photographs and the annotation data, It could be affected its low accuracy of detection. In this study, we annotated the degradation in pixel level.

4.1.2 Model Architecture

The damage detection network is built on the SegNet, which is deep convolutional encoder-decoder architecture designed for multi-class pixel-wise segmentation and developed by members at the University of Cambridge, UK.

4.2 Experimental evaluation

To evaluate the performance of the model, out-of-sample images are used for inputs, and detects water leakage, free lime, cracks. Figure 9 shows the results and its ground truth.

4.2.1 Evaluation for water leakage and free lime detection

As a result of water leakage and free lime detection, it assumed that simple degradation are mostly extracted. However, the degradation where the damages are compounded or covered by a repair net tend to fail to be detected.

4.2.2 Evaluation for crack detection

Although cracks that are clearly visible in the images are generally detected, narrow cracks and those that were difficult to distinguish from chalks or shadows were over detected.

On the assumption that the model trained with various types of cracks in the images can extract cracks in all sizes and conditions, however the trained network has failed to converge and resulted in over detection.

By examining the cause of failure, the initial model

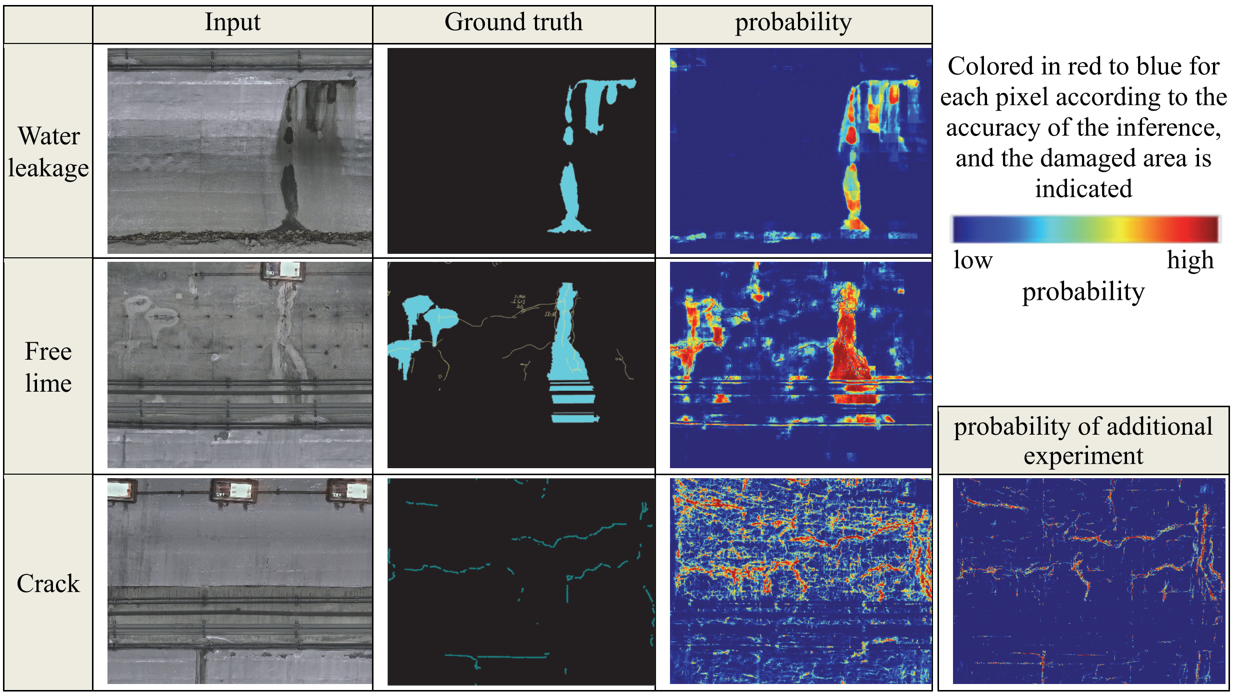


Figure 9. Results of damage detection using AI

has trained with a mixture of images in various qualities. The images in low quality could be a cause of non-convergence in the training process. In additional experiment, new training data has been set only with high-quality images, and it has achieved successful training process. The bottom right image in figure 9 shows the result from the retrained model, which has been achieved the desired performance.

5 Visualization in 3D

The mobile inspection vehicle is capable of not only image measurement also geometry measurement by built-in laser scanners. It enables to construct 3D model based on the point clouds of the laser, and to generate composite images and obtain the deformation position in synchronized accurate position. Figure 10 shows the 3D model including deformation information.

The image layer and deformation map layers are superimposed on 3D model based on coordinates and positions of the laser point cloud.

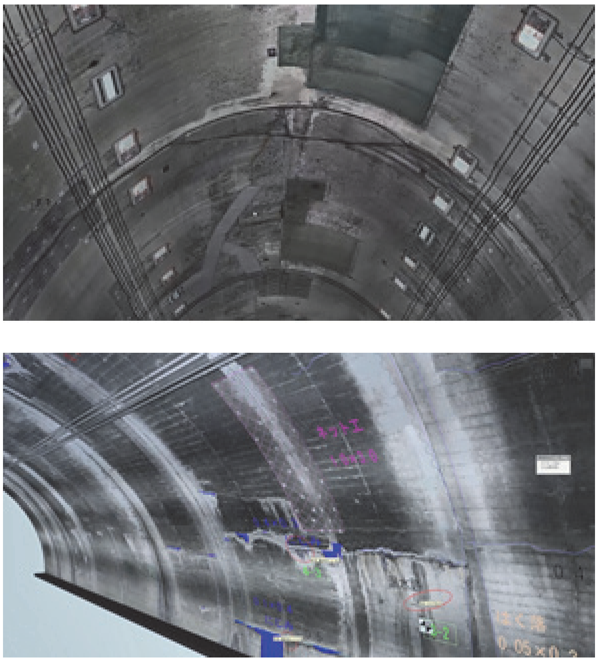


Figure 10. 3D models（bottom: damage map）

6 Development of Integrated Diagnosis System

To support diagnosis evaluation, it is necessary to comprehensively analyze not only images but also data from laser and radar units;

(1) Detecting degradation, such as cracks, water leakage and free lime, from acquired images

(2) Identifying deformation mode and damaged position by utilizing laser point clouds, estimating the cause of the deformation mode, and identifying progressive degradations

(3) Detecting lining thickness and cavity behind concrete lining with analyzing acquired data from radar units

To diagnose correctly and certainly, a system which is capable of intuitively displaying details of those information is needed. The integrated diagnosis system to assess the soundness comprehensively and compiling a database of various unsoundness conditions, including inner defects by a 3D visualizing technology. The overview of the integrated diagnostic system is shown in figure 11. The integrated diagnostic system has the functions listed below.

(1) Point clouds analysis: Automatic detection of construction joints, extraction of cross-sectional shapes and span axes for each span, deformation mode analysis

(2) Damage map generator: Lining surface images are combined with the positional information of point clouds to create a damage map of cracks and leaks.

(3) Radar measurement analysis: The results of measurement and analysis of internal defects, lining thickness and cavity can be synchronized with the point cloud information and displayed in 3D, contour, longitudinal and transverse views.

(4) 3D visualization: A function to support the estimation of the cause of deformation and diagnosis by displaying the results of image, laser, and radar analysis in 3D and superimposing them on each other.

(5) Database: Stores images and records of multiple tunnels and inspection, deformation and countermeasure history.

To develop the function that detect progressive degradations, measuring the difference in relative position of the detected degradation in two different years. Also, the system has export function that allows integrate the both in 2D and 3D visualized result into other database systems, which make it possible to use the analyzed data for linking to BIM models. The system analyzes and visualizes the obtained data in 3D, and also visualizes and exports in 2D when necessary. These results are used to optimize the priority of the implementation of countermeasures, budget allocation, and to provide support services for facility management.

7 Conclusions

While visual inspection requires human labors to manually judge by sight, the integrated diagnosis system, which effectively utilize technologies, supports visual inspection to improve the efficiency of diagnosis, to extract deformation objectively and accurately, and to draw damage maps efficiently.

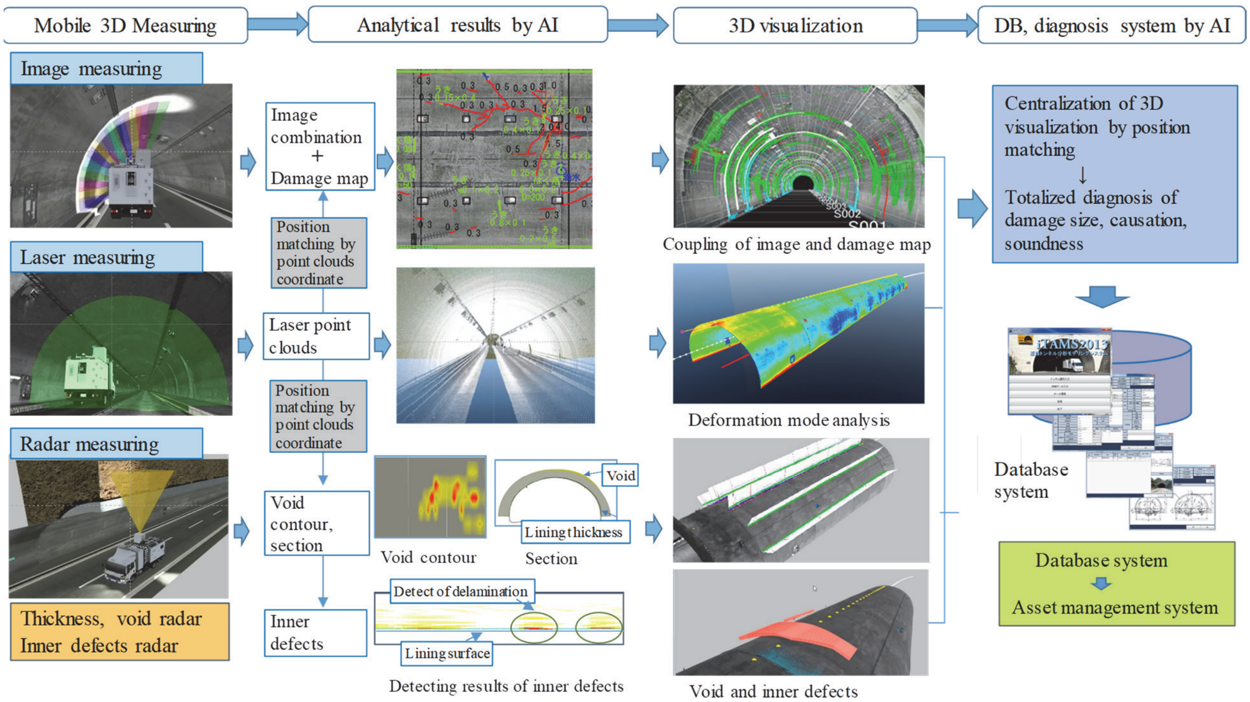


Figure 11. Totalized diagnosis and asset database system using 3D visualization and AI

It is not suitable to completely replace humanity to technologies, since it is responsible to human to make judgements to ensure the safety. However, it is sufficiently possible to use the results from the mobile measurement and its analytical data to conduct effective human visual inspection. The Usage of mobile inspection vehicle before conducting a human visual inspection, will reduce the cost and time involved in the overall workflow. Pre-inspection by the vehicle extract areas that requires attention at visual inspection and hammering tests. The visualization in 3D supports to understand integrated information of cameras, lasers and radars, and to appropriately judge the diagnosis and soundness.

The application of AI to inspection and diagnosis is in the development, although some results have been achieved. It will be our next challenges to improve accuracy of damage detection, reliability of evaluation and quality. Also, as a supportive technology for overall maintenance management, we will work towards the establishment of the system and the achievement of safe and secure society through smart tunnel management.

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