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**Paper:**

# Utilization of Unmanned Aerial Vehicle, Artificial Intelligence, and Remote Measurement Technology for Bridge Inspections

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**In recent years, aging of bridges has become a growing concern, and the danger of bridge collapse is increasing. To appropriately maintain bridges, it is necessary to perform inspections to accurately understand their current state. Until now, bridge inspections have involved a visual inspection in which inspection personnel come close to the bridges to perform inspection and hammering tests to investigate abnormal noises by hammering the bridges with an inspection hammer. Meanwhile, as there are a large number of bridges (for example, 730,000 bridges in Japan), and many of these are constructed at elevated spots; the issue is that the visual inspections are laborious and require huge cost. Another issue is the wide disparity in the quality of visual inspections due to the experience, knowledge, and competence of inspectors. Accordingly, the authors are trying to resolve or ameliorate these issues using unmanned aerial vehicle (UAV) technology, artificial intelligence (AI) technology, and telecommunications technology. This is discussed first in this paper. Next, the authors discuss the future prospects of bridge inspection using robot technology such as a 3-D model of bridges. The goal of this paper is to show the areas in which deployment of the UAV, robots, telecommunications, and AI is beneficial and the requirements of these technologies.**

**Keywords:** bridge inspection, UAV, AI, remote measurement technology

## 1. Introduction

In recent years, aging of bridges has become a growing concern in various parts of the world. For example, in Japan, a large number of bridges that were built during the high economic growth period of the 1960s and 1970s are approaching the 50-year mark after construction, which is one measure of aging. The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) estimated that half of the bridges will reach or pass this 50-year mark by 2027 [1]. As aging progresses, the number of bridges for which traffic restrictions are in place, as it is impossible to ensure safety, is increasing. The number of bridges with restrictions is 2.9 times that 10 years ago (**Fig. 1**) [1]. In the United States, according to the Infrastructure Report Card 2017 by the American Society of Civil Engineers (ASCE), approximately 4/10 of 614,387 bridges were beyond the 50-year mark since their construction [2].

Conventionally, for managing bridges, a corrective maintenance approach, in which large-scale repairs or reconstructions were undertaken after damages became severe, was applied. However, if a corrective maintenance approach is applied to the large number of aging bridges, which will only increase in number in the future, it can be expected that the frequency of collapse of bridges, suspension of operation, and long-term or repeating traffic regulation will increase, resulting in major social loss for the users of the bridges. Furthermore, as annual budgets of bridge owners, such as national or local governments,

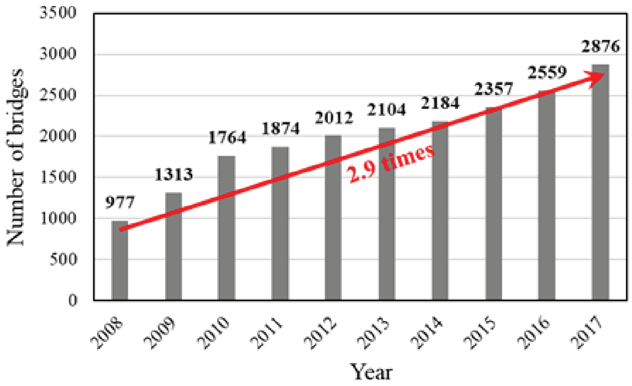



**Fig. 1.** Increasing number of traffic restrictions on municipal bridges.

are limited, if it were necessary to repair the large number of bridges simultaneously, the costs would exceed the annual budgets. Moreover, if the damage progresses further and repair is no longer an option, rebuilding is necessary, and the cost of taking countermeasures will significantly increase. An example is shown in **Fig. 2**. It is Inubou Bridge. Such a bridge structure is called a truss bridge. The truss bridge uses slender members to make many triangular structures, and they are connected to construct the bridge. It is frequently employed owing to its extremely high efficiency and beauty. However, owing to the lack of allowance, if a member is broken even at just one place, the bridge may collapse or come close to collapse. Inubou Bridge is an example in which four diagonal members that essentially should never be broken were damaged. This is because the members thinned as rust progressed, and probably because overloaded vehicles passed, the shock caused broke these four diagonal members in succession. The upper figure of **Fig. 2** shows the overall distortion, and the lower figure shows a magnified image of the damaged area. If the bridge were properly inspected and the rust were discovered several years earlier, it would have only required to be recoated with paint. However, the bridge was deemed unusable, and it was decided to build a new bridge, leading to extremely high costs. Reconstructing rather than recoating a bridge of this size generally costs 10 times or more. We have also dealt with other bridge collapses [4].

Considering such a situation, it is necessary to perform preventive maintenance on civil infrastructures, including bridges. In preventive maintenance, inspection is performed first; next, a diagnosis is made based on the results of the inspection; then, soundness is evaluated. Then, after making predictions regarding how it will age, repairs can be performed at appropriate times. This will allow systematic implementation of repairs and prevent situations in which repair costs exceed the annual budget; otherwise, it becomes too late to repair, as a large number of bridges suddenly need to be repaired. This in turn will help to avoid a situation in which failure to repair leads to exacerbation of the damage. Furthermore, if the bridges are repaired while the damage is still minor, the associated costs are less. Therefore, if they are repaired at an early stage, the life cycle costs of the bridges can greatly be reduced. For example, **Fig. 3** shows a situation in which cracks are appearing in a concrete slab. For this type of damage, if these cracks are quickly filled with epoxy resin, it is possible to prevent penetration of salt content and moisture, which are harmful for the interior of steel rebars. In this way, corrosion of the steel rebar, which is a major damage for the bridges, can be prevented at a low cost. However, dealing with the corrosion of the steel rebars after its exacerbation would result in higher costs. Thus, taking early measures is the key to reducing costs. However, to move forward with such processes without delay, bridge inspections should be precisely conducted to discover damages early.

Typically, bridge inspections involve a visual inspection in which inspection personnel come close to the bridges to perform inspection and hammering tests to investigate abnormal noises by hammering the bridges

**Fig. 2.** Example of damage to Inubou Bridge. The upper photo shows the whole image of the bridge, and the lower photo is an expanded photo of the cut bridge members (the area circled in the bottom photo) [3].

**Fig. 3.** Example of cracks in concrete slabs on the back of a bridge [5].

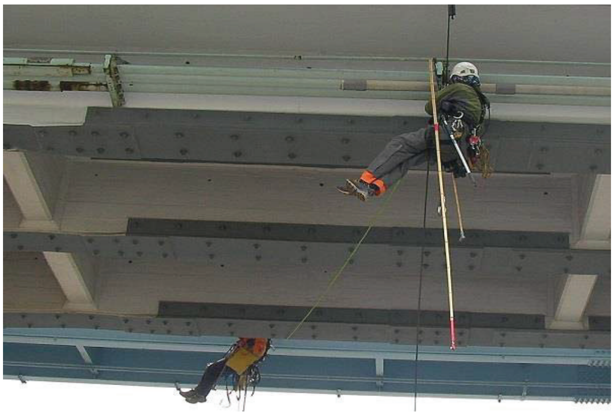


**Fig. 4.** Example of inspection using rope access.

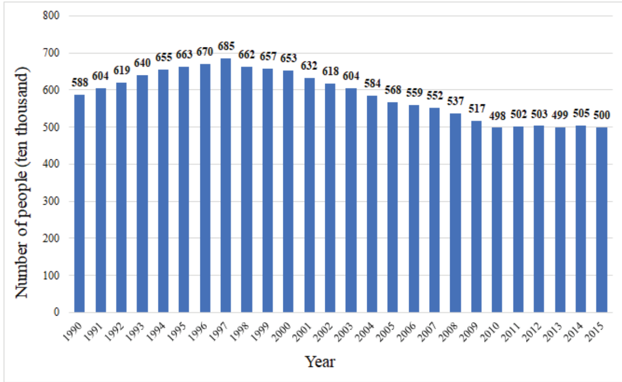



**Fig. 6.** Transition in the number of skilled workers in the construction industry.

**Fig. 5.** Example of inspection using high-location work vehicle for bridge inspection.


**Fig. 7.** Number of skilled workers in the construction industry by age.

with an inspection hammer. However, in the cases of inspecting bridges at high locations, it is not easy to get close to them to perform the visual inspection and the hammering test. Methods to approach high locations include, for instance, a rope access (**Fig. 4**) or using a high-elevation work platform vehicle for bridge inspection (**Fig. 5**). However, inspecting the large number of bridges is a huge burden in terms of costs and labor. In addition, inspections using rope access (**Fig. 4**) are highly dangerous. Furthermore, the issue of visual inspection from a proximate distance is that it lacks reliability because there is a wide disparity in its results owing to the experience, knowledge, and competence of inspectors.

In addition, securing human resources is another issue. In Japan, the number of people working in the construction industry has decreased from 6.85 million to 4.92 million (**Fig. 6**) [6]. Moreover, as shown in **Fig. 7**, these workers are aging. Considering that 780,000 workers who are at or over the age of 60 will retire in 10 years, further decline is inevitable. Furthermore, as these retiring workers will be those with the richest experience, the reliability of inspections is expected to decrease.

Therefore, introduction of unmanned aerial vehicle (UAV), artificial intelligence (AI), and telecommunications technology is expected to reduce the workload and cost involved in inspections, as well as the disparity in results among inspectors. From Section 2 onward in this paper, the authors will discuss research and development approaches taken and present future prospects. The goal of this paper is to show the areas in which deployment of UAV, robot, telecommunications, and AI is beneficial and the requirements of these technologies.

## 2. Introducing Technologies to Reduce Workload and Cost of Bridge Inspections

As stated in Section 1, bridge inspection currently requires significant workload and cost. Therefore, research and development aiming at reducing the workload and cost of inspections and increasing their reliability by introducing a variety of new technologies is underway. These approaches can be broadly classified into three types. The first is an approach to reduce the cost of the visual inspection from a proximate distance and the hammering inspections, the second is an approach to manage them remotely, and the third is an approach that utilizes AI to increase the reliability of the inspection. Following is the discussion on the respective approaches based on the activities of the authors.

**Fig. 8.** External view of the developed UAV.

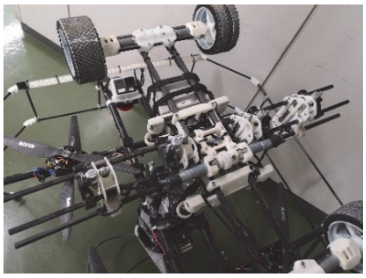
## 2.1. Reducing the Workload and Cost of Proximate Inspections

As discussed above, bridge inspection is conducted by getting close to the bridge to inspect its appearance via visual observation and the condition of the interior with hammering tests. The problem of this process is that the inspectors' approach to the bridge is laborious and requires high cost. Thus, if it is possible to capture pictures by approaching the bridge with a UAV in place of visual inspection, it could resolve the issue. Furthermore, it would be even more desirable that the UAV could perform the hammering test. The authors will introduce such a UAV in Section 2.1.1. Moreover, a simple scaffolding that would allow approaching the bridge inexpensive than the high-elevation work platform vehicle for bridge inspection shown in **Fig. 4** would contribute to a reduction in costs, and the authors are engaged in its development, which is introduced in Section 2.1.2.

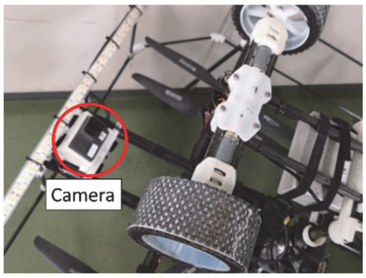
### 2.1.1. Bridge Inspections Using UAV

UAVs have already been in practical use in a wide variety of fields [7–10], and several studies are being conducted on their practical use in bridge inspections. In Japan, for instance, MLIT is conducting performance evaluation using UAVs for bridge inspections. However, although a general UAV can capture images and record videos, its shortcoming is that it is merely used to replace the visual inspection, and it cannot perform hammering inspections. Therefore, the authors developed a UAV equipped with a hammer to perform the hammering test and are conducting demonstration experiments at actual bridges. **Fig. 8** shows the external view of the UAV, and **Fig. 9** shows the impact mechanism, camera, and laser rangefinder (hereinafter referred to as LRF) installed on the UAV.

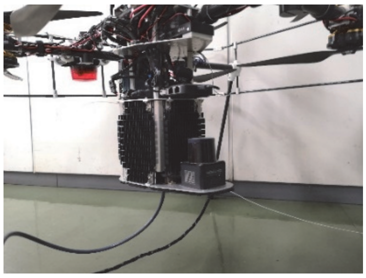
This UAV pushes a wheel traveling mechanism mounted on its upper part against the undersurface of the bridge and performs the inspection while traveling. The sound of concrete being struck with the four piston-type impact mechanisms is recorded with a microphone, and



(a) Impact mechanism




(b) Camera (HERO7 Silver, GoPro, Inc.)



(c) LRF (UTM-30LX-FEW, Hokuyo Automatic Co., Ltd.)

**Fig. 9.** Equipment installed on the UAV.

by analyzing this hammering sound, floating and peeling can be detected. In addition, using a mounted camera, it is possible to assess the impact location and perform visual inspection. The location information of the inspected sections is managed by acquiring their distance from the marker and bridge members using the LRF installed on the robot.

This UAV was actually used for the inspection of Deai Bridge (bridge length 210 m, five-span steel bridge) in Ehime Prefecture, Japan. **Fig. 10** shows an image from this inspection. **Fig. 11** shows an image captured by the drone. Cracks of 0.1-mm width, which should be detected by bridge inspection, were detected with sufficient resolution, fully satisfying the accuracy of the inspection.

Meanwhile, the hammering sound recorded by the microphone during the hammering test also contains the sound of, for example, a rotor blade, and it is necessary to extract only the hammering sound from the recorded sound. Using a directional stereo microphone, this system is able to separately record the hammering and rotor blade sounds and extract the hammering sound to be evaluated.

For evaluation, the acquired hammering signal is transformed into a spectrum using Fourier transform, the results of which are shown in **Fig. 12**. The healthy section

**Fig. 10.** View of the Deai Bridge inspection.

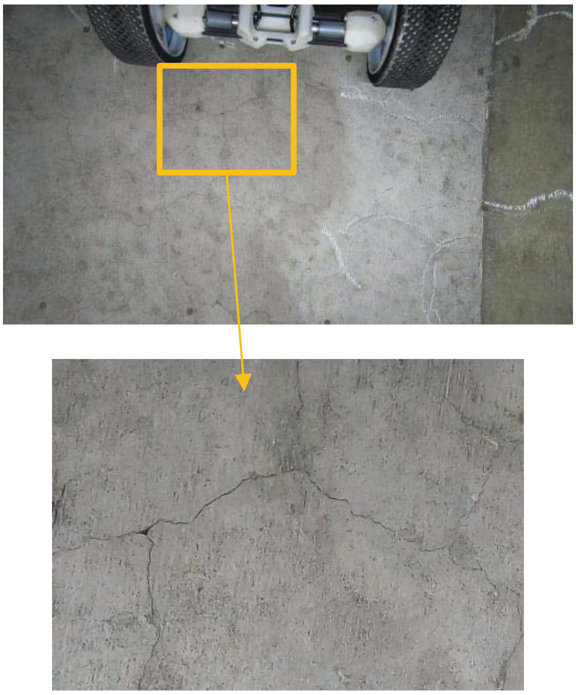


**Fig. 11.** Results of capturing the floor slabs using the UAV. The diagram on the right shows cracks of 0.1 mm.

has a broad distribution, whereas the abnormal part tends to have a sharp distribution [11]. Therefore, subsequent to normalizing the hammering sound signal spectrum, evaluation indicator is derived as the area between the waveform and the axis (the shaded area in **Fig. 12**), which is the integrated value of the normalized frequency [11]. When this value exceeds the experimentally obtained threshold of 18, the section is regarded as a healthy section, whereas when the value is 18 or below, it can be regarded as an abnormal section.

The authors also performed an actual inspection of the overhanging floor slabs of Deai Bridge. The impact interval was set at 130 mm in a direction perpendicular to the bridge axis and 40 mm in the bridge axial direction; the results are shown in **Fig. 13**. All evaluation indicators exceeded 18, indicating that the bridge was healthy. This result is consistent with the results of the follow-up inspection conducted by experts from a proximate location.

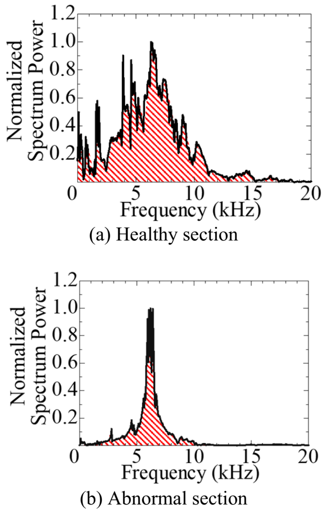



**Fig. 12.** Hammering signal spectrum example.

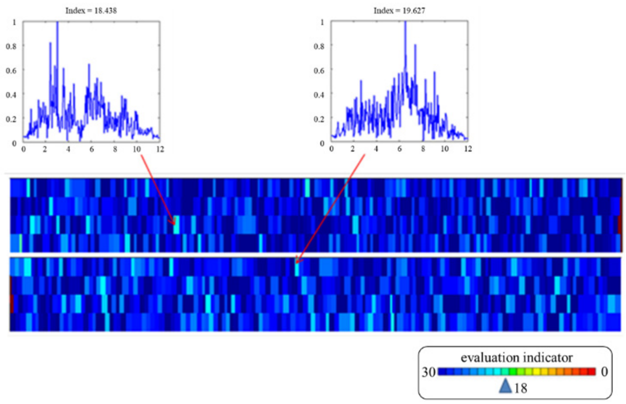
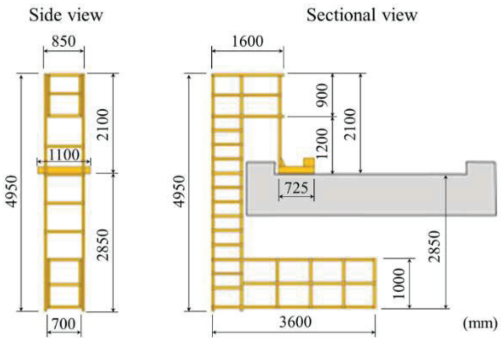



**Fig. 13.** Results of the hammering test on the overhanging floor slabs of Deai Bridge showed all of them to be below the threshold, and judged not to be damaged.

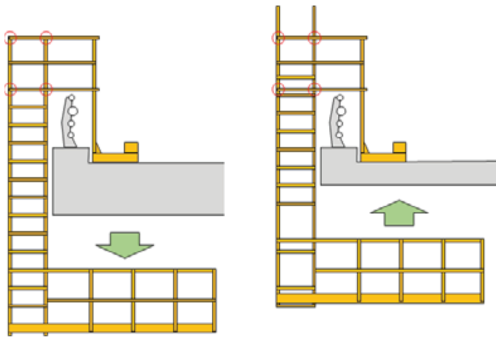
### 2.1.2. Development of a Simple Portable Scaffolding

A dedicated inspection vehicle such as the one shown in **Fig. 5** is convenient; however, the cost involved in its procurement is an issue. In addition, the road has to be closed when using the high-elevation work platform vehicle for bridge inspection on a narrow bridge with a width of 4 m or less, and this poses significant impact on the traffic at the site and the lives of the residents of the surrounding area. To address these issues, the authors have developed an inexpensive, simple, and portable scaffolding that does not require road closures even when used on a bridge with a width of 4 m or less, with the following performance requirements.

1. It should be able to avoid road closures during the inspection of narrow-width bridges (effective width 3–5.5 m).
2. It should be easy to transport, assemble, and move.
3. It should enable proximate visual inspections under the bridge girders.




(a) Representative measurements



(b) By changing the clamp jointing, it is possible to adjust its height with respect to the height of the bridge girders

**Fig. 14.** Simple portable scaffolding.

**Fig. 15.** Moving the scaffolding using a pallet lifter.

4. The maximum loading weight of the scaffolding should be 100 kg or more.
5. It should be movable on the bridge.

A simple portable scaffolding satisfying these performance requirements was designed using the finite element method. Its representative measurements are shown in **Fig. 14(a)**. Note that it can adapt to the change in the height of bridge girder by changing the location of the clamp joint, as shown in **Fig. 14(b)**, and it can be moved using a pallet lifter, as shown in **Fig. 15**.

**Fig. 16.** View of Shiriguro Bridge, where the verification test was conducted.

**Fig. 17.** View of the simple portable scaffolding assembly.

**Fig. 18.** View of the inspection elevator (left) and hammering inspection (right).

The authors conducted a demonstration experiment of the equipment on Shiriguro Bridge, which has an effective width of 4 m, in Kochi Prefecture, Japan, on December 16, 2016. The appearance of Shiriguro Bridge is shown in **Fig. 16**, and the simple portable scaffolding being assembled is shown in **Fig. 17**. **Fig. 18** shows the elevator for the inspectors and how the inspection was performed. The inspection using the developed simple portable scaffolding is safer than the one with rope access and does not require road closure, which is necessary when using the high-elevation work platform vehicle for bridge inspection.

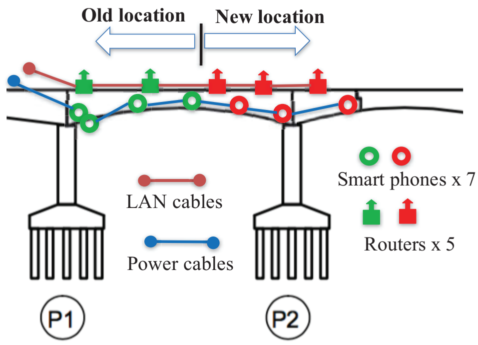
However, it currently takes approximately 45 min to assemble and disassemble the scaffolding by manual labor using truck-mounted cranes. If this time can be shortened to around 15 min by devising a mechanism or mechanizing the process, there be would be greater interest in using this scaffolding; the authors are conducting research to achieve this.

### 2.2. Approach for Remote Management

In Section 2.1, the authors discussed the technical development for reducing the cost of the proximate inspection. Meanwhile, if it were possible to remotely control the test, there would be no need to go to the location of the bridge. This would save a significant amount of workload and cost in mountainous regions and remote islands, where access to bridges is difficult. In this section, the development of technology that focuses on remote inspection is discussed.

### 2.2.1. Bridge Monitoring Using Smartphones

The authors are constructing a low-cost bridge health monitoring system that extracts vibration characteristics from a normal vibration of the bridge by recycling used smart phones. The vibration waveform of a bridge provides valuable information that can be used to understand the soundness of the bridge and its response during an earthquake [12, 13]. The developed system, which uses edge computing, is able to perform every task from data analysis to uploading the results to the server in bulk [14]. Moreover, seven smartphones (iPhone 5s) were placed on Takamatsu Bridge in Miyagi Prefecture [15], as shown in **Fig. 19**, to measure bridge vibrations caused by earthquake and traffic load and evaluate the safety of the bridge. As shown in the figures, the smartphones were installed in six locations, numbered 1 to 6, to monitor the cantilever box girder vibration on the top of the two piers, P1 and P2. Devices 1a and 1b were on the top of P1, and device 5 was on the top of P2. Devices 2, 3, and 5 were in the 1/4, 1/2, 3/4 locations of the P1 to P2 span, respectively. Device 6 was installed near the end of the Gerber girder, where the transportation sourced vibration is considerably large. The noise of iPhone 5s was kept at 5 Gal or below (when its acceleration range was ±2 g), and it was shown to have sufficient performance in measuring bridge vibration. Note that while it is possible to connect the smartphones to the Internet using LTE lines, the authors installed a LAN cable and Wi-Fi router as shown in the figure to upload the measurement results in real time to the Dropbox Server through Wi-Fi for this occasion as they were measuring the interior of the box girder. In addition, this system and the servo-acceleration sensors (SU501, Hakusan Industrial), which were installed for comparison, were able to measure the acceleration of a 5.3-magnitude earthquake centered in Miyagi Prefecture 37 km below mean sea level, which occurred at 23:53 on March 2, 2017. The observed data are shown in **Fig. 20**. Even upon comparison with a high-precision accelerometer, the error in amplitude was 2.4% (smart device: 0.12 Gal/Hz, SU501: 0.123 Gal/Hz) and error in dominant frequency was 0% (1.311 Hz for both), indicating extremely high accuracy.




(a) iPhone 5s installation position, router, LAN cables, and the power source


(b) Views of installation on Takamatsu Bridge

**Fig. 19.** Installation of smart devices on Takamatsu Bridge.

### 2.2.2. Monitoring Using LPWA Network

When monitoring civil infrastructure, automatic collection of data is preferable for reducing the fixed communication costs associated with continuous human on-site monitoring and freedom from the geographical constraints of the communication area. Although approaches to wirelessly acquire the vibration acceleration of a bridge have been proposed, problems such as synchronization of multiple sensors and securing power need to be overcome [16–18]. This study provides an approach to use the low-power wide area network (LPWA) [19], which has the disadvantage of low speed but low power consumption and the advantage of reaching a long distance, for the monitoring using the inclinometer with small amounts of data traffic. From various LPWA communication formats, the authors selected a long-range wide area network (LoRaWAN), which is suitable for low-power telecommunications and for which a source code for communication devices is published, and conducted a feasibility study aimed at using it for bridge monitoring. As shown in **Fig. 21**, the study assumed that an inclinometer was to be installed on a bridge. When the bridge sustains critical damage owing to, for instance, a landslide or local

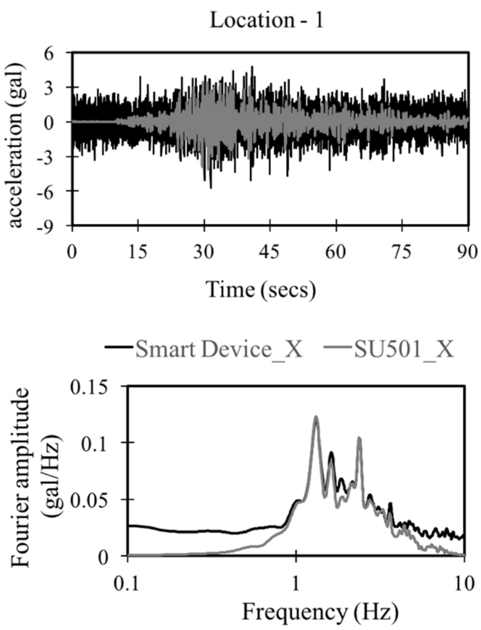



**Fig. 20.** Time history and frequency domain comparison for an earthquake that occurred on March 2, 2017.

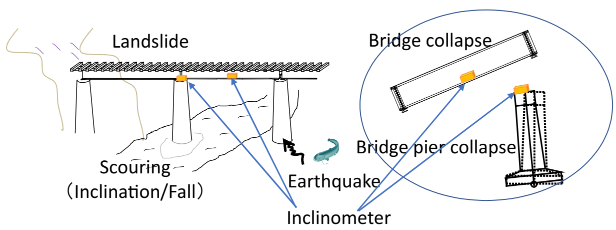



**Fig. 21.** View of the inclinometer installation.

**Table 1.** Specifications of the transmitter and receiver.

| | |
|---|---|
| Transmitter | |
| Output power | 20 mW |
| Spreading factor | SF 12 |
| Module | SX-1276 (Murata CMWX1ZZABZ-093) |
| Antenna | Omnidirectional whip |
| Receiver | |
| Module | RFM95W |
| Antenna | Yagi-Uda (Gain 10 dB) |

**Fig. 22.** Installation of the LoRa transmitter and receiver.

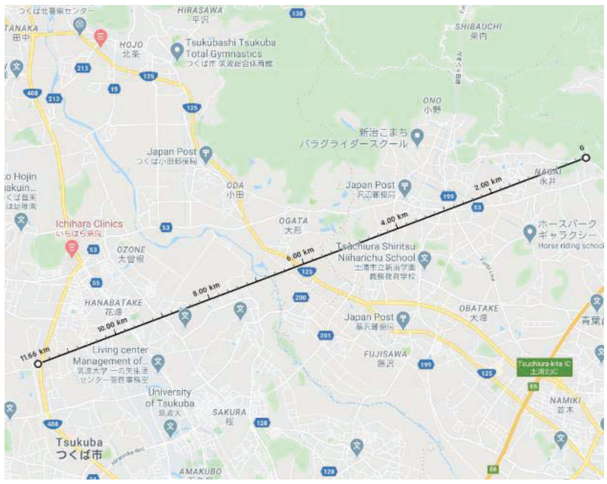



**Fig. 23.** Positional relations of the LoRa transmitter and receiver.

scouring, an irregularity is registered. Thus, through continuous monitoring, it would be possible to learn about threatening or critical situations without the risks associated with sending personnel to the bridge.

The inclinometer shown in **Fig. 21** indicates that data are recorded once per minute. The specific ID of the measurement device is identified on the LoRaWAN protocol side; therefore, it is not necessary to include it in the data payload, and date/time, incline direction, and inclination angle can be handled as monitoring data. With the date/time set to 32 bits and both the incline direction and angle set to 16 bits, it becomes six bytes. Thus, the authors investigated the receivable distance of this FS using a 10-byte payload.

First, the authors installed a long-range (LoRa) transmitter and receiver with a transmitting output of 20 mW on the roof of the National Institute for Land and Infrastructure Management of the MLIT (eight stories) building and performed a communication test at a distance of 11.6 km between the high points at a positional relation in which both were mutually visible. **Table 1** lists the specifications of the transmitter and receiver, **Fig. 22** shows the installation, and **Fig. 23** shows the mutual positional relationship.

In the communication test, assuming an even longer distance, a reception using a $-20$ dB attenuator, which was equivalent to the attenuation when the distance was 10 times longer, was also attempted. The result confirmed that even with antenna, good reception could be achieved. The reception strength from the software is given in **Table 2**. The relation between distance and signal strength is expressed as follows.

$$2 \times 10 \times \log_{10} \frac{D}{D_{ref}} = S, \qquad (1)$$

where $D$ is distance, $D_{ref}$ is reference distance, and $S$ is signal strength (dB units). By substituting the actual values used in the test to Eq. (1), i.e., $D_{ref} = 11.66$ km and $S = -20$ dB, it was observed that $D = 116.6$ km. Thus, the use of the $-20$ dB attenuator is equivalent to reception

**Table 2.** Received signal strength and signal-noise ratio (SNR).

| | Received Signal Strength Indication (RSSI) | Signal-Noise Ratio（SNR） |
|---|---|---|
| Distance: 11.66 km | -103 dB | 10 dB |
| Distance:11.66 km + ATT 20dB | -117 dB | -3 dB |

over a distance of 116.6 km.

According to this study, a range exceeding a diameter of 100 km from the monitoring office can be included, suggesting automatic monitoring of states of multiple bridges from a single remote monitoring office at a high altitude.

### 2.3. Approach to Utilizing AI to Increase the Accuracy of Inspections

In recent years, AI technology, typified by deep learning (DL), has been rapidly developing. It is being used in a wide variety of fields, and its performance and power have been revealed. In bridge inspections, the use of AI is being considered for reducing the workload of the inspection or diagnosis and reducing disparities in results among technicians. The research and development in this field are discussed below.

#### 2.3.1. Detection of Cracks in Concrete Structures

The authors are studying the automation of crack detection using image processing and AI to increase the efficiency of the inspection of concrete structures. For example, LightGBM was used to assess a given pixel unit when scanning for the presence of cracks, in which it was possible to set feature values for intelligently conducting this process [20–22]. However, if a pixel value is the only feature value to be used, darkened areas due to shadow or dirt might be evaluated as cracks. Therefore, the authors decided to use the pixel values of the surrounding pixels of the darkened areas and "whether a row of darkened areas lies long and narrowly" as the feature values. The results are shown in **Fig. 24**. It shows that although there were sections with low pixel owing to shadow or dirt, the cracks were detected with high accuracy by carefully analyzing the surrounding situation.

The authors also conducted research on combining this crack detection method with a structure from motion (SfM) technology. SfM enables the construction of a three-dimensional (3-D) model of the bridge [23]. Plotting the cracks detected with the above-mentioned technique on the 3-D model has the following advantages: (1) indoor post-inspection verifications becomes straightforward; (2) it would be possible to record the surrounding situation, which contributes to the accurate estimation of damage factors; and (3) it is simple to track any changes in the damage over time, ensuring appropriate responses.

However, when photographing the bridge for 3-D reconstruction, not only the concrete of the bridge itself but also various other objects, such as surrounding trees and lakes, were captured. Among these were some that might

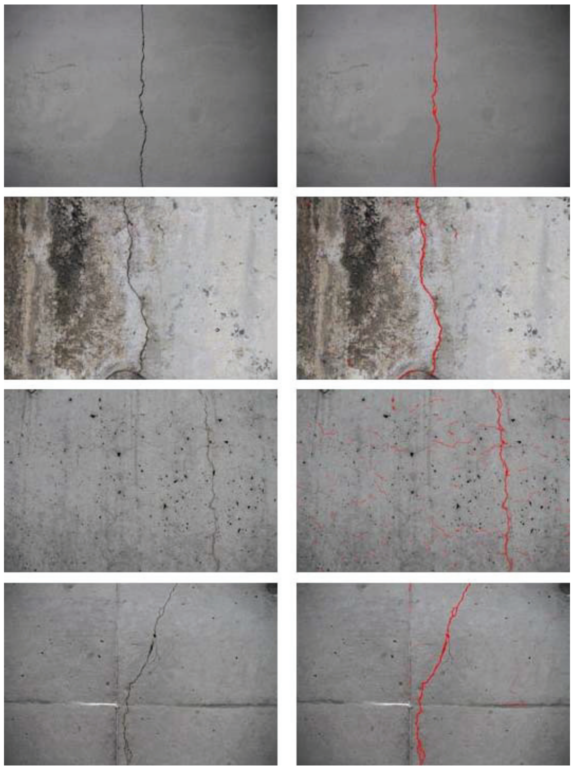


**Fig. 24.** Detection results obtained using the random forest method [20].

**Fig. 25.** Result of specifying the analysis range using Mask R-CNN [23]. (left: before analysis, right: after analysis).

mistakenly be assessed to be cracks. Clearly, they could lead to improper results when reconstructing the crack detection results in three dimensions. Therefore, the authors first conducted a study to specify the analysis range using a deep neural network called Mask R-CNN [23]. The result specifying the analysis range is shown in **Fig. 25**, which clearly shows that only the floor slabs within the range to be analyzed were appropriately detected. The outcome of bridge reconstruction that includes these results is shown in **Fig. 26**. This reconstruction enables the investigation of the presence of cracks and other damages, which is extremely useful for maintenance purposes. Furthermore, this technology can be combined with the UAV that photographs bridges.

It is worth noting that cracks are not the only damage to concrete. For example, the authors are studying a method to evaluate the corrosion of reinforcing steel in concrete by nondestructive testing [24] and a method to evaluate anomalies using deflections [25, 26].

**Fig. 26.** 3-D reconstruction and recreation of cracks using SfM [23].

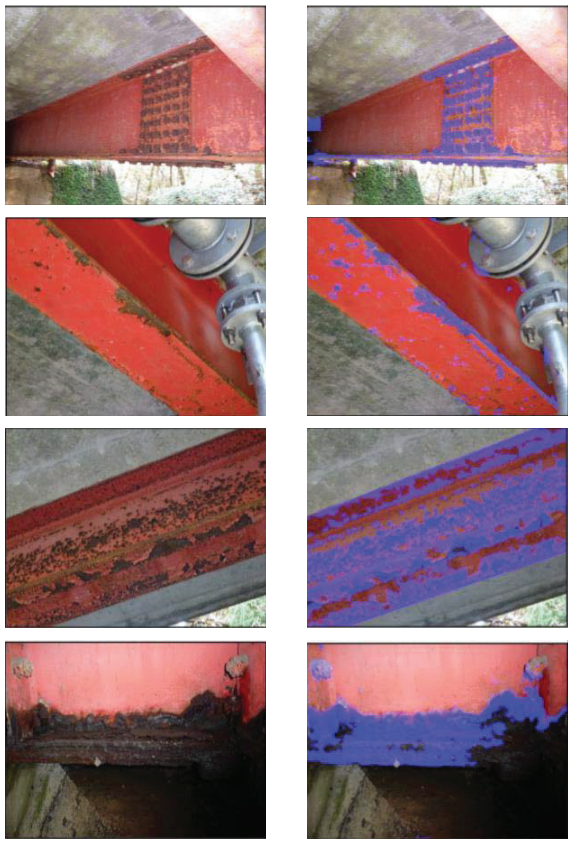


**Fig. 27.** Corrosion detection results of steel girders using an FCN [28].

### 2.3.2. Detection of Corrosion Damage

The authors are also conducting studies on not only the inspection of concrete structures, but also improving the efficiency of steel structure inspections. For example, the authors detected corrosion positions using the semantic segmentation method with a fully convolutional network (FCN), which is a type of DL [27, 28]. Its result is shown in **Fig. 27**.

As shown in **Fig. 27**, the corrosion area was identified with extremely high accuracy. Assessment of the corrosion area is not only important for evaluating the level of damage but also affects the calculation of workload required at the time of repair, potentially making a considerable contribution toward reducing the workload. Similar to the detection of concrete cracks described in Section 2.3.1, this technology can be easily combined with the UAV.

## 3. Future Outlook for the Use of Robots in Bridge Inspections

In Section 2, technologies that are currently in use or those which will be implemented in the near future are discussed. All of them are continuously developed and are promising technologies. Meanwhile, the i-Construction system academic contribution course, to which the authors belong, is aiming for further reduction in workload and costs. In particular, the UAV discussed in Section 2.1 has a problem at present that continuous operation for one hour or more exhausts the operator, implying that it does not achieve a reduction in workload. Another problem is the labor cost of the operator, which limits the reduction in cost. To resolve these issues, research on automatic inspection using an autonomous flying UAV is being conducted. However, at the current stage, it is considerably difficult for the UAV to fly and capture images comprehensively without hitting anything without any information because the GNSS signal used for self-position estimation of the UAV generally cannot be received under the bridge and because the technology used for accurately recognizing the shape of the bridge or obstacles has limitations.

Therefore, the authors are conducting research and development on a method to automatically generate a path from the 3-D model of a bridge and to perform autonomous inspection by flying along the path using a position estimation technology and path-following control that do not require GNSS. In Japan, an approach called Construction Information Modeling/Management (CIM) is being intensively promoted. This approach aims at improving the operation efficiency and quality of a series of construction and production systems by introducing a 3-D model from a survey and design phase and coordinating it

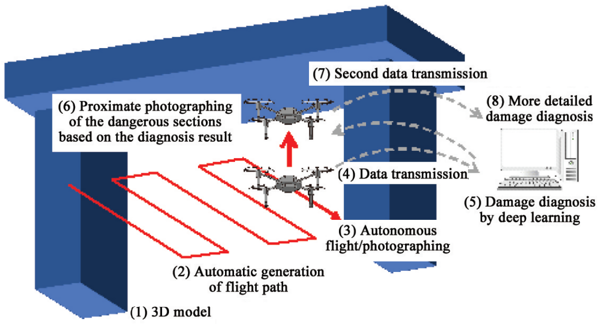



**Fig. 28.** Automatic bridge inspections assuming 3-D models and UAV autonomous flight required for the future.

with and developing it into a 3-D model of the construction or maintenance phase. Moreover, the bridges currently being maintained through two-dimensional (2-D) CAD drawings are expected be managed using 3-D models in the near future.

If 3-D model management becomes commonplace, it will be possible to realize automatic inspection of bridges with high accuracy using UAVs with the framework shown in **Fig. 28**. Its procedure would be as follows. First, a map is created for autonomous flight [(1) in the figure]. Next, a path is automatically generated based on this map. Following this, the UAV is flown along this path to capture images and the resulting data are uploaded to the server [(2)–(4) in the figure]. Later, damage diagnosis is performed using the DL, and subsequent to extracting the sections that require more detailed inspections [(5) in the figure], the UAV uses this information to approach the sections, captures more images, and uploads them to the server [(6) and (7) in the figure], at which point fresh damage diagnosis is performed using the DL. Thus, the state of the bridge can be automatically diagnosed with high accuracy. The method of generating the map in (1) is currently the biggest obstacle in this process.

Basically, the shape of a bridge does not differ much from the 3-D model constructed from the design stage in CIM; therefore, it can be used to obtain the map information. However, as there might be obstacles in the real-world bridge that do not appear in the early plans, it is not desirable to base the map solely on the early design, and it is necessary to use simultaneous localization and mapping (SLAM) as well. There are several techniques to implement SLAM, such as light detection and ranging (LiDAR), which acquires environmental information as point groups and Visual SLAM that uses captured images. However, these techniques have disadvantages in that LiDAR SLAM is not adept at recognizing fine objects such as a thin steel column and Visual SLAM is not adept at recognizing objects with less feature values such as a uniform wall that is common in large-scale bridges. Furthermore, compared with a robot that travels on the ground, the UAV has a small payload; therefore, it is necessary to limit the number of sensors that are installed on it. In addition, one must be aware that there is a vast array of environmental elements surrounding outdoor bridges, including natural features, such as forest, lake, and coastline, and artificial structures such as residential and urban environments. Consequently, as there are many difficulties associated with applying SLAM to the inspection of a variety of outdoor bridges, most of the similar investigations have fallen short in partial demonstration experiments, and the technology has not yet reached the practical stage. Therefore, the authors are advancing investigations based on the belief that the aforementioned issues can be solved and that the position estimation can be significantly facilitated by performing SLAM after securing the 3-D model of the bridge to be inspected as known information. If the above belief can be realized, the 3-D model and SLAM can mutually compensate weaknesses and reinforce strengths to generate maps suitable for autonomous flight.

Among the items shown in **Fig. 28**, studies on inspection using the UAV itself and on damage diagnosis using DL are underway, as described in Sections 2.1 and 2.3, respectively. In addition, the path planning and uploading to a server in the environments where SLAM is effective are not particularly new technologies. However, as there are no 3-D models of bridges, they cannot be integrated and only exist as separate technologies. However, in the future, technologies in UAV and AI to enable the above-mentioned inspection as well as the platform to integrate these are expected to be developed in the view of the increase in 3-D models. Achieving automatic inspections based on 3-D models will make it easier to link inspection information back to the models and significantly contribute to the realization of a one-stop management of design, installation, and maintenance data, which is the objective of CIM.

Moreover, this is not limited to UAVs; it is the same for other robots as well. The development and implementation of inspection methods using UAVs and robots are important; however, unless they are superior to the previous methods from the workload and cost perspectives, they cannot be successfully implemented. Therefore, it is important to promote automation as much as possible to install UAVs and robots in the civil engineering field, including the maintenance of bridges. In addition, such automation is expected to greatly reduce the time required for training and mastering the required skills, which will enable its implementation to efficiently proceed within the field.

## 4. Conclusion and Future Issues

This paper describes the technology development and future outlook for reducing workload and cost for bridge inspections. The authors introduced the following three approaches: reduction of the cost of visual and hammer inspections performed at proximate locations; remote management; and the utilization of AI for raising inspection accuracy. There have been interesting technical developments in each of these approaches, which are progressing toward the implementation phase. However, these have not reached the stage of drastic reduction in labor and cost because manual labor is still required when applying the technology and interpreting the acquired results.

To address this problem, it is necessary to integrate multiple technologies. Through the application of autonomous flight to robots, including UAVs, a large part of the inspection process can be automated by capturing images of the state of bridges and making assessments and interpretations using AI. This can eliminate most of the manual work and lead to significant reduction in workload and costs. The authors are working on developing a framework based on 3D bridge models as a method for integrating multiple technologies, which is also discussed in this paper.

Some future challenges are described below. When introducing a new technology into bridge inspection, unless the required performance is clear, disagreements will inevitably occur between the developer and user. However, the range of performance required by bridge inspection professionals with respect to new technology is extremely broad, and it is not possible to standardize this within the industry. Considering the example of concrete cracks, there may be people who want to detect cracks of 0.05-mm width, those for whom a width of 0.1 mm is sufficient, and those who are satisfied with a width of 1 mm. This major difference stems from how they wish to use the new technology and what they wish to investigate. Therefore, it is important to review the objectives of the inspection and consider the mechanical aspects necessary to achieve the required performance. Such a natural thing is not yet possible in the present situation. The civil engineering industry must take the responsibility for this to move forward.

Regarding a robot performing the inspections, there are issues related to the localization and recognition of the surroundings of bridges. Furthermore, questions such as "Can inspections be performed by robots?" and "Is it practical and likely to become widespread?" are separate issues. To develop a robot to realize the latter, it is necessary to design systems and operations that are easy to use, have reasonable introduction and operational costs, and reflect the opinions in the field.

Regardless, in countries such as Japan where the working population is decreasing, it will not be possible to handle the deterioration in bridges using the current framework, and the introduction of new technology is therefore essential. To this end, the authors are currently involved in research on making the installation of the technologies as easy as possible.

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