Research and Development on Inspection Technology for Safety Verification of Small-Scale Bridges using Three-Dimensional Model

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Abstract –

In 2014, a regular inspection of public infrastructure facilities (bridges, etc.) once every five years be-came a legal system. Of the approximately 730,000 bridges nationwide, 530,000 are small-scale bridges with a bridge length of 2-15m. These bridges are often not easily accessible by inspection engineers. Therefore, in this study, for the purpose of studying inspection methods as an alternative to visual inspection for small-scale bridges, development of inspection robots, examination of efficient methods for creating 3D CAD data, inspection using 3D models. We examined the results from four viewpoints, the management system of results and the extraction of damaged parts from photographs by AI. As a result of the research, we conducted demonstration experiments several times, arranged the scope of technology application according to the usage scene, and clarified the definition of functional requirements. This can be expected to contribute to the development of more efficient inspection, improvement of productivity, safety, etc. in future small-scale bridges, as a material for development for actual operation.

Keywords –

Bridge Inspection; Structure from Motion; 3D Damage Figure; AI Damage Detection

1 Introduction

In 2014, the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) put in place regulations requiring periodic inspections of public infrastructure facilities (e.g., bridges) once every 5years [1]. This meant that municipally managed bridges that were not previously subject to regular inspections, were inspected all at once. Many of these bridges are relatively small and difficult to inspect. Provisions were often made for sites that could not be approached without risk to inspectors, such as use of various inspection equipment or adjustments of inspection timing, but even this was insufficient for some sites, resulting in “inspection impossible” categorization.

There are about 730,000 bridges in Japan, of which around 530,000 are small structures measuring 2–15 m in length. Many such small bridges are not easily accessible to inspectors, making visual inspections according to the designated procedure impossible. In 2019, the MLIT revised the inspection procedures, allowing them to be based primarily on close-up visual inspections, and permitting the use of new technologies for complementing or replacing close-up visual inspections by inspectors [2]. These revisions allowed conditional use of drones or robots for inspecting conditions at sites that are otherwise difficult to approach. Further, there are plans to develop guidelines on the use of new technologies, which requires the development of efficient inspection technologies and investigation into their scope of application.

2 Objectives and Methodologies

In this study, we conducted proof-of-concept experiments targeting various issues and risks for small bridges with the aim of investigating the scope of application of technologies according to usage scenarios, clarifying functional requirement definitions, and providing material for developments toward actual operations.

We develop a robot for use in place of human visual inspections at sites that cannot be entered, or where entry is possible, but space is insufficient for inspections. Such a robot would likely be effective for application to various civil engineering structures, but in this study, we focus on its application to small bridges.

The implementation plan and focus of this study are as follows. To investigate and extract various issues and the scope of application, we conducted proof-of-concept experiments such as robot operation tests, data acquisition via mounted equipment, and post-processing tasks using the acquired data, and provided comments regarding their implementation.

2.1 Development of an inspection robot

Concerns surrounding safety, labor shortages in the construction industry due to low birthrates and the aging population, and a shortage of engineers in local governments have prompted active research and development of inspection robots for the purpose of more economical inspections. The MLIT has published materials on inspection support technologies [3], but most are related to the use of drones and target relatively large bridges. In this study, we developed a robot capable of entering beneath bride girders in place of a human.

2.1.1 Conditions

Based on our knowledge accumulated over 20 years of experience in bridge inspections and surveying tasks, we set the primary specifications for the robot as follows. A height of 70 cm is sufficient to allow human inspectors to enter the space beneath bridge girders but make it difficult to look up at the girders (slabs) that are the target of inspections. Figure 1 shows the state of inspection tasks for a bridge of the same scale as the bridges targeted in this study.

- The robot must be capable of entering and exiting a 70 cm space beneath bridge girders.
- It must be possible to mount cameras or other devices capable of recording damage.
- The robot must be capable of traversing over small rocks, mud, and other surface irregularities of up to several centimeters in size.

2.1.2 Implementation plan and focus

In developing the robot, we first selected usage scenarios for various issues such as expected operational environments, communication environments, and robot operations under low visibility situations. We next investigated what equipment should be installed. In proof-of-concept experiments, we first verified factors such as the operational performance of the robot, wireless communication quality between it and its controller, and the mounting position of the mounted devices, and then we varied and investigated types of mounted devices, their mounting positions, and settings for data acquisition methods. Figure 2 shows the robot developed in this study, and Table 1 lists its primary specifications.

Figure 1. Status of inspection work on small bridges

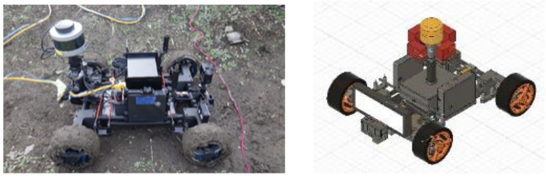


Figure 2. Developed robot and 3D CAD

Table 1. Primary specifications of the robot developed in this study

Specification	Value
Size	Width: 498mm/Depth: 592mm /Height: 375mm
Weight	4.0kg
Transmitter device	Futaba 14SG
Receiving device	COOLTECH R7008HV
Tire	140mm Off-road tires
Athletic performance	4WS

2.2 Efficient method for 3D model data creation

The MLIT has been carrying out common information model (CIM) tasks since 2012 and has confirmed information sharing and safety improvement effects among stakeholders using three-dimensional (3D) models during infrastructure design and at construction sites. Based on the CIM model creation specifications, Yamaoka et al. [4] , [5] verified usage methods in maintenance management using precise CIMs created at the design stage. Further, Shimizu et al. [6] developed a system for managing photographs taken during inspections in a 3D model. They also proposed a method for constructing 3D models by parametric modeling, and this method is highly effective for newly creating 3D models of existing bridges that are undergoing maintenance and for which models do not exist. However, humans or drones generally take photographs in these cases, and there are no examples of creating 3D models from photographs taken beneath the girders of small bridges using an autonomous robot.

In this study, we therefore investigated methods by which data obtained from a robot entering the space beneath bridge girders can be easily and efficiently applied to creation of 3D model data. In bridge inspections as well, there are increasing opportunities for converting 2D image data into 3D point group data through "structure from motion" (SfM) processing, allowing creation of 3D model data. Specifically, a fixed laser scanner is used to interpolate complex forms that could not otherwise be acquired. These are conditions like those of the small bridges targeted in this study.

2.2.1 Conditions

Bridges are built in various forms, but we limit our focus to girder bridges with reinforced concrete slabs and box culvert bridges, which account for the majority of small bridges.

2.2.2 Implementation policy and focus

As an initial point of interest, it is important to acquire still images with sufficient overlap for performing SfM processing. We performed proof-of-concept experiments to investigate how such images can be acquired not by humans, but by robots. Specifically, we established photo acquisition methods (for still images and video), photo resolutions, overlap ratios, distances to the target structure, view angles, and the presence or absence of feature points, and evaluated accuracy for point cloud data generated through SfM processing under various environments.

For our second point of interest, we created 3D modeling data from the generated point cloud data. Currently, computer-aided design (CAD) engineers must select (click) arbitrary points among point cloud data to create line segments and surfaces based on their experience and knowledge of bridge construction and combine these to create 3D model data. This is a bottleneck because the process requires huge amounts of time and labor. We therefore investigated methods for performing this task more efficiently and with less effort.

2.3 Inspection results management using 3D models

We constructed a prototype support system for 3D damage map creation as a management method for accurate and reliable sharing of structural lifecycle information among facility managers, inspectors, and repair workers, and investigated its necessary functional requirements. As the development environment, we used Unity [7], an integrated game development environment by Unity Technologies that can handle 3D models.

Table 2 shows the performance requirements. It is important to confirm the system's use as a platform that allows information sharing between stakeholders in different positions.

Table 2. System function Lists

No	Function
1	Bridge Specific Data Registration
2	Specifications Data of bridge Registration/Browse/Editing
3	Data Search
4	View and Operation of 3D model of bridge
5	Damage Data of bridge Registration/Browse/Editing
6	Narrowed-down display of damage information (Part of Member/Damage Kind/Damage Rank level)

2.4 Application of AI to detection of damage in photographs

We investigated conditions for application and operation of artificial intelligence (machine learning) to extract training data for automatically discovering damage from among the huge amounts of image data acquired by robots that are unable to distinguish between soundness and abnormalities.

Inspectors apply machine learning using as training data photographs of damage taken as in conventional inspection methods from near the structure, thereby creating a discriminator. This discriminator is used to identify damage in photographs taken by the robot and consider the results.

3 Implementation

3.1 Development of the inspection robot

3.1.1 Mounted equipment

Primary mounted equipment consists of a camera for robot operations, a camera for photographing damage (we compared two models, a Panasonic GH5S and a GoPro Hero7), and LiDAR (Velodyne VLP-16 Hi-Res) for position tracking.

3.1.2 Robot dimensions, maneuverability, and operability

Table 1 shows robot data, such as its dimensional specifications. The requirements call for an ability to enter beneath a bridge girder of height 70 cm and to acquire images of its underside, so as to ensure a constant view angle; the design is for a 15 cm distance from the tire contact surface to the baseplate on which the equipment is mounted. We must also consider possible obstacles to the robot's undercarriage as it advances beneath small bridges, such as sediment (mud and sand), gravel, pebbles, dead leaves, and vegetation. Therefore, to improve its operability and obstacle avoidance performance, we adopted four-wheel steering (4WS), a steering method that allows independent setting of steering angles for each wheel of the robot. Further, we set the tire diameters to 140 mm to allow operation in small amounts of water. We attempted use of continuous track propulsion in preliminary experiments but leaves and twigs frequently became caught in the treads, immobilizing the wheels, so we adopted tires instead. For the battery, we used a small, lightweight, high-power lithium polymer battery, and allocated sufficient space in the robot's middle for mounting a battery with capacity for 1 hour of continuous operation. In terms of image transmission between the operator and the robot that has entered a narrow space, we confirmed that transmissions were not interrupted from beneath the target bridges with which we conducted our experiments. We further confirmed that image transmissions were uninterrupted during gradual movement of the operator's position about 20 m upstream and downstream from the center of the road surface and beneath the bridge. We did not conduct tests from farther distances because 20 m was considered sufficient for the small bridges targeted in this study.

3.1.3 Proof-of-concept experiment I

We performed this experiment with a bridge of length 2.0 m, width 4.5 m, and 80 cm clearance beneath girders. We confirmed positioning of onboard devices, the quality of SfM processing results using acquired images, and the possibility of position tracking by the LiDAR. Tables 3 and 4 list parameters investigated in each proof-of-concept experiment.

When investigating parameters related to SfM processing, we used two camera models to confirm differences in camera image quality and view angle. We also confirmed differences arising due to turning the high dynamic range (HDR) setting on or off in each installation direction and when using or not using wide-angle mode. To investigate whether substitution of the equipment used for normal inspections as a photocontrol point improves the results of SfM processing, we also used the presence or absence of photocontrol points as a parameter.

When setting LiDAR-related parameters, to verify any differences due to the incident angle of the laser on the structure and the reference object, we investigated three horizontal installation angles, using the presence or absence of a reference object as a parameter.

Table 5 shows primary specifications for the bridge used in this proof-of-concept experiment, and Figure 3 shows a photograph of the proof-of-concept experiment being carried out. Figure 4 shows the installation angles. Figure 5 shows conditions for camera installation directions.

Panoramic view (bridge1/ bridge2/ bridge3)

Side view (bridge1/ bridge2/ bridge3)

Material installation status
(aluminium staff/ white line/ eslon tape)

Figure 3. Demonstration work status

Horizontal direction Vertical direction

Figure 4. LiDAR installation angle

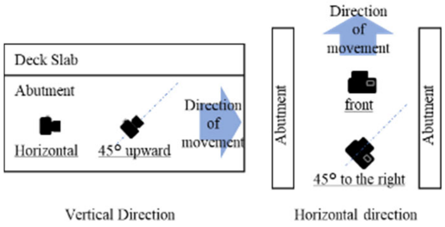
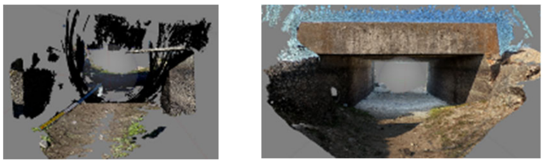


Figure 5. Camera installation directions



SLR camera at Bridge1 Action camera at Bridge1

Figure 6. SfM processing results

The results of this experiment showed that when performing position tracking using the LiDAR, the bridge form was not reproduced in any case where the reference object was not installed on a side face of the bridge. Also, form replication tended to improve when the LiDAR was installed horizontally. This is likely because the ability of a laser to capture the installed reference well is more effective for shape reproduction than for capturing the bottom surface of slabs.

However, installing plates for use as reference objects during inspections would be labor intensive and time-consuming, making inspections highly inefficient. Further, wind could blow plates over, which is a potential task hazard.

We next confirmed generation of 3D forms through SfM processing using robot-acquired image data. Figure 6 shows the results of SfM processing using image data for the same bridge as acquired by a single-lens reflex (SLR) camera and an action camera. The SLR camera could partially capture forms before entering beneath girders but capturing structures beneath the girders was nearly impossible. In contrast, the action camera could capture the entire form, including beneath girders. Due to this difference, there were many omissions in point cloud data created using the SLR camera. One effect likely influencing this is the difference in brightness when entering the dark environment beneath the bridge compared with the bright environment outside. Figure 7 compares still images captured by the SLR and action cameras. The action camera automatically and immediately changes brightness settings when entering beneath the girder, allowing capture of clear images while operating there. It is of course possible to change brightness settings for an SLR camera, but considering operability during inspections, the ease-of-use of an action camera likely makes it better suited to inspection tasks. Such cameras are also superior in terms of their small size and low weight.

Table 3. Study parameters (SfM)

	Value	Note
Camera Type	Single-Lens Reflex (SLR) camera Action camera	
Installation direction	Vertical / Horizontal	
Shooting method	Still Image / Video	Shooting interval 3 Cases
Control point	With or Without	Eslon tape paste on Deck slab bottom
Camera Settings	Wide angle mode: On / Off HDR mode: On / Off	

SLR camera Action camera

Figure 7. Comparison of still images from single-lens reflex cameras and action cameras

Table 4. Study parameters (LiDAR)

	Value	Note
Installation direction	Horizontal/15°/45°	
Reference object (Board)	With or Without	change distance
Reference object (White Line)	With or Without	
Reference object Shape/Size	Aluminium staff/board/man	change distance

Table 5. Bridge Specification

No	Length	Width	Height of under the girder	Structure type
1	2.0 m	4.5 m	85 cm	RC Deck Slab bridge
2	2.2 m	4.0 m	70 cm	RC Deck Slab bridge
3	13.0 m	1.8 m	85 cm (Inner)	Concrete Box Girder bridge

3.1.4 Proof-of-concept experiment II

Based on the results of proof-of-concept experiment I that concerned LiDAR-based position tracking, in proof-of-concept experiment II we verified whether equipment used in conventional inspection tasks or inspectors themselves could substitute for the reference object. To confirm any influences of surface shape or size of the reference object, we investigated cases where an aluminum staff and an inspector were used as reference objects. Figure 8 shows a photograph of the installed reference object.

In proof-of-concept experiment II, we set investigated parameters with a focus on photography conditions for the action camera, and we considered what effects these might have on the generation of 3D forms.

To confirm the conditions inferred from the results of proof-of-concept experiment I, we set investigated parameters in consideration of improved operability, efficiency, and safety of inspections, confirmed whether similar trends were reproduced in experiments performed on two bridges of similar type, and investigated the validity of the inferred conditions.

The results suggested that parameters minimizing defects in the 3D form were a fisheye lens mode, horizontal installation direction, and illumination turned on. No differences were seen between still images and video capture. Because video capture has improved on-site operability, and clipping intervals can be adjusted for still image extraction in post-processing, video capture is likely most appropriate.

Board Man Aluminium staff

Figure 8. Installed reference object

3.2 Efficient methods for 3D model data creation

In LiDAR-based form measurements beneath a bridge girder was possible to capture the form of bridge1 and bridge2, but not bridge3. This was likely because it was impossible to maintain continuous recognition of the installed reference object.

We constructed an algorithm for generating 3D model data from 3D point cloud data. Table 6 describes an overview of processing, investigation content, and processing content in each step. First, we prune the point cloud data to improve processing speed. We next perform clustering to estimate planar regions in the target object. The existence of point cloud data other than those belonging to the modeled bridge lowers modeling precision, so we remove such data and perform 3D labeling before processing for planar-surface fitting. When planar surfaces are formed, their intersections with other planes are taken as edges. We created an algorithm that creates a surface model from the vertices generated up to this point, and then a triangulated irregular network (TIN), finally converting data into a specified CAD format.

Table 6. Process overview and examination/process details of each process

No.	Process	Overview	Investigation/Processing
1	Point cloud data pruning	Reduce point cloud data acquired by SfM	Pruning processing is sped up by using an octree data structure.
2	Normal vector clustering	Group the resulting point cloud data for each generated plane	Generate planes from points in a given space by the least squares method and perform clustering by the K-means method using the angle formed by the Z-axis and the normal vector for each plane.
3	3D labeling	Remove point cloud data not subject to modeling	For all spaces in the space octree, merge connectable grids (labeling by distance), leaving only spaces containing point cloud data, and remove labels that do not correspond to some minimal volume.
4	Planar fitting	Generate fitted planes for each label	Use the least squares method for fitting. Planes determine the outer region within the range including the projected points.
5	Edge extraction	Generate surface model vertices	Search for intersections between a given plane and other planes; where intersections are found, update boundary as edges.
6	Surface modeling	Generate surface model from generated vertices	Generate a TIN using Delaunay triangulation. Convert the TIN into a specified CAD format and output.

To confirm the utility of the algorithm, we performed trials using highly accurate point cloud data as verification data and confirmed that the 3D model data were generated as expected. We used a ground-based laser scanner (Focus S350; FARO Technologies, Inc.) to generate ideal point cloud data for verification. Further, we performed SfM processing using image data acquired by the robot, performed verification using the generated data, and were thereby able to construct a model. By calculating root mean square values for planes in the generated 3D model data and the point cloud data, we confirmed that accuracy was within the LiDAR catalog value of ±0.030 m. This can be considered as sufficient accuracy for 3D model data applied to the maintenance management that is the objective of this study.

No method for quantitatively evaluating SfM-generated point cloud data has been established. Therefore, there is need for performing various verifications in the future to establish evaluation methods and confirm robustness in actual operations.

3.3 3D model-based inspection results management system

We constructed a prototype support system for 3D damage map creation to allow stakeholders to intuitively and accurately grasp and share locations and states of damage and identified and organized application ranges and issues for various parties.

The Windows application maintains a database of bridge specification data, damage information, and damage site ID numbers. The Unity application displays 3D model data on a screen. This system has functions for superimposing damage data on model data and for confirming and editing damage information.

The system is designed to maintain minimal information on bridge specifications, assuming there are components such as a ledger system already managed by the local government. Similarly, for inspection information, we prepared a database table using a damage location identifier as its key to represent damage locations, assuming a connection with an existing system.

Table 7 lists the main issues as indicated by persons responding to a survey that involved 200 visitors to an exhibition. Figure 9 shows the main screen of the constructed prototype system and the damage data input screen. In future work, we will develop a mechanism or device that allows efficient association of damage sites on the 3D model data.

. Many small bridges in Japan have a low maintenance cost per bridge. Therefore, the current situation is that there is almost no cost to newly create 3D model data. How to efficiently create 3D model data is important.

In this study, it was found that the structure and shape of a small bridge is simple, and it is difficult to understand the damage situation if a damage map is expressed by a 3D model.

In such a case, the use of CAD data as 3D model data, rather than using CAD data with colored point cloud data or textures attached, improves the grasp of damage conditions.

In future R&D, it is necessary to add a function that can read such data to the system.

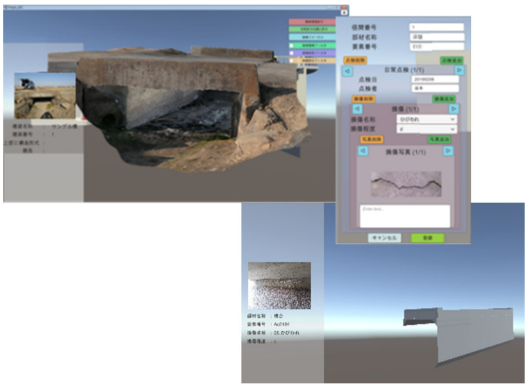


Figure 9. System screen and damage data registration/browse screen.

Table 7. Main issues as indicated by persons

Role of each persons	Main issues
Facility manager	Support function to make an optimal maintenance plan. Interoperability with the existing road management system (ledger system).
Bridge Inspectors	Output function for inspection reports. Automatic registration of damage location.
Repair workers	Optimal repair method and construction planning support. Automatic calculation of construction quantity.

3.4 AI application to identification of damage sites from photographs

We investigated algorithms and prepared an environment for introduction of AI methods. For training data, we used photographs previously taken by the authors or other inspectors judged as indicating damage.

For damage photograph labeling, we compared cases of labeling performed by inspectors and those by inexperienced persons provided with samples.

The results of discrimination in robot-acquired images included misidentification of cracks, peeling, and rebar exposure, an overall lack of recognition of peeling, and differences in scopes of occurrence. The results thus included many misidentifications of locations, scopes, and types of damage to be extracted. However, we obtained knowledge about constructing a learning environment and learning data, which enabled identification of requirements for condition setting. The following are items we identified as being particularly important development policies:

- Ensure consistent labeling of training data and prepare learning data that are high-quality (annotated) as well as abundant. Document how inspectors think for conversion from tacit to formal knowledge and identify what should be learned and how.
- Clarify relations between the required learning data scale and classification performance for each target damage class (e.g., damage type and degree) to be identified.
- Develop and formulate tools, interfaces, and operation processes that are linked with tasks so that learning data can be collected without placing burdens on primary tasks.
- Manage training data not as individual image files but matched with bridge specifications and other related information.

4 Conclusion

In this study, we summarized the requirements for robot development that can enter the girders of small bridges and acquire necessary and sufficient data for post-process work from the viewpoints of technological trends, development and maintenance costs, and versatility.

We have developed a robot that enters and exits under the girder of a small bridge with a space below the girder height of 70 cm or less. In addition, we performed a comparative verification of the conditions and installation methods of the equipment mounted on the robot and proposed an efficient method for 3D model data.

Regarding the 3D damage map creation support system, the system requirements and issues were organized from the perspective of the relevant parties (facility managers, inspection operators, repair work operators, etc.). In addition, it is also important to propose activities to replace the current 2D drawing management method with the proposed method.

Regarding damage extraction by AI, the requirements for a series of maintenance up to the introduction of AI have been arranged.

In the future, further verification in various bridge types and under girder environments will be required for actual operation.

Acknowledgements

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