Research and Development of Infrastructure Diagnostic Robot System (ALP) for Detailed Inspection of Concrete Structures at Elevated Heights

Junichiro Nojima¹*, Toshiaki Mizobuchi² and Kenji Hayashi³

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Abstract

This paper describes the research and development of an inspection diagnostic system that applies robot technology to the detailed inspection of infrastructure such as concrete walls in high places. ALP uses a vacuum suction pad improved by testing on real structures as a moving mechanism. ALP is also fitted with a measurement system that consists of a high-resolution camera, an electromagnetic wave radar, and a hammering sound diagnostic device. The result is a highly capable self-propelling inspection system that can carry out detailed inspections of infrastructure in difficult-to-access locations such as high places.

1. Introduction

Health monitoring (Chang 1999; Housner et al. 1997) is a technology that began in mechanical engineering and more than 40 years ago to find out the damage of structures in real time. The field of civil engineering has been studied since the 1980s. As the items to be measured by structural health monitoring, for example, in the case of a bridge, the wind speed, temperature, humidity, displacement, load, acceleration, strain (static/dynamic), displacement by inclinometer, etc. are various according to the purpose. There are many international conferences on the use of sensors to conduct monitoring, and an encyclopedia of structural health monitoring has also been published (Boller et al. 2009).

For the inspection of concrete structures, the surface condition of concrete structures is investigated by examining the crack interval, crack width, and crack length using visual inspection, hammering, crack scale, etc. directly conducted by humans. On the other hand, there is a method of nondestructive inspection in order to determine the progress of deformation and deterioration inside the concrete member using various inspection devices. New techniques have been adopted for techniques for inspecting this concrete structure, in particular for nondestructive inspection. The authors also presented a paper on the application of salinity estimation by electromagnetic waves (Nojima et al. 2013), in a thematic session on Structural Health Monitoring and Inspection of Advanced Materials, Aerospace and Civil Infrastructure. Also, in the 7th European Workshop on Structural Health Monitoring, held in Nantes, France, a paper on salinity estimation using electromagnetic waves was presented (Uchida et al. 2014).

In the case of visual inspection, it is basic to look as close as possible, but in the case of infrastructure concrete structures, many cannot be seen closely, and the most expensive part of this inspection and survey work is nondestructive inspection. It is said that rather than the labor cost of the engineer who analyzes and investigates, it is the temporary scaffolding that costs more. In recent years, the use of UAVs for infrastructure inspection has been increasing. However, detailed inspection such as described above necessitates bringing measuring equipment of a certain weight in stable contact with the wall surface, and considering the counterforce that must be applied to the wall surface to establish sufficiently stable contact with the structure, the use of UAVs is problematic.

Therefore, the authors focused on vacuum suction pads and decided to develop an infrastructure diagnostic robot system called ALP. ALP is an abbreviation of the word "alpinist," and as such it carries the implied meaning of achieving the goal of executing detailed inspections even in difficult conditions such as high elevations (Nojima and Mizobuchi 2018). Current wall-climbing robots from around the world are listed in Table 1. ALP was developed with the goal of achieving an apparatus capable of self-propelling up and down and left and right while stably adsorbed on a wall while equipped with various measuring devices.

2. ALP system configuration

ALP is constituted by the system configuration shown in Table 2, and is roughly divided into a moving mechanism and a measuring mechanism.

¹Manager, Civil Engineering Dept., J-Power Design Co., Ltd., Kanagawa, Japan.
*Corresponding author, E-mail: r_j0092@yahoo.co.jp
²Professor, Department of Civil and Environmental Engineering, Faculty of Engineering and Design, Hosei University, Tokyo, Japan.
³President, Stella Rtec Inc., Kanagawa, Japan.
2.1 Moving mechanism

(1) Suction units

ALP has five suction units, three on the upper side and two on the lower side of ALP (see Fig. 1). Besides a microprocessor, each suction unit has also an adsorption unit equipped with a vacuum pump and a vacuum seal for secure adsorption on walls.

The adsorption power of the adsorption unit is very strong. The adsorption power (N) is calculated simply by Equation (1),

\[ F = 0.1 \times r^2 \times \pi \times V_{\text{cur}} \]

where \( F \) is theoretical adsorption power (N), \( r \) is radius of the pad seal (cm) and \( V_{\text{cur}} \) is current vacuum value in the pad’s vacuum chamber (-kPa).

For example, when the pad seal diameter is 16 cm and the vacuum value is -75 kPa in the pad’s vacuum chamber, the calculated adsorption power is about 150 kgf. This adsorption power is equivalent to one adsorption unit of ALP. But, this value is the adsorption force in the direction perpendicular to a smooth wall surface. In actual practice, the adsorption power changes dynamically according to conditions such as vacuum leakage due to suboptimal contact surface conditions, rotational moment in the downward direction of the suction pad.
under gravity, shifting loads on the suction pads due to slipping, movement of ALP, and movement of the center of gravity caused by movement of the measuring devices mounted on ALP.

(2) Structure of ALP’s adsorption unit seal
ALP can adsorb to rough and irregular wall surfaces such as weathered concrete and tiled surfaces with shallow joints with little air leakage. To maintain adsorption power, the adsorption unit seal is sophisticatedly designed to adapt to wall surfaces. The adsorption unit seal that contacts the wall surface is a cylindrical shape with a trumpet shaped edge made of silicone. The adsorption unit seal is over 10 mm high, which allows it to cope with irregularities up to about 5 mm high and weathered concrete walls. However, the surface layer of existing concrete structures tends to deteriorate under the influence of leaching and drying in places where it is exposed to rain, developing higher air permeability compared with parts that are shielded from rain (Torii et al. 1994).

Experiments carried out on concrete walls with high air permeability where cement paste has disappeared in the surface layer revealed that it is not possible to achieve a stable vacuum state only with an adsorption unit seal.

On the other hand, the Torrent method (Torrent 1992) is available as a test method of surface layer. To eliminate the influence of air permeability of the surface layer of concrete, the Torrent method employs a two-chamber vacuum cell. Taking inspiration from this method, the vacuum suction pads used by ALP were designed to achieve a stable vacuum state even on sub-optimum surfaces such as existing concrete whose surface quality has deteriorated by placing cushioning material around the sealing material so as to extend the air permeation path (see Figs. 2 and 3). The seal patent application number is Japanese Patent Application No. 2013-216032, the anti-gravity mechanism patent application number is Japanese Patent Application No. 2015-002441 (Patent Priority Claim No. 2017-002965) and the unit style robot configuration patent application number is Japanese Patent Application No. 2015-234253.

(3) ALP climbing motion on wall surface
The adsorption unit can move right/left and up/down in the suction unit (see Fig. 4). Further, the suction seal part of the adsorption unit can perpendicularly extend toward and retract from the wall surface (see Fig. 5). Extension is done by extending the suction seal at the extremity of the adsorption unit that faces the wall in the direction of the target wall surface. When the suction seal contacts the surface, the suction seal part stops extending and vacuum suction is performed, making the suction seal part adhere to the wall surface and fixing the adsorption unit to the target wall surface.

If the suction unit moves downward while the suction seal part is adsorbed to the wall surface, the suction unit moves upward on the wall surface. If the adsorption unit moves downward while the suction seal part is not ad-
sorbed to the wall surface, the suction unit does not move and only the adsorption unit moves downward. In this way, depending on whether or not the suction seal part is adsorbed to the wall surface, the suction unit will either ascend the wall surface or not. As described above, as the various suction units repeatedly perform this operation, ALP is able to climb up the wall while securely clinging to its surface. The operation of the suction units and the adsorption units is made possible by controlling the suction units and the main microprocessor.

2.2 Measurement mechanism

The measuring mechanism can move the measuring devices by 1 m in the horizontal direction and stably press them against the wall surface for precise measurement.

As shown in Fig. 6, the measurement mechanism is equipped with a high-resolution camera, a hammering device, and electromagnetic wave radar. The high-resolution camera has a resolution of 51.5 million pixels that allows it to discern cracks just 0.2 mm in width. The hammering device uses a solenoid magnet to strike the wall surface, picking up the reflected sound with a microphone to detect scaling of concrete. The electromagnetic wave radar can estimate the position of the rebar and the depth of cover concrete. Moreover, it allows estimation of the chloride content in the cover concrete by using the attenuation rate of the electromagnetic waves reflected from rebar.

(1) Image capture system using high-resolution camera

Close visual inspection is an inspection action that consists in approaching the object to be inspected and visually checking for deterioration such as cracks and spalling, recording observations in the form of sketches. In the case of ALP, a robot approaches the surveyed object on behalf of a person, so a camera must be mounted to perform close visual inspection. For cracks, auxiliary instruments such as a crack scale are usually required for measurement and recording of the width and length of cracks.
For the purpose of supporting close visual inspection by ALP, experiments using imaging with a high-resolution digital camera and 3D modeling were carried out. The camera used was a 51.5 million pixel camera (Table 3), shown in Fig. 6, and a test shooting platform was also employed, with the aim of capturing cracks with a width as small as 0.2 mm, equivalent to a 4-pixel span. Further, since the 3D modeling is done using a precision photogrammetry technique, the camera position was moved using a slider mechanism so that to obtain an overlap ratio between captured images of 60% or more, and a total of seventy pictures covering a surface area of 1 m² were taken.

The acquired image data were combined to create a 3D model using Structure from Motion (SfM) (Snavely et al. 2006, 2007) as shown in Fig. 7, and the accuracy of the constructed 3D model was verified by distance measurement with a TIN mesh (see Fig. 8). Beforehand, a qualified concrete diagnostician confirmed with a crack scale crack widths of 0.1 mm and 0.2 mm, and the crack widths were measured at the same locations on the 3D model. As a result, the measured value was found to be 0.131 mm in the 0.1 mm crack range, and 0.210 mm in the 0.2 mm crack range. From the above, it was confirmed that a 3D model allowing detection of cracks of width as small as 0.1 mm can be constructed by using a high-resolution digital camera from the shooting position of ALP. The resolution of this measurement system is 0.001 mm and the accuracy guarantees 0.1 mm, but in order to dimension the 3D model it has to be arranged so that the scale appears in the captured image.

(2) Electromagnetic wave radar

To detect the position of rebar in the concrete and the thickness of the cover concrete, electromagnetic wave radar was mounted on ALP. Elsewhere, the authors have reported on the possibility of determining the chloride ion content of concrete through the use of electromagnetic waves (Mizobuchi et al. 2003, 2005, 2006, 2007a, 2007b, 2008a, 2008b, 2011). Furthermore, studies by Kurumisawa and Nawa (2005, 2006) have shown the possibility of verifying differences in chloride ion content using the rebar reflected waveform of electromagnetic waves in specimen experiments using the finite difference time domain method (FDTD). This technology is used to determine chloride ion content by non-destructive inspection of structures near the coast and roads where snow-melting agents are used. Compared with the conventional method combining core sampling and potentiometric titration, this technology excels both in terms of the amount of acquired data and implementation cost.

Given that the electromagnetic wave radar is mounted on ALP, it should be lightweight and radio controllable, and thus electromagnetic wave radar of the specifications listed in Table 4 was adopted instead of the equipment that was used for determination of chloride ion content by electromagnetic wave radar.

Principle of technology for determination of chloride ion content in concrete by electromagnetic waves

The authors focused on the following in earlier studies (Nojima 2015; Nojima and Mizobuchi 2011a, 2011b, 2018; Nojima et al. 2012, 2013, 2015a, 2015b, 2016a, 2016b):

(1) Development of a theory of electromagnetic wave attenuation in the presence of chloride ions in concrete;

![Fig. 7 Concrete wall surface (3D model).](image-url)
(2) Determination of the degree of influence of the major electromagnetic wave attenuation factors of "chloride ion content," "electromagnetic wave propagation distance," "moisture content," and "temperature" by varying these factors in concrete specimens;
(3) Development of electromagnetic wave attenuation simulation from the attenuation characteristics of electromagnetic waves in concrete obtained from electromagnetic wave attenuation theory and specimen experiments [hereafter, SAE (Simulation of Attenuation Electromagnetic waves)];
(4) Determination of electromagnetic wave attenuation and chloride ion content in concrete specimens and actual structures under various conditions using with SAE (see Eq. 2 below):

$$E_w = \zeta |E_{w0}| \exp \left[ - \left( \frac{\xi, \kappa, \sigma_{\text{c}+\text{anion}}}{\mu, \mu_0, \varepsilon, \varepsilon_0} \right) \right]$$  (2)

where

- $E_w$: Output amplitude value
- $E_{w0}$: Input amplitude value
- $\zeta$: Synthetic factor of penetration and scattering
- $\xi$: Conductivity correction factor from concrete temperature
- $\kappa$: Conductivity correction factor from concrete relative humidity
- $\sigma_{\text{c}+\text{anion}}$: Concrete conductivity considering chloride ion content (S/m)
- $\mu$: Relative permeability of concrete ($= 1$)
- $\mu_0$: Permeability in the air (H/m: $4\pi \times 10^{-7}$)
- $\varepsilon$: Relative permeability of concrete
- $\varepsilon_0$: Permittivity in the air (F/m: $8.85418782 \times 10^{-12}$)

The amplitude value (see Fig. 9) as used here indicates the ratio of the reflected energy from rebar to the input wave, which is similar to electric field magnitude $|E|$. Figure 10 shows the method of amplitude value acquisition by electromagnetic wave radar in SAE.

**Study toward assessment of actual structures**
With a view to applying SAE to the assessment of actual structures with ALP, the two following two items were investigated.

**Item 1: Investigation of stability of amplitude value of electromagnetic wave radar**

The amplitude value applied in the present study was

![Fig. 9 Amplitude value of electromagnetic wave radar.](image)

![Fig. 8 Concrete wall (3D model + TIN mesh).](image)
confirmed in past research to change as the temperature rises when the antenna circuit inside the equipment is energized, and to stabilize as the temperature becomes constant. Since the electromagnetic wave radar to be mounted on ALP differed from the electromagnetic wave radar used in past research, the optimum stabilization wait time was determined using specimens.

For the chloride ion content of 0 kg/m$^3$ and cover thickness of 50 mm, the measured value was found to come within ±5% of the value measured at 1 hour from measurement start after the lapse of 19 minutes. For the chloride ion content of 2.4 kg/m$^3$ and cover thickness of 100 mm, the value came within ±5% after the lapse of 17 minutes. Based on the above results, it was determined that the measured value can be considered to become stable at about 20 minutes from the start of measurement, since the cover thickness and chloride ion content of concrete are not known when performing measurement of actual structures (see Fig. 11).

**Item: 2 Investigation of the influence of surface roughness on irregular surface reflection of electromagnetic waves**

Indoor test specimens with varying surface roughness were fabricated and used to examine the influence of surface roughness on irregular surface reflection of electromagnetic waves. In addition, the concrete surface of an actual structure was measured with a 3D scanner and the obtained data was processed for data analysis (see Fig. 12).

As a result, it was confirmed that when the surface roughness is large, incident waves are scattered by the concrete surface and the reflection amplitude value from rebars is smaller compared with concrete that has a smoother surface (see Fig. 13).

**Figure 14** shows the results of chloride ion content estimation carried out on a concrete structure by the sea.
The salinity maps shown on the middle and bottom level in this figure indicate differences in estimated values based on the magnitude of correction done in view of the representative surface roughness of each block indicated by a red frame as measured by 3D scan. This figure confirms that the amount of penetration by chloride ions in the two rightmost red frames is small as the result of surface roughness correction, and that the concrete structure is sound. Further, the sea side of the two rightmost red frames is a ship anchoring location, and as such it is protected from the influence of airborne salt.

The result of collecting cores from each red frame and calculating the chloride ion content by potentiometric titration, and the chloride ion content determined by electromagnetic wave SAE are shown in Fig. 15. This figure confirms that through appropriate assessment of the influence of surface roughness, values that closely approximate actual measurement values can be obtained. Since ALP is not equipped with a 3D scan device, the influence of surface roughness will likely be assessed through the use of precision 3D models obtained from SfM.

![Graph showing chloride ion content before and after surface roughness correction](image)

**Fig. 15** Difference between values estimated by surface roughness correction and measured values.
(3) Hammering device

The hammering device mounted on ALP uses a compact solenoid magnet designed specifically for automatic striking to achieve hammering action, and the resulting reflected sound is recorded with a condenser microphone and used to detect scaling and other flaws. Generally, bending vibration theory is applied to the reflected sound produced by scaling parts. As shown in Fig. 16 (Utagawa et al. 2013), bending vibration can be used to detect flaws due to the fact that the thinner a member is, the larger the bending vibration it produces. Somewhat similarly for the hammering device of ALP, the characteristic of scaling parts that, compared with the initial wave of the impact sound (P1), the reflected sound (P2) is of greater amplitude, whereas the opposite holds true for the sound parts of concrete, is used to detect scaling (see Fig. 17).

**Improvement of exploration depth of hammering system**

In the conventional type created during the early development period, sufficient hammering energy was not achieved due to the short stroke of the hammer part, the small hammering energy, and voltage drop of the connecting cable. Therefore, a new hammering device improving all these points was created. As a specific countermeasure against the voltage drop, the diameter of the cable was changed to about twice the previous thickness to increase the voltage applied to the solenoid and to prevent the voltage drop of the connecting cable. The old and the improved hammering devices are shown in Figs. 18 and 19. The dimensions and other characteristics of the improved hammering device are as below.

- Shape: φ45 mm × 106 mm (excluding protrusions).
- Sound recording: Waterproof condenser microphone.
- Hammer: φ10 mm cylindrical stainless steel hammer.
- Hammer stroke: 9 mm.
- Hammering cycle (fixed): 2 Hz.

**Specimen test**

To verify the striking element improvement effect, specimens with a simulated void 400 mm wide, 100 mm long, and 100 mm thick were prepared, and the performance comparison of the conventional type and the improved type was conducted.

The areas under each of the numbers from [1] to [7] that are lined up from the left side of the specimen shown in Fig. 20 correspond to the hammering points. The area under [2] has a simulated void 10 mm below the concrete surface that measures 50 mm × 50 mm × 10 mm (width × length × thickness), the area under [4] has a simulated void 30 mm below the concrete surface that measures 50 mm × 50 mm × 10 mm, and the area under [6] has a simulated void 50 mm below the concrete surface that measures 50 mm × 50 mm × 10 mm, while the other areas under [1], [3], [5], and [7] are sound areas free of flaws.

![Bending vibration](image1)

**Fig. 16 Bending vibration theory.**

![Reflected sound waveform](image2)

**Fig. 17 Reflected sound waveform of ALP hammering device [X axis: Time (μs), Y axis: Recorded sound (mV)].**
The test conditions in this evaluation were the following four cases (Figs. 21 and 22).

Case 1: 9 V driven conventional type
Case 2: 12 V driven conventional type
Case 3: 9 V driven improved type
Case 4: 12 V driven improved type

The test results of each case were as follows.

Case 1: 9 V driven conventional type
The measurement results show reliable detection of the 10 mm deep void, but unreliable detection of the 30 mm deep and 50 mm deep cavities.

Case 2: 12 V driven conventional type
The measurement results show reliable detection of the 10 mm deep void, but unreliable detection of the 30 mm deep and 50 mm deep cavities. This is presumably due to the voltage drop of the cable and still insufficient striking force despite the increased drive voltage.

Case 3: 9 V driven improved type
The measurement results show reliable detection of the 10 mm deep void, as well as the possibility of detecting cavities even at depths of 30 mm and 50 mm.

Case 4: 12 V driven improved type
The measurement results show reliable detection of the 10 mm and 30 mm deep cavities. The 50 mm deep void too gave a discernible waveform, showing the possibility of detecting cavities even at this depth.

Performance verification on actual structures
Performance verification of the hammering device was carried out at the N2U-BRIDGE (New Bridge) facility (Fig. 23) for bridge inspection technology study and research at Nagoya University. Performance verification
was carried out at the following four places. The results of the performance verification are shown below.

**Place 1**: Simulated void specimen depth: 30 mm, size: 500 mm × 500 mm
As the result of the performance verification, a clear difference between the hollow part and the sound part was confirmed. In the hollow part, the peak values of P1 and P2 are both large, clearly indicating a void detection waveform.

**Place 2**: Simulated void specimen depth: 80 mm, size: 600 mm × 350 mm
As the result of the performance verification, a clear difference between the hollow part and the sound part was confirmed. Regarding the detected waveform for the void at the depth of 80 mm, while in some locations the void could not be detected as such, at the center of the hollow portion, the waveform clearly shows the characteristics of a void, and clearly differs from the waveform obtained from the sound parts.

**Place 3**: Cracked specimen depth: 80 mm, size: 300 mm × 300 mm
The performance verification showed that the cracked part returned a waveform similar to that of the sound part, and that the wavelengths of both P1 and P2 both being long makes it difficult to distinguish between the sound and the void part.

**Place 4**: Simulated void specimen depth: 50 mm, size: 500 mm × 500 mm
As the result of the performance verification, a clear difference between the hollow part and the sound part was confirmed. The waveform of P1 and P2 in the hollow part is clearly different from that of the sound part.

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*Fig. 21 Reflected sound waveform of Case 1 (left) and Case 4 (right) [X axis: Time (μs), Y axis: Recorded sound (mV)].*
part and the cracked part.

Place 4: Former Shibue River, with cracked part on back of removed deck slab
The performance verification showed that delamination due to cracks can be detected quite clearly. While detection is possible also to some extent from P1 and P2, in scaling parts, P2 is clearly larger than P1. A clear difference could be seen between the waveforms obtained from sound parts surrounded by cracks or parts without severe delamination, and parts with severe delamination near cracks. Figures 24 and 25 show a color-coded representation of the numerical values measured at the marked location showing delamination.

From the above, taking into consideration the results of the specimen test and the performance verification on actual structures, it was confirmed that the maximum void detection depth of the hammering device mounted on ALP is 50 mm or less.

3. Experimental results on actual structure

3.1 Acquisition method of data by ALP
The ALP demonstration experiment was carried out on the side wall of the intake gate concrete pier of an arch type dam. Because the ALP is heavy, it was moved from the transport vehicle to the wall of the target using a lifter. ALP uses 100 volt AC supply and consumes less than 3 A, and the power supplied to ALP was supplied by power cable from a small 0.9 kVA gas-cylinder-type generator.

ALP can be operated by remote control via wireless or via a composite cable combining an optical fiber cable, a power cable, and a safety suspension cable. The main microprocessor controlling the entire ALP system can also be controlled from a remote PC via wireless, and it is also possible to connect a PC mounted on ALP.
to a remote PC by optical fiber cable for communication and control purposes. In the case of control via optical fiber cable, very fast communication speed is achieved, allowing not only control of ALP, but also control of the measurement tools and acquisition by the remote PC of the enormous amounts of measurement data they generate, including photographic data.

Thereafter, self-propelled ALP was along the wall and acquired accurate data by remote control. The acquired data was analysed over five hours to generate a three-dimensional model by SfM. Figure 26 shows the high-resolution three-dimensional model obtained as the result of fine inspection by ALP, and the data acquired by the hammering device and electromagnetic wave radar. The data shown in Fig. 26, which covers an area of approximately 1 m², took approximately 2 hours to acquire, including ALP operation and measuring time.

### 3.2 Comparison with measurement by humans

Alongside measurement by ALP, measurement by humans was also conducted at the same locations, and the respective results were compared. The purpose of this comparison was to find out whether ALP can produce results comparable to those achieved by humans at inspection locations that humans are unable to access.

The results are summarized in Fig. 27. As seen from this figure, in terms of precise 3D model by SfM and the results of the electromagnetic wave survey, there were slight differences (Shadow mixing into 3D models and difference of distance to move electromagnetic wave radar) between the data acquired by ALP and by humans, but only to a limited extent, and the data produced by ALP was confirmed to be suitable for practical use without any problem. This is due to the fact that the vacuum suction pads used by ALP provided stable adsorption even on concrete walls with unevenness. On the other hand, the hammering device was unable to achieve stable hammering against unevenness on walls. Going forward, it will be necessary to improve ALP’s pressing
mechanism or the solenoid driven striking element.

3.3 Utilization of acquired data as detailed inspection data
ALP is capable of close-up overlapping photographic capture with a high-resolution camera in high places with good stability. The acquired images can then be used to create a precise 3D model with SfM. Figures 28 and 29 show 3D models created from the image data acquired by ALP. ALP makes it possible to simultaneously obtain non-destructive inspection results from electromagnetic wave radar and hammering device, allowing judgment of factors and progress of deterioration even without engineers near the target structure. Further, ALP surveys are non-destructive inspection, allowing simultaneous inspection of the same location by two or more times. Moreover, for local inspection records using crack scales or the like, ALP’s ability to create 3D models with local coordinates makes it possible to precisely judge the progress of deterioration. Based on the above, ALP can be said to produce valuable data that can be used to verify the deterioration of concrete with considerable precision.

On the other hand, ALP moves slowly compared with UAVs. Considering the time and costs involved in inspection, it would be desirable to first confirm deterioration locations from general imaging results obtained by UAV and then carry out detailed inspection by ALP in a specific range.

4. Conclusions

The results obtained by research and development of the ALP infrastructure diagnostic robot system capable of operating under difficult conditions such as high places are summarized below.

(1) A system to acquire data required for detailed inspection of concrete without direct access by people was created and tested.

(2) Vacuum suction pads that can stably adsorb onto uneven concrete walls were created.

Fig. 28 3D model created from images obtained by close inspection by ALP.

Fig. 29 Expanded view of 3D model from bird’s-eye perspective.
(3) To improve further the judgment accuracy of engineers regarding flaws in concrete, multiple types of non-destructive inspection and precise 3D modeling allow detailed inspection.

On the other hand, as the whole ALP system has considerable weight and its moving speed is slow, it can take much time to access target locations, and in some cases, obstacles may well prevent access altogether. Going forward, the authors expect various innovations and beneficial effects from synergies produced by combining the vacuum suction pads developed this time and other technologies.

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