Proceedings of the Second International Conference on Press-in Engineering 2021, Kochi, Japan – Matsumoto et al (eds)

Research and development for infrastructure maintenance, renovation, and management

Y. Fujino
Institute of Advanced Sciences, Yokohama National University, Yokohama, Japan
Josai University, Saitama, Japan

D.M. Siringoringo
Institute of Advanced Sciences, Yokohama National University, Yokohama, Japan

ABSTRACT: The collapse of Sasago Tunnel, located on the Chuo Expressway about 80 kilometers west of Tokyo in 2012, has led to questions about the current quality and safety of infrastructure, and immediately brought public attention to the issue of infrastructure degradation in Japan. Japanese government decided to invest on the research and development for efficient management of infrastructure through implementation of science and advanced technologies. The new research and development (R & D) program named "Infrastructure maintenance, renovation and management" is started in 2014 under the Council of Science, Technology and Innovation (CSTI)'s Strategic Innovation Program (SIP). The 5-year program covers various subjects of infrastructure maintenance with the key technologies in condition assessment using advanced technologies such as non-destructive testing, monitoring and robotics, long-term performance prediction of infrastructure, development of durable high-quality of material for repair and replacement, and data management of bridges and other infrastructure using advanced information and communication technologies (ICT). In this paper, outline and outcomes of this program are explained.

1 INTRODUCTION

Economic sustainability, security and well-being of a nation depend heavily on the reliable functioning of infrastructures typically such as roads, highways, and bridges. Civil and transportation infrastructures in Japan need to cope with not only the vast territorial challenging landscape and large population, but also natural disasters, such as earthquakes, tsunamis, and typhoons. They have suffered severe damage from natural disasters, so that the design specifications have been regularly revised to provide more resilient infrastructure (Fujino and Siringoringo 2008; Fujino et al. 2016; Fujino, 2018). In addition, large amount of infrastructure stocks built during the peak of economic periods have now started to enter the last periods of their service. Significant portion of civil and transportation infrastructures such as bridges and tunnels are now deteriorating, and they require extensive efforts for maintenance. As a tool for infrastructure condition assessment, structural health monitoring (SHM) is becoming more and more used in civil engineering infrastructures and they have been implemented for infrastructure assessment in many parts of the world, including Japan (Boller et al. 2009).

On December 2nd, 2012, suspended roof for air ventilation in Sasago Tunnel of the Chuo Expressway near Tokyo collapsed onto traffic causing nine deaths. More casualties were avoided even though the collapse roof was over 130 m length because the traffic volume was low at the time of accident. This is the first maintenance-related accident with involvement of human loss. The accident has attracted public attention to the issue of infrastructure degradation and led to strong doubts about current quality and safety of infrastructures. Realizing this condition, Japanese government decided to invest on research and development for efficient infrastructure management. A new research and development program named "Infrastructure maintenance, renovation and management" was launched in 2013 under the Japanese Council of Science, Technology and Innovation (CSTI)'s Cross-ministerial Strategic Innovation Promotion Program (SIP). The 5-year program covers various subjects with key technologies in condition assessment, non-destructive testing, monitoring, and robotics; long-term performance prediction, development of high-quality durable material for repair and replacement, and infrastructure management using advanced information and communication technologies (ICT). The program consists of over 60 research

DOI: 10.1201/9781003215226-1

projects involving universities, research institutes and industries. This initiative is expected to prevent further accidents and setting an example for efficient infrastructure maintenance by reducing the burden of maintenance works and cost (SIP, 2014a).

Five research and development fields were set up under this program with the budget of about 30 million US$ allocated to all themes every year since 2014. The five research and development fields programs are as follows (Figure 1).

1. Inspection, diagnosis, and monitoring technologies. To develop efficient and effective inspection or monitoring technologies that can effectively gather data showing the infrastructures deterioration.
2. Structural materials, deterioration mechanisms, repair and strengthening technologies. To develop simulation technologies for modelling deterioration mechanisms of structural materials or predict deterioration process of structures.
3. Information and communication technologies. To develop data management technologies and systems that can maximize the use of information on infrastructure maintenance, renovation, and repair.
4. Robotics technologies. To develop maintenance or repair robots that can implement efficient and effective inspection/diagnosis. To develop the robots that allow investigation and/or work needed at dangerous disaster sites.
5. Asset management technologies. To develop technologies or systems that can maximize the use of information and facilitate efficient and effective infrastructure asset management.

The research and development for asset management technologies includes development of systematic management technologies aiming at minimization of lifecycle costs, development of asset management technologies applicable to local governments and nationwide, and establishment of basis for overseas expansion by organizing technical exchange platform with overseas infrastructure owners and individuals with relevant knowledge and experience. In the following sections, examples of research and development projects in the five sectors are given. More detailed explanations on the projects are given in (Fujino & Siringoringo 2020).

Figure 1. Five fields of R&D in SIP-Infrastructure.

2 RESEARCH AND DEVELOPMENT PROGRAMS FOR INSPECTION, DIAGNOSIS AND MONITORING TECHNOLOGIES

2.1 *Tunnel inspection technology using rapidly scannable non-contact radar*

Generally, tunnel inspections consist of close-range visual examination, but the conventional inspection technology has been criticized for inadequate safety and objectivity, high oversight risks, and the inability to properly evaluate the deformation progress because: inspection records are in the form of hand drawings and judgments are subjectively made by inspectors. To solve these issues, a mobile tunnel inspection vehicle called MIMM-R is developed under SIP program (Figure 2). In the system, the inspection vehicle is equipped with MMS (Mobile Mapping System; co-developed by Mitsubishi Electric Corporation), MIS (Mobile Imaging System; co-developed by Keisoku-kensa.Co.,Ltd), and MRS (co-developed by Walnut Ltd.). MIMM-R does not require traffic control but allows the high-precision and objective detection of irregularities while traveling at high-speed, typically 50-70 km/h and has been used at practical level. (Yasuda et al., 2014, 2016).

Details of specifications and sensors mounted on the inspection vehicle are provided on Table 1. The purpose of this new inspection technology is to detect inner defects in lining concrete using a rapidly scannable non-contact radar system. Ultimately, a synthetic diagnosis system to assess the soundness of tunnel comprehensively is expected. The inspection system also provides database compilation of various defects including inner defects by a 3D visualizing technology.

The inspection system employs a principle of subsurface indirect radar survey. The radar utilizes physical characteristics of electromagnetic (EM) waves that reflect at boundaries between different

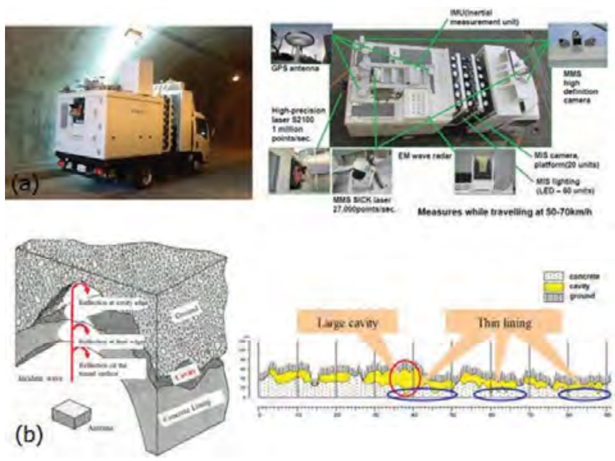

Figure 2. (a) mobile tunnel inspection vehicle MIMM-R and its specification, (b) Basic principle of EM wave reflection for tunnel inspection, and example of tunnel inspection by EM wave reflection-based principle (Yasuda et al. 2014).

Table 1. Detail specifications and sensors mounted on the inspection vehicle MIMM-R (Yasuda et al., 2016).

High-precision topographic survey	Road data and road framework data (based on the 3D point cloud data)
Laser Tunnel Surveys Deformation mode analysis	The high-precision laser device (1 million-point data per second), highly dense point cloud data, identification of lining shapes and deformations
Tunnel Image surveys Soundness assessment	Cracks as small as 0.2 mm (while travelling at 50 to 70 km/h). Identify the progressive of unsoundness conditions, the causes of deformation.
Radar Tunnel Surveys Cavity Evaluation	Non-contact radar system to detect lining thickness and back cavities (while travelling at 50 km/h) The system aims to quickly detect hazard locations with thin lining and cavities, as shown in Figure 2.

substances. When electromagnetic (EM) wave released from an antenna into the ground, reflected wave will have different electrical properties on the boundaries of layers consisting of different substances. Typical cross-section of tunnel is shown in Figure 2 which has three layers consisting of different substances, namely, concrete lining, cavities, and ground layers, respectively. As shown in the figure, the reflected EM waves from each layer boundary are received by the antenna. Some of the energy is absorbed when an EM wave propagates through a medium with different damping capabilities and this results in the reduced amplitude of reflected waves. Because of this, the general characteristics of the reflected waves coming from deep locations lack necessary strength and thus are undetectable on radar records. This damping effect is closely related 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.

Key innovations and developments were made to overcome the challenges and difficulties in implementation of high-speed non-contact inspection system (Yasuda et al., 2016): 1) Developing a technique to evaluate polarity and coefficient of EM wave reflection to overcome the difficulty in analyzing the pattern of reflected waves, 2) Development of a new horn-type antenna with high directionality and sensitivity to keep measurement target accessible in a non-contact manner. The new antenna can move up and down, slide and rotate above the inspection vehicle to gather more information about the inner defect (Figure 2) allowing measurement from approximately 3 m. Note that in the case of contact antennas, the diffusion characteristics of EM waves create difficulties in keeping an adequate distance with measurement target, and 3) Performance improvement of controller and sampler to allow the non-contact radar system operates on inspection vehicle moving at normal speed 50 km/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. High speed data collection was made possible by enhancing the sampling speed and increasing the speed of analog/digital converter. This is necessary to obtain data in the same volume as the contact type while travelling at a speed of 50 km/h or faster.

2.2 *Ultrasensitive magnetic nondestructive testing for evaluation of steel infrastructure*

A non-destructive testing (NDT) method using highly sensitive magnetic measurements for evaluation of deeper and extended defects on steel infrastructure such as bridges was developed in the SIP-sponsored study (Tomioka et al., 2017). The system is named an extremely low-frequency eddy current testing (ELECT) and the basic instruments are schematically shown in Figure 3. The system consists of oscillator, AC power supply, magnetic field applying coil, compensation coil, anisotropic magnetic resistive (AMR) sensor probe, amplifier, and PC. The measurement system operates in the following procedure. A compensation coil circled around AMR sensor probe will generate magnetic field in the opposite direction to the applied magnetic field of the AMR sensor. The AMR sensor and modulation coil are driven by the power supply with the current applied 0.15A. A magnetic field in the z-axis direction in the figure is measured by the AMR sensor. For thickness estimation, spectrum analysis of the magnetic field (SAM) is applied by measuring multiple frequency magnetic field vectors. Using SAM analysis, measurement of the thickness changes and

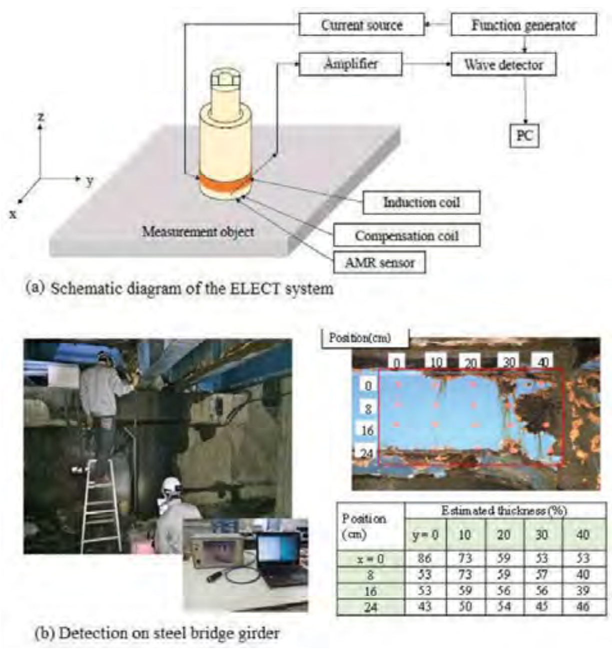

Figure 3. Bridge corrosion investigation using ELECT.

imaging of the steel plate are possible. In addition, a serious problem with magnetic noise caused by the magnetization fluctuation of iron steel is resolved using ELECT-SAM.

Two defects can be detected by this system, namely, the thickness reduction due to corrosion and inner steel crack. To detect the depth reduction of steel plate caused by corrosion of thick steel plate, extremely low-frequency eddy current testing (ELECT) with an applied magnetic field ranging from 1 Hz to 1 kHz was developed. The steel thickness is estimated based on the magnetic spectroscopy, which is traced using the obtained multi-frequency magnetic vector signals as shown in Figure 3. As a result, steel plate thinner than 20 mm can be measured within 0.1 mm resolution. Moreover, the shape of the back-side corrosion is determined by scanning with a magnetic probe. Compared with ultrasonic testing, ELECT has the advantage of noncontact, which enables detection even on rough, corroded, or coated surfaces. For inner crack in steel, unsaturated AC magnetic flux leakage (USAC-MFL) testing using an MR gradiometer was developed. Conventional MFL methods need a strong applied magnetic field to ensure that the magnetization characteristic of the steel becomes saturated so that the magnetic field leakage is measurable. They need a strong power source, and therefore they are not suitable for field testing. To solve this problem, a gradiometer with two highly sensitive MR sensors to detect weak magnetic field intensity and the change in the phase-shifted signal caused by the crack were applied. A sharp signal change is detected just above not only the surface but also the inner crack without being influenced by the variations in steel remnant magnetization. As the frequency of the applied magnetic field is decreased, a deeper inner crack is observed, and then an inner crack at a depth of 10 mm can be detected. USAC-MFL is helpful for covering undetectable regions of the sur-face and subsurface (the dead zone) of ultrasonic testing.

The two detection procedures were tested experimentally and then applied for steel bridge inspection. Based on the above fundamental experimental results, ELECT-SAM was applied to the real corroded parts of the girder of a bridge, where it was not easy to apply ultrasonic testing. The applied current was 0.15A and the frequencies of the applied magnetic field were between 1 Hz to 20 Hz to obtain the differential vector. Figure 3(b) shows the detection results on a severely corroded steel bridge plate. Measurement was taken at 20 different points (5 points at the intervals of 10 cm in the *x* direction and 4 points at the intervals of 8 cm in the *y* direction). The reduction in thickness was successfully estimated even at the surface of the corroded part where it was difficult to apply the ultrasonic testing. More detailed explanations on the measurement system and practical application are provided by Tomioka et al. (2017) and Tsukada et al. (2016).

2.3 *Concrete slab condition assessment using a vehicle equipped with Ground Penetrating Radar (GPR)*

Bridge slabs are important parts of bridges while the evaluation of their structural conditions requires significant manpower and time because dense hammering tests must be conducted; the need on efficient and reliable assessment of typical damage on RC bridge slab is high. Presently, a GPR system mounted on a moving vehicle are utilized for high-speed assessment (Figure 4). Even at a speed of 80 km/h, the radar signals reflected from the slab can be captured; the obtained signals are visually examined by inspectors to assess the slab condition. However, the signal is not so sensitive to the damage because the wavelength of the existing GPR system is much larger than the damage scale; the accurate detection is difficult, and the accuracy depends on inspectors. Image checking by inspectors is also time consuming. Thus, recently an algorithm to automatically detect damage from the GPR signals has been proposed (Mizutani et. al. 2017).

The algorithm first calculates the cross-correlation between signal from non-damaged area called 'reference' and that from target area. If the target area is not damaged, the waveform of the GPR signal has high similarity to the reference, resulting in a large cross-correlation value. On the other hand, the cross-correlation at damaged area becomes small. By applying a certain threshold to the cross-correlation, the damage and non-damaged areas are distinguished. The hammering test and GPR assessment are in good agreement.

3 R&D PROGRAMS FOR STRUCTURAL MATERIALS, DETERIORATION MECHANISMS, REPAIR AND STRENGTHENING TECHNOLOGIES

3.1 *Remaining fatigue life assessment of damaged RC decks using data assimilation of multiscale model and site inspection*

Reinforced concrete (RC) bridge decks constructed in urban areas sustain heavy traffic load during its lifetime. The increase of traffic loads and intrusive

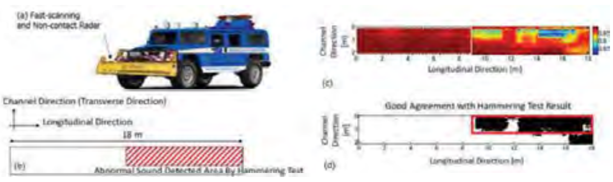

Figure 4. Concrete slab condition assessment using a vehicle equipped with GPR. (a) GPR measurement vehicle. Comparison between hammer test results and GPR signals after processing: (b) measurement bridge slab and its hammering test result, (c) Maximum of cross-correlation function, (d) after applying threshold (Mizutani et al. 2017).

environment condition have increased the risk of bridge deck deterioration and even failure. Damages on RC bridge deck is not uncommon in Japan, especially on the old bridge decks because they were designed for thinner slab decks to reduce the top-heavy mass required in seismic resistance design. Typical damages on the RC bridge deck such as lattice cracks developing over the bottom face of the decks. Repair works of the damage on the bridge deck is not easy technically, and it may create extended problem financially to the highway or road network such as traffic closure or detour. Therefore, maintenance of reinforced concrete bridge decks has been a primary concern for roadway or highway operators.

Estimating the remaining fatigue life of RC bridge decks subjected to traveling wheel-type loads is an important aspect of maintenance. Operators needs a good model to estimate the remaining life of bridge deck so that the necessary corrective actions such as repair and replacement can be taken timely and properly. Given that periodical inspection data of real bridges is available for the whole life, the series of data could be useful to verify its reliability of remaining life assessment. However, past ambient states and traffics to individual bridge have been rarely recorded and the initial quality of constructed concrete on which the scientific discussion can be based on is generally unknown or unrecorded in practice. One of the ways to verify the life assessment method is to apply for statistical analysis of big data of maintenance (Yamazaki and Ishida, 2015). The other way is to follow the mechanical and chemical states of the target.

The SIP-sponsored program proposed a method to estimate the remaining fatigue life is proposed using data assimilation procedure, i.e., coupled life-span simulation with inspection data at site. Multiscale analysis with hygro-mechanistic models is employed as the platform of data assimilation on which the visual inspection of cracking on the members' surfaces and the acoustic emission (AE) tomography are numerically integrated. For verification, the wheel running load experiments of slabs (Figure 5) were conducted with continuous data acquisition of both crack patterns and the acoustic emission data over the life till failure (Tanaka et al., 2017b). Visually inspected cracks are converted to space-averaged strains with Bernoulli-Euler theory. Imbalance in deformation and forces are compensated by numerical predictor-corrector cycles and non-inspected internal cracks are reproduced. During the loading, non-destructive tests (NDT) were conducted to detect the degree of structural concrete deterioration at periodical interval of times. The crack patterns observed on the lower surface, flexural cracks were induced at the very beginning of loads. Number of cracks gradually developed with increase in the wheel load passages. Radial cracks were formed by 100000 cycles. Then, both number and average crack width increased by 200000 cycles

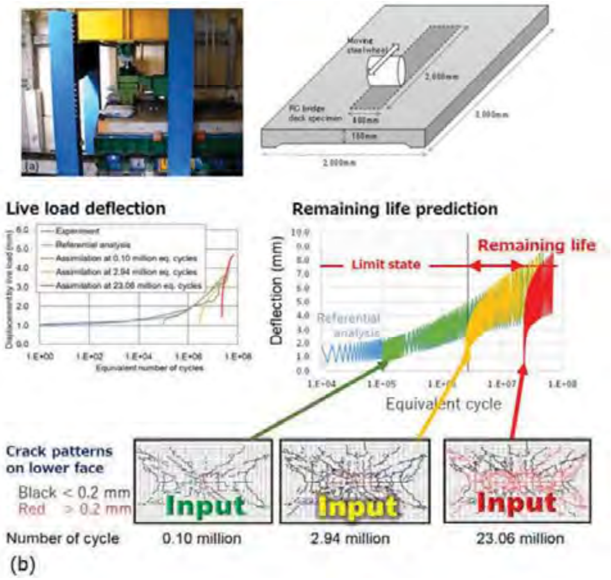

Figure 5. (a) wheel running test machine and dimensions of RC deck specimen and position of wheel load, (b) Data assimilation with crack patterns in wheel running test (Tanaka et al 2017).

(2.94 million equivalent cycles). At 250 thousand cycles (23.06 million equivalent cycles), lattice-type cracks were clearly formed, and the large crack width was observed (Figure 5).

Data assimilation method to combine the visual crack inspection data at site and the multiscale modelling was developed for remaining fatigue lifetime to failure, and its applicability was experimentally verified with moving load slab experiments. The numerical predictor-corrector method is used as a search-engine of most plausible solution of internal damages for existing slabs, where the visible cracks are set to be flexural ones as a start-up of data assimilation. As the first set-up for the subsequent predictor-corrector cycles, the elastic wave velocity field is converted to the fictitious isotropic stiffness, based on which the most possible cracking is searched. The proposed assimilation method successfully reproduces most probable internal cracks over the volume of analysis domains, and with this approach the remaining life of the deck slabs inspected can be successfully estimated (Tanaka et al. 2017 a,b).

3.2 *Performance assessment of Chromium bearing steel in concrete under salt-intrusive coastal environment*

In the SIP-program research, Nishimura (2018) studied the performance of Cr bearing steel in concrete on the bridge located in a coastal environment in Miyako-island in Okinawa prefecture. The nano structure of the rust of Cr bearing steel in concrete was investigated in detail using TEM – EELS (Electron Energy Loss Spectroscopy). The objective was to find relationship between the high corrosion resistance and the rust formation was discussed for the Cr bearing steel in concrete exposed under coastal environment. The exposure

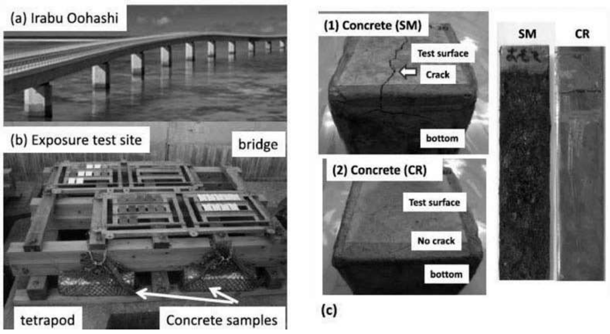

Figure 6. Photos for the (a) Irabu Oohashi and (b) Exposure test site. (c) Photos for the concrete samples and embedded (1) SM (carbon steel) and CR (Cr steel) after the exposure test (Nishimura, 2018).

test was conducted for 2 years at the exposure test site near Irabu Oohashi (bridge) in Miyako-island as shown in Figure 6. As the test samples were exposed on the tetrapod located 4 m from the sea, the sea water was splashed directly on the samples. The chemical composition of Cr bearing reinforcing steel (CR) was 7% Cr - 2% Si–Fe in mass%, additionally, carbon steel (SM) was used for the comparison. After the exposure test for 2 years, the steels and concrete blocks were compared. The carbon steel (SM) has a considerable corrosion on the surface, and the concrete block had large cracks. This behavior is explained that the expansion of the corrosion product (rust) causes the cracks of the concrete block. In contrast, CR has little corrosion on the surface, and there is no crack on the concrete. Thus, it is possible to demonstrate that CR has significantly higher corrosion resistance than that of SM in concrete at the exposure site.

From the exposure test, it was demonstrated that Cr bearing steel (CR) has significantly higher corrosion resistance than SM in concrete. SM had a considerable corrosion on the surface, and the concrete block had large cracks. However, Cr had little corrosion on the surface, and there was no crack on the concrete. Based on the TEM-EELS measurements, the chemical shift of Cr–L3 and Cr–L2 were recognized in inner rust, which corresponded to Cr (II) and Cr (III) oxide state. In inner rust of CR, Cr and Si were enriched in nano iron oxides, which was believed to increase the corrosion resistance of CR in concrete. The importance of this study is to confirm that CR has high corrosion-resistant performance in concrete, thus is effective to be implemented in the bridges located on the coastal environment.

4 R & D PROGRAMS FOR INFORMATION AND COMMUNICATION TECHNOLOGIES

4.1 *Automated recognition and 3D CAD modelling of standardized steel bridge members in a laser scan*

Management of bridge inspection records based on 3D models facilitates not only the intuitive understanding of damage distribution on the structure by the inspectors, but also ensures smooth communication among stakeholders involved in the maintenance. However, a major obstacle for the 3D management model is that 3D models of the existing bridges, such as computer-aided design (CAD) models, are not provided in most cases. Laser scanning is a promising method for obtaining reliable 3D measurements of large-scale structures, such as bridges. Therefore, several researchers have studied automated 3D as-built modelling of bridge structures based on laser-scanned point clouds. The proportion of steel bridges in Japan is quite high; therefore, these bridges strongly require an automated as built 3D modelling technique. In particular, the superstructures of steel bridges generally include a lot of standardized steel members, such as L-shaped or H-shaped angle steels. Therefore, for standardized steel members, there is a strong need for automated 3D modelling method based on laser-scanned point clouds captured from bridge superstructures. The primary algorithm for the 3D modelling method is to recognize the steel members using a variety of standardized cross-sectional shapes in laser-scanned point clouds.

In a SIP-sponsored research (Kanai et al., 2016), a fully automatic method to recognize standardized steel members from point clouds captured by a single laser scan is developed. The recognition process is illustrated in Figure 7. The process mainly consists of three stages: (1) the creation of a cross-sectional database, (2) the segmentation of primary planar region groups from the one-scan point clouds, and the extraction of feature dimensions of the region groups, and (3) the estimation of the type and size of the standardized steel members. The first stage is the pre-process phase; the second and third stages are executed in the actual recognition phase.

In the first stage, the cross-sectional database was built by registering the following geometric attributes characterizing the visually feasible cross-sectional shape of a standardized steel member. Using the attributes, a broad range of steel bridge member types, including L-shaped, CT-shaped, H-shaped, and U-shaped members, whose size variations were standardized according to ISO 657-1:198. In the second stage, the extraction of primary planar regions, segmentation of the planar region groups, and extraction of feature dimensions of the groups were carried out using the region growing method. Finally, in the last step of the recognition, geometric attributes of each planar region group were cross-checked with those registered in the collating table in the cross-sectional database to identify the type and size of the standardized steel member that fitted to the laser-scanned point cloud of the planar region group. Detailed information on the complete algorithms is described in (Kanai et al., 2016).

The proposed automated recognition system was tested on a short-span steel beam bridge in Yamanote, Sapporo, Japan. The bridge was scanned from the dry

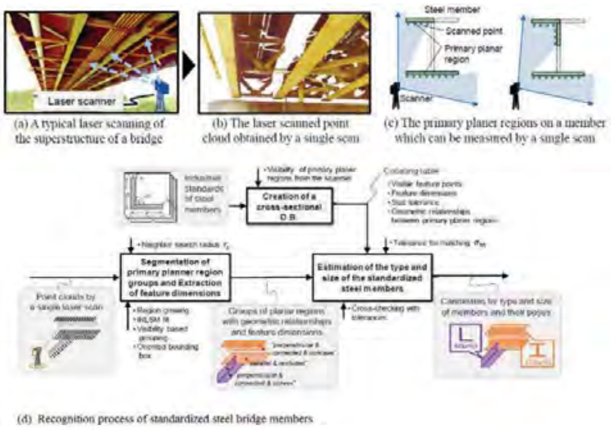

Figure 7. Laser scanning of steel bridge members and a scheme for automatic recognition process of standardized steel bridge members (Kanai et al. 2016).

riverbed by using a terrestrial laser scanner (FARO Focus 3D). As shown in Figure 7, the point cloud captured from the partial structure between two consecutive support bracings by a single laser scan was used as the input for recognition. The point cloud included 4,037,897 points, and the distance between the adjacent sample points ranged from 3 to 8 mm.

Three types and sizes of standardized steel members were used in the structure: three L-shaped, two L-shaped, and four CT-shaped steel members. The actual condition and sizes were manually examined in advance by the steel rule according to the registered cross-sectional database of steel members. The results show that the developed automatic recognition system can successfully recognize all L-shaped and CT-shaped steel members.

4.2 *Efficient registration of laser scanned point clouds of bridges using linear features*

The use of Terrestrial Laser Scanning (TLS) for bridge survey and inspection is quite common. Large number and precise 3D point clouds can be acquired with TLS measurement. The large numbers of point clouds from laser scanning and as-built 3D models from the point clouds of the structures can be utilized to support efficient maintenance, for examples, regular monitoring, detecting geometric changes of the structure, inspection planning and inspection data management. In the laser scanning of bridges, multiple scanning by TLS at different positions are required for acquiring point clouds without lack of points caused by obstruction. The origin of the coordinate system for the point clouds of each scan is the position of the TLS system. Therefore, an efficient, and accurate registration is required. Efficient registration of point clouds from terrestrial laser scanners enables us to move from scanning to point cloud applications immediately.

In the SIP-sponsored research, a new efficient rough registration method of laser-scanned point clouds of bridges is developed by Date et al. (2018). The method relies on straight-line edges as linear features, which often appear in many bridges. Efficient edge-line extraction and line-based registration methods are proposed. The method comprises of algorithms divided into four steps as explained in Figure 8(a). At first, the regular point clouds based on the azimuth and elevation angles are created, and planar regions are extracted using the region growing method on the regular point clouds. Then, straight lines from edges of the planar regions are extracted as linear features. Next, vertical, and horizontal line clusters are created according to the direction of the lines. To align the position and orientation of two-point clouds, two corresponding nonparallel line pairs from line clusters are used. Finally, in the registration process the well-known RANSAC approach with a hash table of line pairs is used. In this process, the hash table is used for finding candidates of corresponding line pairs efficiently. Sampled points on the line pairs are used to align the line pairs, and occupied voxels and down-sampled point clouds are used for efficient consensus calculation. The flowchart of proposed algorithms for pairwise rough registration is shown in Figure 8(a) (Date et al., 2018).

Performance of the methods was evaluated using laser-scanned point clouds of three data sets from different types of bridges: a small steel bridge, a middle-size concrete bridge, and a high-pier concrete bridge as shown in Figure 8(b). In the experiments, successful rates of the rough registration were 100%. It was shown that the registration based on linear features was effective for registering the laser-scanned point clouds of the bridges. The

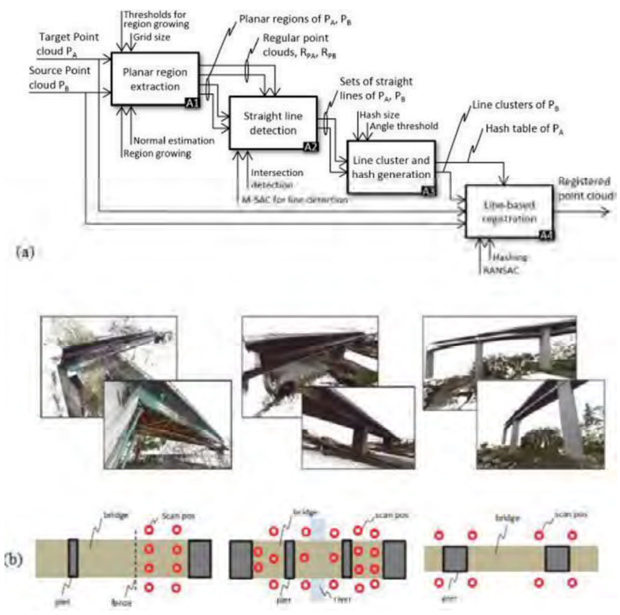

Figure 8. In the inspection of bridges using Terrestrial Laser Scanning (TLS), dense and precise 3D point clouds (a) Proposed algorithm for pairwise rough registration, (b) Precise results of application and scanning point registration results (Date et al., 2018).

observed registration errors were in the order of tens centimeters and they were modified by precise registration with processing time for rough registration of 19-point clouds was about 1 min.

5 R&D PROGRAMS FOR ROBOTIC TECHNOLOGIES

5.1 *Unmanned Aerial Vehicle (UAV) for bridge inspection*

A full-scale maintenance that includes the implementation of routine close visual inspection is recommended for all bridges every 5 years. However, the number of personnel for bridge inspectors in Japan is insufficient to cover all domestic bridges and will not increase significantly in the future because of safety concern about inspectors, decreasing birthrate, and an aging population. In addition, there are issues that manual inspection requires special access to bridge components through temporary scaffolds, special cranes or overhang buggy that are not always available, expensive and take time to maneuver, as well as ladder trucks that often block traffic. For these conditions unmanned aerial vehicle with its operationability, and accessibility is seen as a promising tool. UAVs have also become attractive in the field of disaster robotics, where it is expected to be used for exploration of disaster sites. However, during exploration, the UAV may encounter complex spaces such as a narrow space in a partially damaged building, between steel frame of bridges, connections of bridge deck and pylon, and piping of factories. Thus, an ordinary UAV without proper protection and a mechanism to maintain stability during a collision with obstacles cannot be used in this type of environment due to the high risk of falling.

Figure 9 shows PRSS-UAV and its main components. Spherical shell that can rotate freely covers the entire body of the UAV and protects it from colliding with obstacles without compromising the UAV's attitude and flight stability. Additionally, the system allows for flexible movement that is possible when the system contacts any surface because its spherical shell can function as a wheel. This mechanism enables the UAV to operate in a complex environmental condition without the need for complex sensing and avoidance strategies. In this program the PRSS-UAV is developed for close visual bridge inspection. There are two research issues to solve based on these requirements: (a) the hardware (mechanism) and (b) software (image processing).

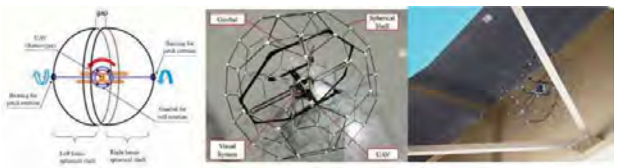

Figure 9. Unmanned Aerial Vehicle (UAV) with a passive rotating spherical shell (PRSS), (a) Basic configuration, (b) Photos of the components, (c) Operating for with a close space during steel bridge inspection.

The system of visual inspection requires a camera to capture images of cracks, corrosions, or any other problem in all critical parts of the bridge. A good image resolution is necessary for better analysis of the bridge condition. Further, at the visual inspection, bridge damages may appear from different angles (at the side, top, or edges), thus this requires a camera that can adjust its position with the addition of yaw rotation/movement, that enables a full overhead view for the application. The system utilizes the lightweight and high-resolution GoPro Hero camera, which is good for indoor and outdoor use. The system also provides a real-time wireless transmission of video from the camera using DJI Lightbridge. The raw data acquired from the motion capture system were used for postprocessing, extracting useful data for analysis. The recorded average flight duration of several test flights was 5.7 min. The average speed of the PRSS UAV was 0.65 m/s.

The overall weight of PRSS-UAV is equivalent to 2,583 g, which is about 92.25% of the maximum takeoff weight of the UAV. Likewise, the power rating of the system was more than doubled using a 7,800 mAH battery at 11.1 V. The system also provides easy maintenance by allowing the PRSS-UAV assembly to be split into two subassemblies. Detailed specification of PRSS-UAV system is given in Table 2. In this configuration, it is possible to easily remove and insert the UAV and other components inside the spherical shell if needed. The optimal size, weight, and configuration of the system was also designed for ease of transport and deployment (Salaan et al., 2018).

The second type of UAV for bridge inspection developed in the SIP program is two-wheeled multicopter with three-dimensional modeling technology (Hada et al., 2017). The system consists of multicopter as an inspection support robot, automatic geotagging technology and 3D model-based bridge maintenance database. For the inspection robot, a UAV two-wheeled multicopter shown in Figure 10 is developed. The two-wheeled multicopter system can crawl along a surface vertically and get into small space in the bridge. It has two main advantages compared to conventional UAV system. 1) Wind-resistance capability against crosswind by using contact friction between wheels and structure surface. This allows measurement along tall bridge pylon. 2) It allows movement along the surface of structure with constant distance between onboard camera and the structure surface that make it possible to capture close-up image of structure surface.

In most cases, the UAV used for inspection need to operate under the bridge girder where GPS signal is unreliable or even unavailable. To realize a position estimation of the UAV, a method of position estimation using automatic geotagging technology based on the structure from motion (SFM) technique using a 360-degree spherical camera is developed. The position estimation is used for geotagging, which is

Table 2. Specification of Passive Rotating Spherical Shell Unmanned Aerial Vehicle (PRSS-UAV) (Salaan et al., 2018).

	Initial quad	New quad	Unit
Frame diameter	450	450	mm
Propeller diameter	10	11	in
Overall diameter	704	730	mm
Overall weight	1	1.45	kg
Max take-off weight	2	2.8	kg
Battery@11.1 V	3300	7800	mAH

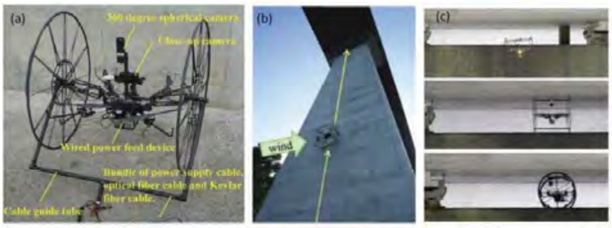

Figure 10. (a) model of two-wheeled multicopter UAV system and the ability of the system to operate in difficult conditions: (b) crawling on tall bridge pylon subjected to crosswind, (c) crawling into close-space between bridge pylon and girder.

a process of adding information to photos of video. The geotagging software can show both the close-up of deterioration images and their locations. The bridge inspection system consists of two main works, namely the field work and office work. The field work consists of capturing the images of inspected bridge components, automatic geotagging of inspection images, and employing three-dimensional laser scanning that can be used for semiautomatic 3D CAD model generation. Based on this information, the 3D model-based bridge maintenance database is constructed in the office work. Bridge conditions, possible damage or defects can be located. The system is tailored to accommodate supervisor's usage such as scheduling for bridge inspection, planning for bridge repair and prediction of bridge deterioration. This system is developed within collaboration of research groups from Fujitsu Limited, Hokkaido University, The University of Tokyo, Nagoya Institute of Technology and Docon Co. Ltd.

6 R & D PROGRAMS FOR ASSET MANAGEMENT TECHNOLOGIES

6.1 *Bridge Information Modelling (BIM) based on IFC for supporting maintenance management of existing bridges.*

One of significant information technologies in the Architecture, Engineering, and Construction (AEC) industry is Building Information Modelling (BIM). Maintenance of infrastructures that consist of inspection and repair process in the life cycle can also take advantage of the advanced development in BIM for more effective and efficient asset management.

In the SIP program a research on bridge information model that extends the Industry Foundation Classes (IFC) international standard is proposed (Tanaka et al., 2016). This information model satisfies the information requirements for inspection, evaluation, and maintenance processes. The bridge information model consists of interactive web system that combines the history data related to inspection, evaluation, and repair of the bridge is recorded in the 3D bridge model. A web content providing system is constructed to show the model in the outside field of maintenance. The web content system includes the product data, data extractor, data converter and webserver. The web content providing system is based on the three.js library (WebGL) that makes it available for the outside field maintenance purpose. The design data from CAD are exported as IFC-data and stored in the product data. Measured data such as photo image of degradation and as is bridge model are also stored in the product model. The current bridge conditions are obtained from latest measurement using advanced technologies such as laser scan and radar, and they are stored using IFC Engine library.

The system input past inspection reports as a PDF format. For paper reports, scans and scanning software are employed to obtain PDF file. From PDF data, text data, degradation photo image data and degradation sketch data are extracted by software. From degradation sketch, position of degradation is extracted using image recognition software. Character recognition techniques are utilized to identify type of degradation and photographic image. Later, these data are integrated into bridge information model.

The information system has function of viewing not only 3D shape model but also 3D model with photo texture. By extracting information from the past and associating it with 3D model, it is easier for bridge operator to create a repair plan. Figure 11

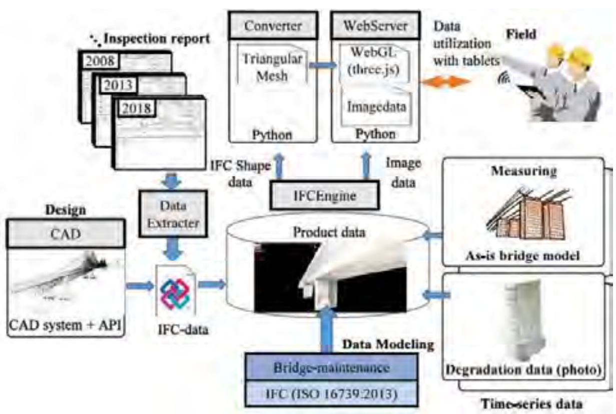

Figure 11. Structure of developed web content for supporting maintenance management of existing bridges (Tanaka et al., 2016).

shows the structure of developed web content for the system. More detailed information of the system is provided by (Tanaka et al., 2016).

7 CONCLUSIONS

This paper describes the new research and development (R & D) program named "Infrastructure maintenance, renovation and management". It is started in 2014 under the Japan Council of Science, Technology and Innovation (CSTI)'s Strategic In-novation Program (SIP) and covers various subjects of infrastructure maintenance with key technologies in condition assessment using non-destructive testing, monitoring, and robotics; long-term performance prediction of infrastructure, development of durable high-quality of material for repair and replacement, and management of large number of bridges and other infrastructure data using advanced information and communication technologies (ICT). The program consists of about 60 research projects involving universities, government research institutes and industries. The common goal is to have all the out-comes finally implemented in infrastructure maintenance, renovation, and management. The outcomes of SIP-Infrastructure would be implemented inside and outside Japan.

REFERENCES

Boller, C., Chang, F. K., & Fujino, Y. (Eds.). (2009). *Encyclopedia of structural health monitoring*. Wiley.

Date, H., Yokoyama, T., Kanai, S., Hada, Y., Nakao, M., & Sugawara, T. (2018). Efficient Registration of Laser-Scanned Point Clouds of Bridges Using Linear Features. *International Journal of Automation Technology*, *12*(3), 328–338.

Fujino, Y. (2018). Vibration-based monitoring for performance evaluation of flexible civil structures in Japan. *Proceedings of the Japan Academy, Series B*, *94*(2), 98–128.

Fujino, Y. and Siringoringo, D.M., (2020). Recent research and development programs for infrastructures maintenance, renovation, and management in Japan. Structure and Infrastructure Engineering, 16(1), pp.3–25.

Fujino, Y., Siringoringo, D. M., & Abe, M. (2016). Japan's experience on long-span bridges monitoring. *Structural Monitoring and Maintenance*, *3*(3), 233–257.

Fujino, Y. and Siringoringo, D.M., (2008). Structural health monitoring of bridges in Japan: An overview of the current trend. In *Fourth International Conference on FRP Composites in Civil Engineering (CICE2008*) (pp. 22–24).

Hada, Y., Nakao, M., Yamada, M., Kobayashi, H., Sawasaki, N., Yokoji, K., … & Yamashita, A. (2017). Development of a Bridge Inspection Support System using Two-Wheeled Multicopter and 3D Modeling Technology. *Journal of Disaster Research*, *12*(3), 593–606.

Kanai, S., Hashikawa, M., & Date, H., (2016), Automated recognition and 3D CAD modeling of standardized steel bridge members in a laser scan, *Proc. of 16th Int. Conf.. on Computing in Civil and Building Engineering (ICCCBE2016)*,July 6–8, 2016, Osaka, Japan.

Mizutani,T, Nakamura,N., Yamaguchi,T, Tarumi, M., Ando, Y. and Hara,I, (2017), Bridge slab damage detection by signal processing of UHF-band ground penetrating radar data, Journal of Disaster Research, vol. 12, no.3, pp. 415–421, Aug. 2017.

Nishimura, T. (2018). Exposure Test Performance for Chromium Bearing Steel in Concrete under Coastal Environment. *ISIJ International*, *58*(5), 936–942.

Salaan, C. J. O., Okada, Y., Mizutani, S., Ishii, T., Koura, K., Ohno, K., & Tadokoro, S. (2018). Close visual bridge inspection using a UAV with a passive rotating spherical shell. *Journal of Field Robotics*, *35* (6), 850–867.

SIP (2014a) (Cross-ministerial Strategic Innovation Program), Pioneering the Future: Japanese Science, Technology, and Innovation, Council for Science, Technology and Innovation, Cabinet Office, Government of Japan, 2014 (http://www8.cao.go.jp/cstp/gaiyo/sip/index.html, access Feb 18th, 2018)

SIP (2014b) (Cross-ministerial Strategic Innovation Program), Pioneering the Future: Japanese Science, Technology, and Innovation, Council for Science, Technology and Innovation, Cabinet Office, Government of Japan, 2014.

Tanaka, F., Hori, M., Onosato, M., Date, H., Kanai, S., (2016), Bridge Information Model Based on IFC Standards and Web Content Providing System for Supporting an Inspection Process, *Proc. of 16th Int. Conf. on Computing in Civil and Building Engineering (ICCCBE2016)*, July 6–8, 2016, Osaka, Japan

Tanaka, Y., Maekawa, K., Takahashi, Y., and Ishida, T. (2017a), Life assessment of bridge decks by data assimilation and survival analysis, Proceedings of the 2nd ACF symposium 2017.

Tanaka, Y., Maekawa, K., and Takahashi, Y. (2017b), Remaining fatigue life assessment of damaged RC decks-Data assimilation of multi -scale model and site inspection-, Journal of Advanced Concrete Technology, Vol.15, pp.328–345.

Tomioka, T., Goda, T., Sakai, K., Kiwa, T., Tsukada, K., (2017), Imaging of internal corrosion of steel structures using an extremely low-frequency eddy-current testing method. *Proc. of 15th Asia Pacific Conference for Non-Destructive Testing (APCNDT2017*), Singapore.

Tsukada K., Haga Y., Morita K., Nannan S., Sakai K., Kiwa T, and Cheng W, (2016),Detection of Inner Corrosion of Steel Construction Using Magnetic Resistance Sensor and Magnetic Spectroscopy Analysis, IEEE Trans.Magn., 52, 6201504

Yamaguchi,T, Mizutani T,Tarumi M, and Su,D (2018). Sensitive Damage Detection of Reinforced Concrete Bridge Slab by Time-Variant Deconvolution of SHF-Band Radar Signal, IEEE Transactions on Geoscience and Remote Sensing, 2018 (under peer review).

Yamazaki, T. and Ishida, T. 2015. *Application of Survival Analysis to Deteriorated Concrete Bridges in East Japan*. J. JSCE, Ser.F4, Vol. 71, No.4, 2015, pp. I_11-I_22.

Yasuda, T., Yamamoto, H., & Kitazawa, R. (2014) Cavity Detection behind Tunnel Lining using Non-contact Radar at 50km/h, *Construction Machinery and Construction*, 66(12), 51–56.

Yasuda, T., Yamamoto, H., Shigeta, Y., Ishii, H., & Kitazawa, R. (2016), Tunnel Inspection Technology using Rapidly Scannable Non-Contact Radar, *Proc. of EASEC-15*, January 6–8, 2016, Ho Chi Minh City, Vietnam.