Clarification of Performance Requirements for Utilizing Robotic Technology for Regular Inspection of Steel Bridges

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ABSTRACT: Adopting advanced technology such as UAV into bridge inspection is attracting attention. This study focused on steel bridges. The field testing was conducted on two selected steel bridges in Gifu prefecture, Japan. The results of field testing showed that some of the advanced technologies already have enough performance to support bridge inspection. Based on those results, this paper clarified the technology advantages/limitations and suggested the foundation of guidelines for adopting advanced robotic technologies in steel bridge inspection by clarifying the performance requirements. In terms of the performance requirements for those technologies, it was required to obtain the wide-area and narrow-area information to detect defects such as corrosion, coating deterioration and fatigue of the steel bridge. As the specific requirements for steel bridges, the operability to narrow areas and approaching function for each structural design of the bridge were clarified.

1 INTRODUCTION

In Japan, many bridges are managed by municipalities. So far, the regular bridge inspections have been mandated by human inspectors and it was conducted based on the visual inspection. However, this method requires many inspectors, takes high costs, and it is a time-consuming work. Therefore, it has been desired to conduct regular inspection to be efficient. In order to achieve the efficient inspection, the utilization of advanced robotic technologies have been considered. Under this background, the project titled "Infrastructure Maintenance, Renovation and Management", which is one of the projects under the Cross-ministerial Strategic Innovation Promotion Program (SIP), was conducted by Cabinet Office, Government of Japan in order to accelerate the research and development on infrastructure maintenance technologies from April 2014 to March 2019 (JST 2014a). As one of the SIP projects, Gifu University conducted a research titled “Implementation of effective SIP maintenance technology by maintenance expert (ME) network” (Gifu University SIP 2017) from September 2016 to March 2019. Under this project, the research which tried to adopt some advanced robotic technologies such as UAV into the inspection of the concrete bridge, that managed by Kakamigahara city in Japan, was conducted by authors (Hasuike et.al. 2018). From this research, it was revealed that the critical consideration while adopting any advanced robotic technologies into the bridge inspection would be understanding the technology advantages/limitations and required performance for technology, and formulating the matching standards as well as implementation approaches. Therefore, the standards were proposed (Gifu University SIP 2018) and the regular inspection for the concrete bridge was conducted (Hasuike et.al. 2019).

On the other hand, regarding the existing bridge types in Japan, the concrete bridges occupied about 59% and the steel bridges are 38% (Road Bureau 2018). Thus, adopting advanced technologies into steel bridge inspection is thought that one of the important needs. In this study, the author’s previous research about the concrete bridge (Hasuike et.al. 2018, 2019) was extended into steel bridges. In particular, the differences between concrete and steel bridge inspection were clarified, then field testing were conducted on two steel bridges which are managed by Gifu city and Mino city in Gifu prefecture, Japan. After that, based on the results derived from the field testing, this paper identified the technology advantages/limitations and suggested the foundation of guidelines of adopting advanced robotic technology into steel bridge inspection by clarifying the performance requirements.

2 DIFFERENCES BETWEEN CONCRETE AND STEEL BRIDGE INSPECTION

Nowadays, a lot of research on bridge inspections by advanced technologies focused on the concrete bridges (Drafshan & Maguire 2018). In this section, to expand those researches into steel bridges, the differences between concrete and steel bridge inspection were investigated.

2.1 *Differences in bridge structural design*

Many of the structural design of concrete bridges are simpler than steel bridges. For instance, the main structure design of concrete bridges is deck bridge and girder bridge. In contrast, many steel bridges have complex structure design such as truss bridge, arch bridge and suspension bridge etc. In addition, the complex structure design leads to increase the surface where have to be inspected. For those reasons, when to inspect steel bridges, it is more difficult to access them than a concrete bridge and it will be more time-consuming. Those structural design differences are thought that one of the reasons to do not accelerate to adopt the advanced technologies into steel bridge inspection.

2.2 *Differences in evaluation methods of defects*

In the regular inspection, obtaining the information which can help to make a diagnosis of the bridge member’s condition is required to understand the bridge conditions. Table 1 shows the types of defects which are required by the *Bridge inspection manual* (Road Bureau 2019a) for concrete and steel members. In this manual (Road Bureau 2019a), the width and length of cracks on the concrete bridges are clarified with the specific values. In contrast, for the defects in steel bridges, the specific values are not defined. Thus, in steel bridges, understanding the performance requirements for advanced technology is more difficult to compare with concrete bridges.

3 FIELD TESTING ON STEEL BRIDGES

In order to understand the ability of the advanced technologies that have been developed nowadays, field testing were conducted on two real bridges (Table 2). In this field testing, to consider the applicability for different bridge structural types, the girder bridge and the truss bridge were selected. As the advanced robotic technologies, three types of technologies as shown in Table 3 were selected.

3.1 *Field testing at the girder bridge*

Figure 1 shows Chidori Bridge which is a 3-span steel girder bridge with a spanning 215.5 m over Nagara River. This bridge had been used from 1969 as a bridge for vehicles such as cars. In 1988, the steel box girder bridge, which is for the path of vehicles, was constructed on the upstream side, and the utilization of previous girder bridge was changed for a pedestrian/bicycle path. This previous girder bridge has a narrow space as shown in Figure 2 because of a lot of attachments. It makes the

Table 1. Types of defects on each member.

Concrete Members		Steel Members	
	Crack *Crack width, Crack spacing		Corrosion
	Spalling, Exposed rebar		Crack
	Water leaking, Free lime		Loose/dropped bolts
	Severe spalling		Fracture
	Crack on the deck *Crack width, Crack spacing		Deterioration of the coating
	Delamination		

Table 3. Used advanced technologies in the field testing.

Type	Name of technology	Working
UAV/UAS, Drone	**(A) UAV with a passive rotating spherical shell**	
Robotic Camera	**(B) Robotic camera indicating crack scale for bridge inspection**	 
	(C) Camera system for bridge inspection	

Table 2. Selected bridges in the field testing.

Bridge structural design		Length (m)	Manager	Completion year	Used advanced technologis (A to C are shown in Table3.)		
					(A)	(B)	(C)
Steel Bridges	3-span steel girder bridge	215.5	Gifu city	1969	○	−	−
	5-span steel (wrought iron) truss bridge	325.1	Ogaki city	1886	−	○	○

inspection difficult by disturbing the inspector to approach for the inspection objects, such as the slab.

The UAV type technology which has a passive rotating spherical shell and the outside diameter is 96cm (Table 3 (A)) was selected in this field. This technology enables stable flight even when touching a member by attaching a passive rotating spherical shell. This function allows taking images by a close distance which is up to approximately 50 cm to the inspection object. According to the results from this field testing, it was possible to take images from a close distance to the inspection object even if there was some attachments as shown in Figure 3. In addition, as shown in Figure 4, the damage map can be created from the obtained data. The map was created by the following steps: detecting the damages such as cracks, mapping it, then processing the images to a panorama. From those results, the possibility of taking photography from a close distance in a narrow space by this technology was confirmed.

3.2 *Field testing at the truss bridge*

Figure 5 shows Ibigawa Bridge which is a 5-span steel truss bridge with spanning 325.1 m over Ibi River. This bridge was constructed as a railway bridge in 1886, and the material is a wrought iron from British. From 2000, this bridge has been used as a pedestrian/bicycle path. In addition, in 2008, it was recognized as one of the important cultural properties in Japan, because it was constructed as an

Figure 1. Chidori bridge.

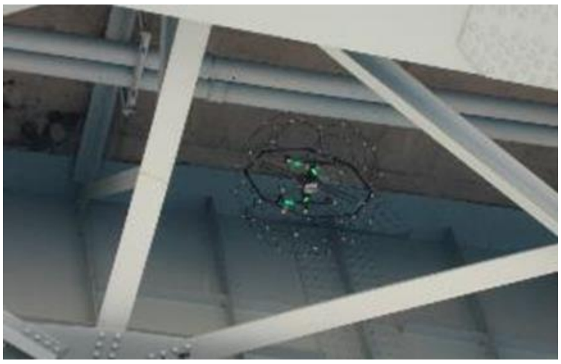


Figure 2. Narrow space in the girder.

Figure 3. Attachments on the girder.

Figure 4. Created crack damages map.

(a) A view of the entire bridge.

(b) Road Surface.

Figure 5. Ibigawa bridge.

important large-scale railway bridge and the state-of-the-art techniques in the Meiji period (1868 to 1912) were used to construct it. Therefore, not only management as a road structure but also management as an important cultural property is required. In other words, there are many maintenance limitations such as restrictions on the installation of scaffolds during bridge inspections and using the same materials (wrought iron) as when it was constructed for repair work such as corroded members. From those limitations, the inspection costs will become higher than common bridges.

This bridge locates close to the railway line, thus the UAV type technologies that require flying were not selected for the safety. Therefore, the two robotic camera technologies that are placed and used on the upper surface of the bridge were selected. The "Robotic camera indicating crack scale for bridge inspection" (Table 3 (B)) detected the deformation of diagonal member and upper chord of truss, and the "Camera system for bridge inspection" (Table 3 (C)) detected the deformation of lower chord, floor assembly members and RC slabs. At this field testing, the applicability of the two advanced technologies in the following four contents were confirmed:

(I) Application to bridges with complex structures,
(II) Detection of deformation such as corrosion and cracks on coating,
(III) Detection of falling off bolts and rivets etc.,
(IV) Application to the area in the river.

Firstly, (I) Application to bridges with complex structures was confirmed. The "Robotic camera indicating crack scale for bridge inspection" was set up on the bridge surface, and the arm with the camera was expanded upwards. Then it can reach to close to the target member and images were taken by remote control. The camera size is enough small to insert into complex parts in the truss, and it can obtain the images as shown in Figure 6. Also, the function to zoom up the images as shown in Figure 6 (b) makes it possible to detect deformations of steel bridges. This function can be used to obtain the images of the complicated structure such as the panel point as shown in Figure 7. The "Camera system for bridge inspection" was set up on the bridge surface as well. The arm with the high-resolution camera was moved along the bridge, and the arm and the camera were inserted into the gap between the diagonal members. By this technology, the images as shown in Figure 8 were obtained, and the deformation of the lower surface of the bridge can be detected. When considering using such an arm-type technology in a truss bridge, to reduce the work-time to insert the arm between the diagonal members is one of the important points to conduct an efficient inspection. In this field testing, the time from positioning on the bridge surface to completion of arm insertion under the girder was about 5 minutes, and the arm movement between the truss panels was about 12 minutes. It was thought that the work efficiency was good enough. Next, about (II) Detection of deformation such as corrosion and cracks in coating and (III) Detection of falling off bolts and rivets etc., were confirmed. In both technologies, it is possible to detect the defects such as corrosion, coating cracking and delaminated coating etc. as shown in Figure 6 and Figure 8. In addition, by using the zoom up function as shown in Figure 6 (b) and Figure 8 (b), a narrow area's corrosion such as corroded rivets can be detected

Figure 7. Panel point of truss bridge.

(a) Wide-area image. (b) Zoom up (narrow-area) image.

Figure 6. Images obtained by the *Robotic camera indicating crack scale for bridge inspection.*

with a precise image. Next, (IV) Application to the area in the river was confirmed. In the case of bridges which locates over the river, inspection scaffolds can only be placed during dry periods, when there is little rain, to avoid disturbing the river flows. Therefore, when utilizing those technologies, whether the inspection scaffolds are required is confirmed. Both technologies were utilized by placing on the bridge surface and the scaffolds were not required. Thus those technologies can be applied to the area in the river.

3.3 *Comparison of the diagnosis*

In order to verify the accuracy of soundness diagnosis based on the results obtained by advanced technologies, the soundness diagnosis results were compared with that based on a visual inspection by human inspectors. Table 5 shows the soundness classes which defined in the Guideline for Periodic Road Bridge Inspection (Road Bureau 2019b). In this comparison, the data which obtained from the truss bridge (Ibigawa Bridge) were used. As the advanced technology to obtain the data, the "Robotic camera indicating crack scale for bridge inspection" was selected. Based on the information obtained by this technology, the soundness was diagnosed for the superstructure such as diagonal member, vertical member, upper chord, lateral bracing, portal bracing and panel point. As a result of this diagnosis, the soundness of the target members were judged as II or III as shown in Table 6. Table 6 also shows the diagnosis result based on visual inspection which conducted at one year before this field testing. According to Table 6, the image quality which were obtained by the advanced technology and human inspectors were almost equivalent, and the soundness class diagnosis was the same. In addition, as for the types of detected damages for diagonal members, similar types of damage were detected. From those results, it can be said that the accuracy of the diagnosis based on the information obtained by the advanced technology has reached the same level as human inspectors.

4 CLARIFICATION OF PERFORMANCE REQUIREMENTS FOR ADVANCED TECHNOLOGY

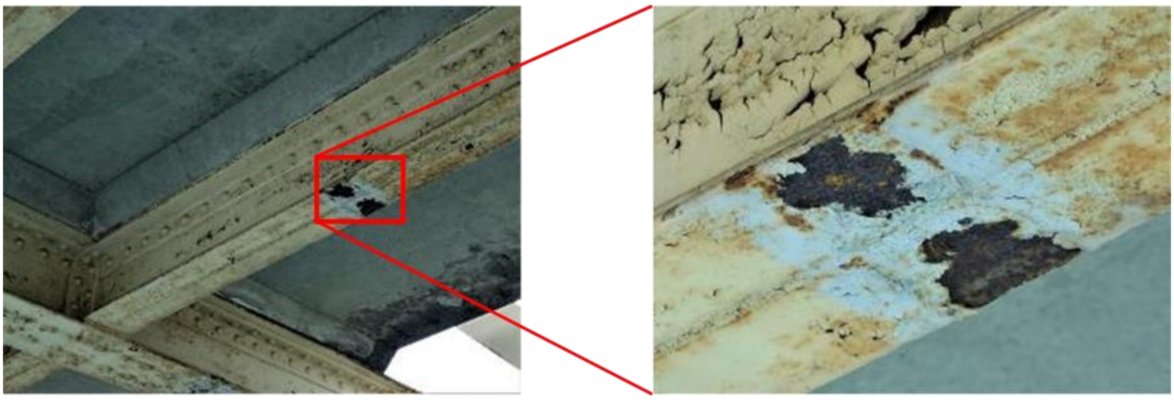
From the results of section 3, the performance requirements for advanced technologies when utilizing them into steel bridge inspection was defined. It was based on the performance requirements for them when utilizing in concrete bridge inspection which was defined in author's previous research (Hasuike et.al. 2018). Advanced technologies were required to enable judgment as to whether the soundness class of a member can be "II or higher", which requires follow-up observation or repair. When conducting inspections on steel bridges, to obtain the defects information regarding the five contents as shown in Table 1 is required. Therefore, the performance requirements for advanced technologies to detect each defect were clarified by systematizing the information which is needed to judge the soundness classes of each member of the bridge.

4.1 *Operability to narrow areas and approaching function*

In steel bridges, the defects are frequently occurring at narrow areas such as the cross points of members and the end of the girder. Therefore, it is necessary to approach such narrow areas in the inspections. At the two field testing which conducted in this study, the approaching function to access about 1 m × 2 m area for the girder bridge and about 1 m × 2 m area

Table 5. Soundness classification (Road Bureau 2019b).

Classification	
I	Good
II	Preventive maintenance
III	Early rehabilitation
IV	Emergency rehabilitation



(a) Wide-area image. (b) Zoom up (narrow-area) image.

Figure 8. Images obtained by the *Camera system for bridge inspection*.

Table 6. Comparison with the diagnosis based on visual inspection.

	Panel point	Diagonal member	Vertical member
Diagnosis based on information obtained by visual inspection	III	III	
			
Diagnosis based on information obtained by advanced technology	III	III	III
			

for the truss bridge is required. The structural designs of those bridges are not specific, hence it is thought that those requirements can be a criterion of the girder and truss bridges. For the arch bridges, it is thought that the almost same requirements for the truss bridges are required. In addition, because the truss and arch bridges have a lot of secondary members, the route to approach the inspection objective is limited more than the girder bridges. Therefore, high operability is required to inspect those types of bridges.

4.2 *Detection accuracy of corrosion*

In order to assess the deterioration of the corrosion, the following two types of information are important: as shown in Figure 6 (a) and Figure 8 (a), the wide-area information to understand the cause of the corrosion such as the deterioration of the coating, and as shown in Figure 6 (b) and Figure 8 (b), the narrow-area information to detect localized corrosion which can cause the downgrade of bridges. For instance, the deterioration of the coating is assessed by *the changing of the coating color*, *the occurring of the bumping in the local area* and *the occurring of the coating deterioration in wide-area by spot rusting* (Road Bureau 2019a) etc. Therefore, the wide-area information is required to understand the coatings conditions compared with the conditions around the target area. Regarding the localized corrosion, the obtained information will be used to judge whether to conduct additional measurements such as thickness reduction. Thus, the narrow-area information is required to detect the localized defects and understand those conditions.

4.3 *Detection accuracy of fatigue cracks*

The fatigue cracking typically initiates at points of stress concentration. In order to detect the fatigue crack, it is necessary to detect the small crack on coating. Therefore, the narrow-area information is required. In addition, to understand the downgrade caused by a fatigue crack, it is important to obtain the location of the defect. Thus, the wide-area information is also required. Regarding the crack on the coating, it is caused by not only fatigue, but also a deterioration or ageing of the coating. In order to confirm whether the crack is occurring, it is necessary to remove the coating and conduct an additional testing such as Magnetic-Particle Test (MT) etc. However, the advanced technologies which have been developed focus on to obtain the images. Therefore, the usage of those technologies is thought that to judge whether conducting the MT etc. based on the obtained images.

Although sufficient discussion is required in the future about the accuracy of advanced technology to detect crack on the coating, it is thought that 0.1 mm to 0.2 mm which is the accuracy requirement in a regular inspection by human inspectors (Road Bureau 2019a) can be defined as the criteria. Furthermore, the fracture can be detected if the technology can detect the cracks because the fracture is larger than the cracks.

4.4 *Detection of falling off bolts*

In the steel bridges, usually the high tensile bolts are used to connect the superstructures, and the bolts are used to connect attachments. To prevent accidents for humans, the loose and falling off bolts should be detected in the inspections. For this detection, it is required to obtain the images which can distinguish each bolt. Regarding the loose bolts, it is thought that to detect them by images is difficult. On the other hand, the advanced technologies with the hammering test function have been developed for concrete bridges (JST 2014b). Therefore, it is considered to use those technologies to detect the loose bolts on steel bridges. However, from the field testing of them on the concrete bridge (Hasuike et.al. 2019), it was shown that to beat a small member such as a bolt is difficult. For this reason, in order to detect loose bolts, further development of the advanced technologies with hammering test function is desired.

4.5 *Functions to obtain images in the dark place*

Various colors are used for coating steel bridges. In the dark-colored coating steel bridges, it is more difficult than concrete bridges to obtain enough brightness at the inspection works. Therefore, a function to compensate for the brightness with lighting etc. is required to obtain the accurate defects information.

4.6 *Proposal of performance requirements for the advanced technologies*

The performance requirements which were explained 4.1 to 4.5 were aggregated as shown in Table 7. The accuracy of the measuring function specified in Table 7 were determined to refer to Gifu Prefecture's Bridge Inspection Manual (Gifu Prefecture 2016), and the tolerances were determined to refer to the results of the field testing. The biggest difference with concrete bridges is the requirements for the functions to approach narrow areas depends on the type of bridge structure. Therefore, the operability of the advanced technology is clarified according to the target bridge type in Table7. Table 7 is based on the performance of the current technologies, and it is presented as an initial value when examining the criteria in steel bridges for the future.

Table 7. Performance requirements for the advanced technology.

Requirements			Verification
Operability	Girder/ Box girder	The technology can freely pass through an area around 1m×2m vertically.	Conducting a field test on actual bridges or structural model bridges.
	Deck bridge	The technology can freely pass through an area about 3m×5m vertically and horizontally. (In truss bridge etc.)	
	Through bridge	The technology can freely pass through an area about 3m×5m vertically and horizontally.Also, it can reduce the closing lane time. (In truss bridge etc.)	
Detection of defect	Presence and type	Defect can be detected and classified.	Pictures and sketches ofdefect are provided to confirm the requirements in the left column. The locations, ranges and directions of defect shown in the provided pictures and sketches are roughly in agreement with those in the defect chart prepared by visual inspection from a short distance.
	Location	Defect can be detected in a manner to allow sketching of defected portions in relation to other members.	
	Size	The overall image can be obtained to judge whether the defect is localized or extensive.	
	Direction and pattern	The d irection (horizontal, vertical, diagonal, longitudinal or transverse to reinforcement, etc.) and pattern (map cracking, etc.) of defect can be detected.	
	Water penetration paths	The source and path of water ingress can be detected regarding defects involving water, such as corrosion and deterioration of the paint.	
Measurement of defect	Size	The deformations can be measured with an error margin of ± 10mm.	The measurement results of defect described in the defect chart prepared by visual inspection from a short distance or artificially created accuracy verification marks are roughly within the tolerances shown in the left column.
		The defects can be measured with an error margin of ± 50mm.	
	Displacement	The displacements of expansion gaps and bearings can be measured with an error margin of 10 mm.	

5 CONCLUSION

This paper described the differences between concrete and steel bridge inspections, the results of field testing on two types of steel bridges by advanced technologies, and proposed the performance requirements for the advanced technologies based on the field testing. The conclusions are as follow:

(1) Based on the results of field testing on the steel bridges, it was shown that the advanced technologies can approach the narrow space such as the inside of girders or the gaps in the truss bridges. In addition, they can obtain the images which have enough accuracy to be used to judge the soundness class.

(2) The performance requirements for the advanced technologies when adopting them into steel bridge inspections were proposed. It is required to obtain the wide-area information to detect the factors of corrosion, and the narrow-area information to detect the crack on the coating etc. Furthermore, as the specific requirements for steel bridges, the operability to narrow areas and approaching function for each structural design of the bridge were clarified.

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