Doctoral Thesis

Utilization of Advanced Inspection Technologies and Image Processing into Bridge Maintenance

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Abstracts

Infrastructure projects refer to critical civil structures ranging across bridges, roads, tunnels and so on. Nowadays, many of these civil structures are encountering severe ageing issues. In order to ensure the structural safety and functionality, it is crucial that routine monitoring, maintenance and repair of these structures should be conducted according to the standards. In Japan, road bridges are required to be inspected in every 5 years by human inspectors, who need to carry inspection equipment, gauge the crack scales, and compare with the benchmarking card to obtain the defects information. This manner is also known as a visual inspection. There are problems, for example, reporting efficiency, safety and road blockage issues, etc.. Nowadays, advanced technologies emerge and start to offer great efficiency, productivity and accuracy improvement to human inspection methods. The three challenges upon which this thesis is based involve: first, the advanced technology abilities are not well-known; second, the utilizing methods of the advanced technology are unclear; and third, the effectively assess methods of the defects detected by the advanced technologies are not available. My PhD work aims to address these three challenges via three steps: first, the research for inventing and utilizing advanced technologies will be reviewed, summarised and classified to identify the ability of those technologies; second, a methodology that can enable to integrate the inspection by the advanced technologies and by the human inspectors will be researched and proposed; and lastly, an innovative deep learning classifier that can effectively identify deterioration patterns of rust from raw images will be formulated. During my PhD study, the above three objectives are achieved. To illustrate: first, a literature review of the research related to bridge inspection is conducted. As a result, many kinds of technologies had enough ability to support the visual inspection by human inspectors.; Second, a guideline which shows the integration methodology of the advanced technologies and human inspectors is proposed based on the two-step investigations: the first step is a preliminary inspection by the advanced technology; and the second step is a visual inspection by human inspectors. Also, the inspection is conducted on a long-span concrete bridge based on the proposed guideline. As the results, the defects information obtained by the preliminary inspection enabled that to reduce the risk of overlooking and the working time of human inspectors in the visual inspection.; Finally, the image processing for classifying the images of corroded steel is conducted. The deep learning classifier, e.g., Convolutional Neural Network (CNN) classifier, is innovated based on the images obtained by the corrosion test. As a result, the classifying prediction accuracy of innovated CNN classifier is 86.7 %.

***Keywords**: Bridge maintenance, advanced technology, image processing*

Chapter 1

Introduction

1.1 Background

Infrastructure projects range across critical civil structures such as bridges, roads and tunnels. Nowadays, many of these infrastructure projects are having serious aging issues. For instance, the number of road bridges in Japan is approximately 720 thousand and almost 50% have been used over 40 years (**Figure1.1**) [1]. Furthermore, as shown in **Figure 1.1**, the number of road bridges which is managed by local municipalities such as prefecture and city, is approximately half a million [1]. In order to ensure these structures are used safety, the maintenance of them is important. In particular, to understand the conditions and identify the structure issue of infrastructures, the timely inspection and repair works are crucial. If these problems cannot be promptly identified, use of these aging bridges would eventually incur fatal structure failures such as collapse. It is therefore understood that constant structure inspections with precise understanding on structure problems are critical to assure the safety and functional performance of these assets.

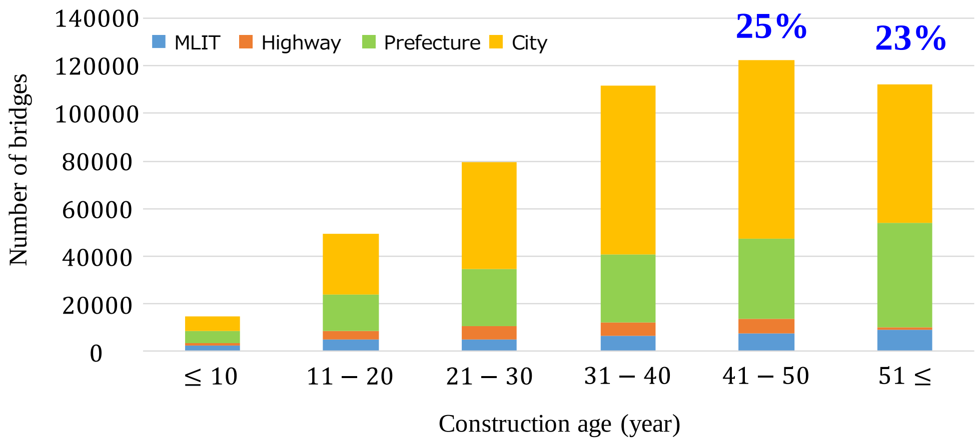


Figure 1.1 Construction ages of bridges in Japan [1]

Under this situation, this thesis focused on the road bridges, and hereafter, the word of bridge means road bridge. In order to maintain the bridges, the bridge inspection is mandated in every 5 years time, there has to be at least one visual inspection by close distance has been conducted since 2014 based on the Ordinance for Enforcement of Road Act [2]. **Figure 1.2** shows the main procedure of bridge inspection by human inspectors as defined at the Bridge Inspection Manual [3]. In the first step, visual inspection is conducted and the information which includes the types and locations of defects are collected. In the visual inspection, the appearances such as cracks and corrosion etc. are checked, the hammering test is conducted to detect voids or delamination of surface, and sometimes the non-destructive evaluation (NDE) methods are used to obtain the additional information. In the second step, inspection reports are written based on the information obtained from the first step. In this report, the defects and those locations are recorded with sketch or/and images taken by a camera. Finally, based on the report written in the second step, the soundness as shown in **Table 1.1** [3] are diagnosed by engineers in the third step. As shown in **Table 1.1**, if the soundness class is higher than II, the bridge requires to take any actions such as prevention, repair, and intensified inspection etc. The diagnosis of the soundness is conducted for each member of the bridge, then the soundness for the whole of the bridge is diagnosed based on the results of each member. Regarding the visual inspection by human inspectors, there are some issues as follows. In the first step, the safety of inspectors is not ensured because they are required to work at height place, the inspection can be quite time-consuming especially in large and complex bridge structures, and traffic restriction is needed while inspection. The second and third steps are also time-consuming, and the diagnosis is not objective because it depends on the experience of the engineer. To overcome these issues, the utilization of advanced technology should be considered. In this thesis, the advanced technology means Unmanned Aerial Vehicle (UAV)/ Unmanned Aerial System(UAS)/ drone, robotic camera, and image processing, etc. Nowadays, many kinds of advanced technology for bridge inspection have been developed, and some trials to utilize them have been conducted [4]. However, adopting those technologies into bridge inspection has not been progressed.

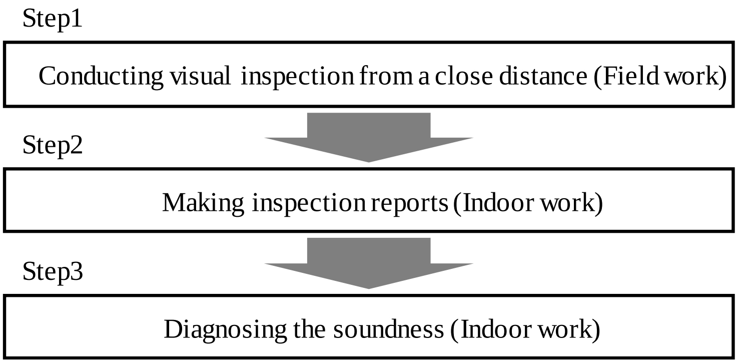


Figure 1.2 Procedure of bridge inspection

Table 1.1 Soundness classification [3]

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

In addition, when considering the maintenance of bridges, the prediction of deterioration is important. **Figure 1.3** shows an example of the deterioration curve and the effect of repair work [5]. In this figure, the vertical axis is soundness classification and the horizontal axis is construction age. The blue curve line means deterioration curve, and if any maintenance does not conduct for this bridge, the soundness will reach IV at the age of X. If the service life is defined as the year when soundness class is reached IV, the service life of this bridge is X years. In contrast, if the soundness class is judged as III at the periodic inspection B, this bridge can be repaired. Therefore, the deterioration curve will restart from the soundness class I as shown in the green curve line. Thus, the service life of this bridge is extended. The deterioration curve is one of the general prediction methods of bridge deterioration, and this method based on construction age and soundness classification as shown in **Figure 1.1** and **Table 1.1**. Therefore, an efficient and objective way to diagnose the soundness class is important. As mentioned above, the soundness class is diagnosed by human inspectors. In order to support the diagnosis by inspectors, the utilization of advanced technology is considered as follow: to use those technologies for detecting serious damages which affect to the soundness classification, or for classifying the soundness class automatically. For both of them, the utilization of the defect's images and image processing techniques are thought that one of the effective way. Furthermore, it is expected that to obtain high-quality images, which contains detailed information, become easier if the inspection is conducted by the advanced technology instead of human inspectors. The high-quality in this thesis means the images have high resolution and do not have many noises, etc.. Regarding the utilization of image processing techniques into bridge maintenance, some researches have been conducting [6]-[12]. Those researches show the effectiveness of image processing, i.e., to identify the cracks on a concrete surface or the changing of weathering steel surface etc. Therefore, it is expected to conduct the automatic classifying method by taking advantage of those image processing techniques.

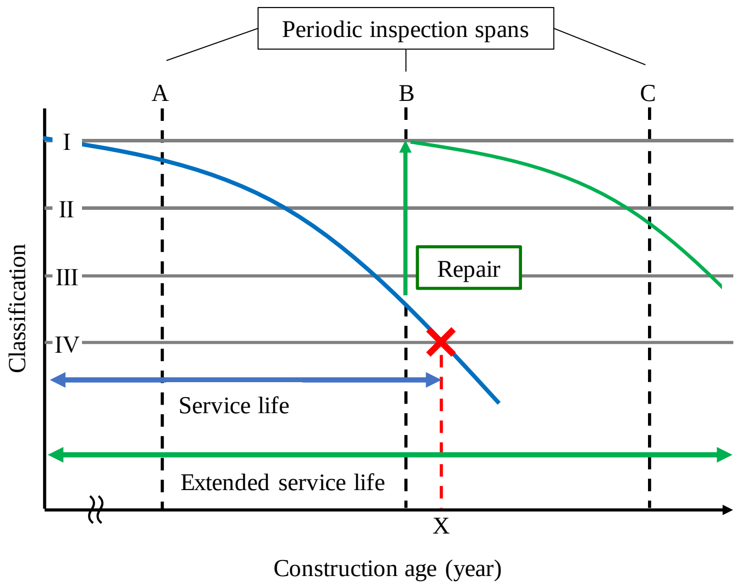


Figure 1.3 An example of deterioration curve [5]

1.2 Aims of This Thesis

Infrastructure maintenance is expected to be more and more important in the future. Nowadays, advanced technologies emerge and start to offer great efficiency, productivity and accuracy improvement to human inspection methods. There are the three challenges upon which this thesis is based involve:

I. The advanced technology abilities are not well-known.
II. The utilizing methods of advanced technology are unclear.
III. The effective assessment methods of the defects detected by the advanced technologies are not available.

This thesis aims to address these three challenges via three steps:

(1) The research for inventing and utilizing advanced technologies will be reviewed, summarised and classified to identify the ability of those technologies.
(2) A methodology that enables to integrate the inspection by the advanced technologies and by the human inspectors will be researched and proposed.
(3) An innovative deep learning classifier that can effectively identify deterioration patterns of rust from raw images will be formulated.

1.3 Outline of this Thesis

This thesis has four main chapters, Chapters 2 to 5. Outlines of all chapters are shown below (**Figure 1.4**).

Chapter 1 showed the background and aims of this thesis. In this thesis, in order to formulate an efficient method of utilizing advanced technology for bridge maintenance, a literature review, questionnaire-based surveys and one-on-one interviews were conducted. Also, a guideline which shows the integration methodology of the advanced technologies and human inspectors is proposed based on the two-step investigations. Furthermore, image processing for classifying the images of corroded steel is conducted.

Chapter 2 reviews the state-of-the-art technologies that have been used in bridge inspection and identifies the ability of those technologies. The main concerns about applying novel technologies into the bridge inspection field are inspection quality (i.e. assessment accuracy), fieldwork efficiency and inspectors safety. Regarding the inspection quality, the inspection by advanced technologies reached the same or higher quality of that by human inspectors. As to use the technology for supporting human inspectors, there are benefits of utilizing advanced technologies. Also, many of the research is focusing on inventing new technologies to detect concrete cracks, rather than steel structure corrosion and fatigue.

Chapter 3 reports the implementation of questionnaire-based surveys and one-to-one interviews. It was conducted to identify the most effective way to adopt advanced technologies into bridge maintenance. The surveys and interviews targeting governance and local municipalities, technology inventors, contractors and overseas engineers were conducted. This hybrid portfolio of survey subjects and interviewees can provide differences and relations of opinions from each survey subject. The solutions for the applicability issues were revealed that it was for the manuals to specify certain advanced technologies. As this solution is difficult to implement, the alternative ways were suggested, which *include providing adoption examples*, *creating an evaluation system for advanced technologies* and *establishing standards and guidelines by academic societies*.

Chapter 4 proposes a two-step investigation guideline, with which the procedures of implementing the advanced technologies in bridge inspection are clarified. The first step is a preliminary inspection, which is conducted by the advanced technology, and the second step is a visual inspection from a close distance by human inspectors. The second step is carried out over the entire bridge based on the preliminary inspection's results. Also, performance requirements for advanced technology were defined, and the functions and performance of advanced technology were verified in comparison with conventional visual inspection techniques. Advanced technologies are 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. With the proposed guideline, an inspection is conducted by six types of technologies on the Kakamigahara Bridge (prestressed concrete bridge). As a result of the two-step investigations, it can reduce the number of days required for the visual inspection. It was shown that to propose the two-step guideline is one of the efficient ways to adopt advanced technology for bridge inspection. In addition, the invented technologies already have enough performance to support visual inspection.

Chapter 5 aims to assess the steel deterioration through the images, which is the obtained data by the advanced technologies the corrosion tests and image classification by Convolutional Neural Network (CNN) analysis were conducted. From the corrosion tests results, there was a relationship between the exterior appearance and the gained weight of the corroded steel specimens. Therefore, the classification was conducted based on the gained weight of the specimens. CNN analysis was conducted by VGG19 classifier. Regarding the input datasets, the dataset contained the images obtained from different environments had the highest accuracy. The prediction accuracy achieved 86.7%, thus, formulating the classifier by the images obtained from different environments based on the gained weight was one of the high accuracy assessing methods.

Chapter 6 congregates the main findings of each chapter and proposes an efficient method of utilizing advanced technology for bridge maintenance.

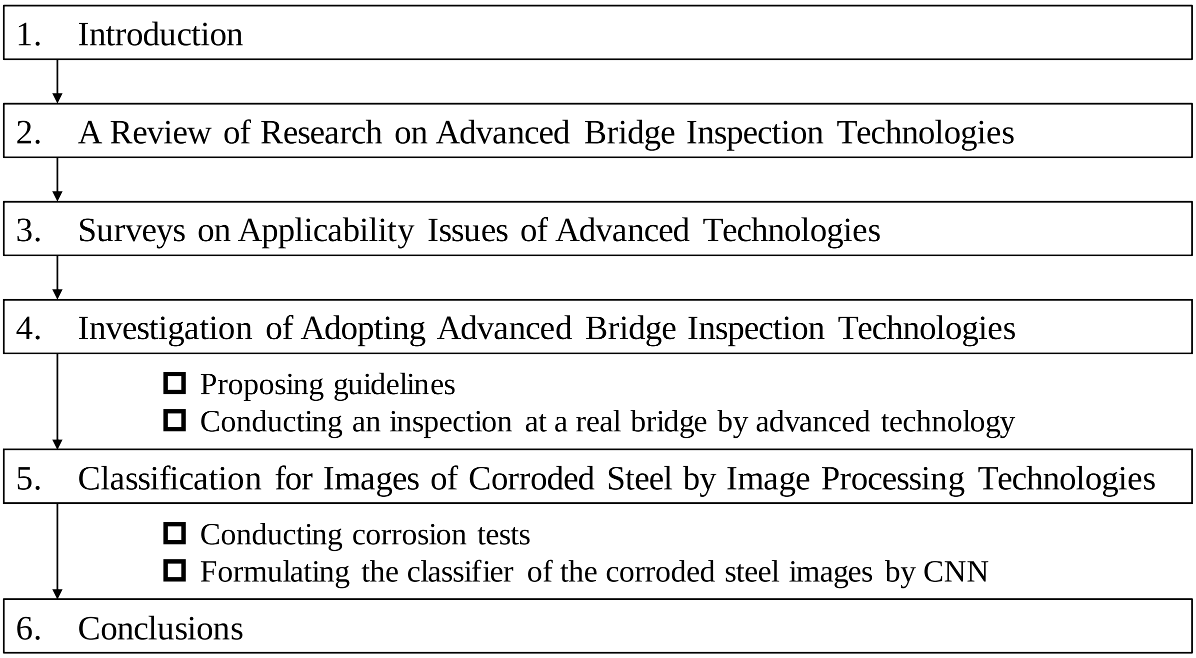


Figure 1.4 Flow of this thesis

Chapter 2

A Review of Research on Advanced Bridge Inspection Technologies

2.1 Overview

Many road bridges have serious ageing issues, and therefore, timely inspection and repair works are crucial to ensure they are safe to use. A bridge has to be designed to meet the structural requirements, which involve load, vibration, weather and many other design codes. However, the lack of appropriate inspections and shortage of repairing the damages which caused by the ageing or some unexpected load such as earthquake could lead to a down-graded condition level of the structure.

In order to prevent such downgrades, periodic inspection of bridges is a common practice around the world. For instance, in the United States (U.S), bridge inspection is mandated by the U.S. Department of Transportation [13]. The National Bridge Inspection Standards (NBIS) are Federal regulations establishing requirements for inspection procedures, frequency of inspections, qualifications of personnel etc. [14].According to the NBIS, inspect each bridge at regular intervals not to exceed 24 months [14]. In Australia, Part 7 of the Austroads Guide to Bridge Technology (AGBT) was published in 2009. In the AGBT, it is mandated that Level 2 inspections, which serve to assess the condition of structural components, are conducted at two to five-year intervals [15]. In Japan, the periodic inspection is mandated in every five-year time, there has to be at least one inspection by human inspectors from close distance. This inspection has been conducted since 2014 based on Ordinance for Enforcement of Road Act [3]. In practice, bridge inspections in those countries are typically conducted primarily by human inspectors. However, the downside of visual inspection is apparent as follow: first, conducting visual inspections can be quite time-consuming, especially in large and complex bridge structures; second, this method cannot well address occupational health and safety issues such as working at height; third, the inspection cost is expensive.

Under this background, the research topics of applying advanced technology to assist human inspectors have gained much attention in recent years. For example, in Japan, many kinds of advanced technology for bridge inspection have been invented and some trials conducted at existing bridges in order to obtain the information of defects [16]. The research not only obtaining the information, but also analysing the information have been conducted by image processing [6] etc.. As the actions for accelerating the research of such advanced technologies by Cabinet Office, Government of Japan, 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 from 2014 to 2018 [17]. In this project, many kinds of new advanced technology were invented and tested.

This chapter reviews the state-of-the-art technologies that have been used in bridge inspection and identifies the ability of those technologies. Methodically, this chapter had examined the publications over the past 20 years, i.e., from 1999 to 2018, and leveraged the tool of CiteSpace to derive significant review findings including to use those advanced technologies for bridge inspection and to improve the safety of inspectors.

2.2 Review Method

In order to find out the current research on applying advanced technology into bridge inspection in recent years, the search of articles was implemented based upon a web system named Web of Science (WoS). In this chapter, the search code of TS, a.k.a. topics, was set as “bridge inspection”. Furthermore, the scope of the search was set to be between 1999 and 2018 to identify changes in heated research areas. As a result, 419 articles were identified: a total number of 90 between 1999 and 2008; a total number of 21 between 2009 and 2013; a total number of 208 between 2014 and 2018 (**Figure 2.1**). The increased amount of publications over the last two decades indicates that not only inventing the advanced technology but also utilizing them into bridge inspection has become a heated research topic. The research topic includes some themes, for example, inventing and utilizing UAV/UAS, non-destructive testing (NDT) and damage detecting by image processing, etc..

Subsequently, CiteSpace 5.5.R2, which is an application for visualizing and analyzing trends and patterns in scientific literature [18], was used to find research hotspots and analysed the relations of research by conducting co-citation network analysis. Based on the result of this analysis, the best practice of current technological approaches and the details of researches were clarified.

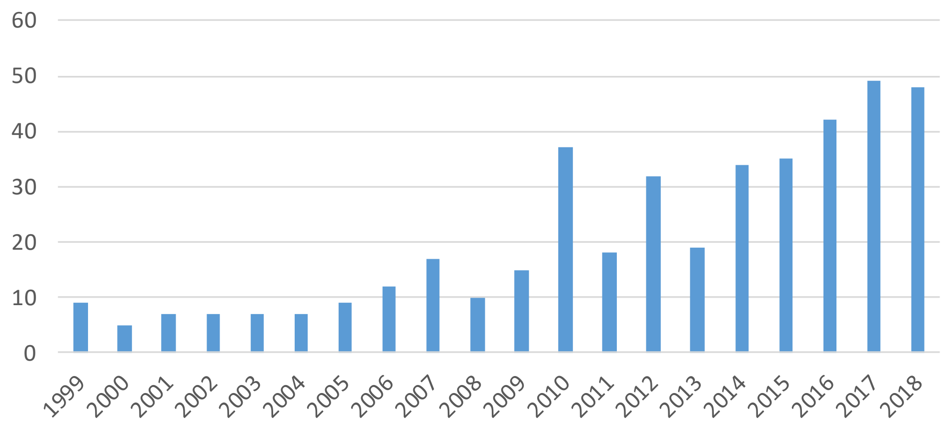


Figure 2.1 Number of articles published between 1999 to 2018

2.3 Analysis of the Knowledge Domains and Key Clusters

Figure 2.2 shows the result of co-citation analysis and labelling clusters with title terms. In this analysis, a document co-citation network that contains 252 nodes and 819 links were generated. The modularity Q and the mean silhouette scores are two important metrics that can tell about the overall structural properties of the network [18]. The modularity Q measures the extent to which a network can be divided into independent blocks, i.e., modules [19]-[21]. The modularity score ranges from 0 to 1, and a high modularity may imply a well-structured network [20]. The silhouette value of a cluster, ranging from -1 to1, indicates the uncertainty that one needs to take into account when interpreting the nature of the cluster and the value of 1 represents a perfect separation from other clusters [20]. In this analysis, the modularity Q was 0.78 which means the network is reasonably divided into loosely coupled clusters. The mean silhouette score of 0.46 suggests that the homogeneity of these clusters on average is not very high, but not very low either. According to the network, the articles were divided into 49 clusters by title terms, and some large clusters were shown in **Figure 2.2**. Clusters are shown with "#" and the numbers and the size of words mean the cluster's scale. These significant clusters identified that the highlighted research area in "bridge inspection" researches. As shown in **Figure 2.2**, the clusters show some advanced technologies such as #0 unmanned aerial system, #1 defect detection, #2 unmanned aerial vehicle application, #3 infrared thermography and so on. The dots which named nodes in **Figure 2.2** means articles in the clusters, and the size means citation of the articles, i.e., the larger the size of nodes, the more citation of the articles. The lines between nodes mean citation at the connected node. **Figure 2.3** shows the clusters and citations in the timeline view. As shown in **Figure 2.3**, some articles are cited from articles in other clusters. It can be thought that the researches in "bridge inspection" area are conducted not only independently but also in combination.

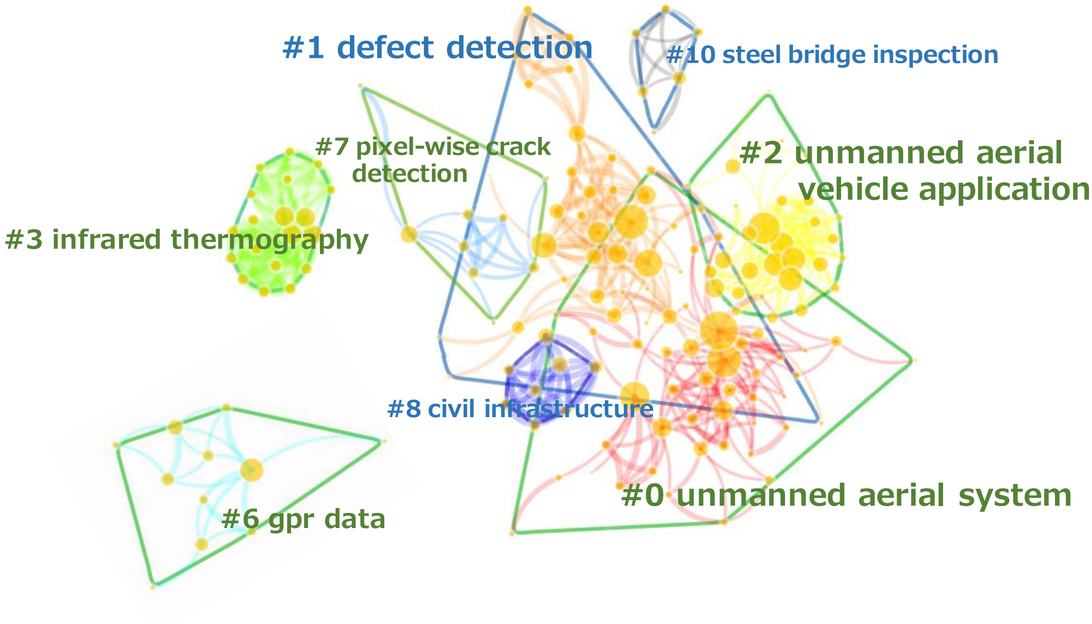


Figure 2.2 An overview of the co-citation network

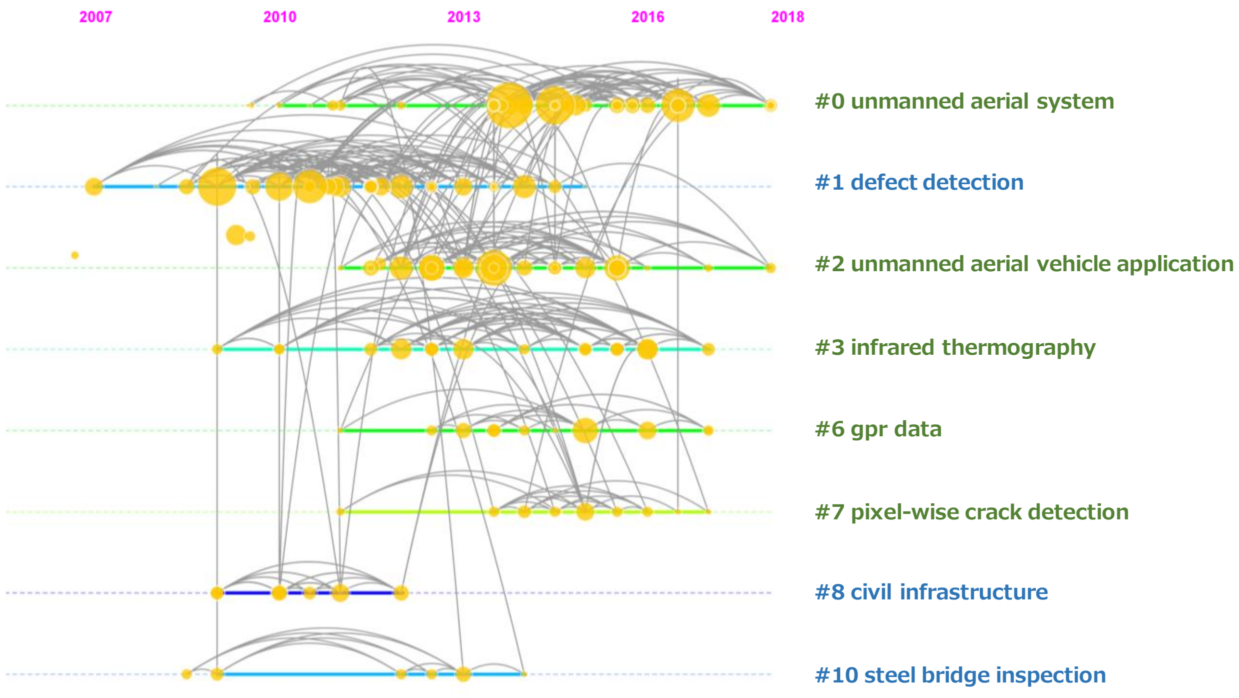


Figure 2.3 Clusters and citations in timeline view

Both of cluster #0 and #2 indicated about the unmanned aerial system (UAS) and unmanned aerial vehicle (UAV), which include inventing a new UAS/UAV, enhancing an existing UAS/UAV's performance, proposing the efficient flight path and suggesting utilizing ways. Regarding to utilize UAS/UAV, keeping stable while the flights is one of the biggest requirement for obtaining data in high quality. In order to clear this requirement, many kinds of UAS/UAV have been invented or the existing UAV/UAS have been enhanced, then they were compared in some test places [4],[22]-[24]. For instance, Khaloo et al. shows the data-driven approach for designing the UAV platform and acquisition of 2D digital images in conjunction with a modern 3D scene reconstruction technique [22]. In this study, the UAV played a role to take images the exterior of the truss and the underside of bridge where is the LIDAR cannot work well. In those research, the UAV/UAS carry consumer-grade digital camera as inspection payload, so the main data obtained by UAV/UAS were images. About the obtained images, a crack detection method has been established by using image processing, deep learning and so on [25]-[28]. In addition, not only detecting the crack but also creating 3D models by images or using laser scanning is getting attention [22]-[25]. On the other hand, the issues to get a stable flight in severe conditions, i.e., in a GPS-denied environment [23],[29], and in unfavorable weather conditions such as rain and windy [26],[30] are also clarified in those studies. Regarding to apply UAS/UAV and drones into bridge inspection, a survey was conducted in the U.S. by Duque et al. [31]. According to this survey for Departments of Transportation (DOTs), one state had used a drone for bridge inspection and six DOTs were planning to use drones in the near future. As shown in this survey, interest in utilizing drones becomes increasing.

Cluster #1 focusses on defect detection. The defects include cracks, rebar corrosion, and other many types of defects. In this research area, concrete crack detection is one of the most highlighted areas [23],[25],[32]. There are two main detection methods, one based on images [23],[25],[32] and the other based on point cloud data [33],[34]. The deep learning technology is used in each. In terms of using deep learning for image-based crack detection, Dorafshan et al. [32] compared the performance of common edge detectors and deep convolutional neural networks (DCNN) in concrete structures, and it showed that the method used DCNN was better than the common one. Fan et al. [35] proposed a crack detection algorithm based on the mesoscale geometric features to effectively distinguish cracks and false cracks. Huthwohl & Brilakis [34] presented a method to automatically identify regions of interest in order to reduce the inspection space to areas which can subsequently be inspected by a human engineer or by an automated defect classifier. Those crack detection methods mainly target to concrete, but fatigue crack in steel has been targeted as well [23]. Moreover, a new technique which possesses the ability to extract dynamic bridge properties from the responses of a vehicle that passes over the bridge at high speed was introduced [36], and to detect rebar corrosion in concrete structure by using ground-penetrating radar (GPR) has been used [37]. Thus, the researches about defect detection have been conducted from many kinds of approach.

Cluster #3 mentions infrared thermography which has been used to bridge inspections. Hiasa et al. [38]-[40] evaluated the accuracy and reliability of infrared thermography (IRT) for high-speed applications to detect concrete delamination. This technology does not require the closing lane, and the test result showed high accurate damage detection. On the other hand, it is considered that to combine IRT and other technologies such as

UAS/UAV or GPR [41],[42]. Abu Dabous et al. [41] introduced an integrated method utilizing IRT and GPR technologies to enhance the detection of concrete bridge defects.

2.4 The Best Practice and Problem

In order to propose more effective inspection method, these technologies are developed not only independently but also in combination, e.g. to obtain data by using UAS/UAV and to analyse those data by using image processing [25],[26]. From those research, it can be said that combining techniques is one of the best practice for efficient bridge inspection. On the other hand, to reduce the negative effect for users of bridges, reduction of traffic control have been desired. In the conventional inspection, the method requires traffic control because the inspectors need to be in close distance with defects to identify and evaluate them. In order to solve this problems, research on using NDE which does not require traffic control is actively implemented [36] as explained in **2.3**. It can be said that the NDE technique is one of the best practice as well.

Focusing on the subject of those technologies, many technologies and researches target concrete bridges, and there is a tendency that many kinds of research focused on cracks among damage. It is assumed that cracks in concrete are selected as the damage easy to detect and check by using image processing or deep learning technology, as the first step of using those technologies for bridge inspections. Subsequently, in addition to cracks, other types of damage have been attempted to be detected as well, e.g. delamination and spalling of the concrete deck. Thus, it can be seen that the development of defect detection technologies for concrete bridges is actively promoted. However, advanced technologies for steels, such as detection of corrosion which formed on steel bridges or rebar in reinforced concrete [37], and detection of fatigue cracks on steel bridges [23] are fewer than those technologies for concrete. It is one of the problems of development of those advanced technologies. Considering a large amount of steel which used in bridges, it can be said that further researches of advanced technology about steel is strongly desired in the future.

In many kinds of research, the main purposes are to objectively evaluate the damage, increase the efficiency of fieldwork, and ensure the safety of inspection work. These purposes have been achieved by the currently developed technology. However, when adopting these technologies to an existing bridge's inspection, it is difficult because of the limitation by the law about inspection [3]. Also, the utilization of them is only as a support for inspectors at this time. As technology development and its verification progress, it is desired to ensure safety when using those technologies and to draft the law about using advanced technologies for bridge inspection. Under such situations, as an indication for future researches to adopt advanced technology into bridge inspection, it can be said that the following certification or evaluation are desired; (1) objective evaluation of technology performance (e.g. specification of crack detection limit size and application condition); (2) certification of the safety on the structure evaluated by the technology (e.g. verification by comparison with the evaluation by conventional methods); (3) certification of the safety when using the technologies. If they are not proved, it will be difficult to draft the law about using advanced technologies or to mandate using those technologies in the law. With regard to (1) and (2), evaluations are in progress by each technology developer, e.g. by comparison with existing methods. One of the criteria for evaluating technology is thought that to satisfy specific numerical values based on the bridge inspection guidelines established by the local municipalities that manage the target bridge. Therefore, further technical development is expected by defining and publishing the required performance when each local municipalities use advanced technology. With regard to (3), it is a particularly legally sensitive part, for example in the U.S. and Japan, there are strictly flight safety restrictions for UAV [43],[44]. To clear those requirements, the research which improves the stability of the UAV and simplifies the operation has been conducted. Some NDEs, including IRT and GPR, have also been developed that can implement the inspection without traffic control, and it is suggested that those technologies can overcome those limitations of the law. In order to accelerate the adoption of advanced technology, it is desired for each country to draft a law on the adoption of those techniques to bridge inspection. In Japan, the Guideline for Periodic Road Bridge Inspection was revised in March 2019, and the order about visual inspection has been relaxed [45]. It is expected that further technological development and introduction will be promoted.

2.5 Summary

In this chapter, a literature review was conducted with a focus being placed around identifying the best practice of current technological approaches and proposing the futuristic research directions for technological refinement and improvement. The results are summarized as follows.

(1) The researches related to UAV are the most frequent. Those researches are being carried out on hardware such as the development of the UAV and enhancement of commercial UAV, and software such as the proposal of flight routes for efficient information acquisition. Test flights on existing bridges are also being conducted. It is pointed out for problems which include flight during bad weather, loss of image quality, and stable flight under non-GPS environment.

(2) The researches related to defect detection technology, high precision detection has become possible, such as using image processing and deep learning. Many kinds of research have been conducted on the subject of concrete crack detection. In addition, researches using NDE for other damage such as delamination of concrete are also increasing. There are still few numbers of research concerning rebar in concrete, fatigue cracks and corrosion in steel bridges, etc., and further studies are desired.

(3) Research on NDE technology such as IR and GPR are also in progress. These technologies greatly increase the possibility of conducting inspections without traffic controls.

(4) With the development of various technologies, when considering to adopt into the inspection of existing bridges, the adoption might be difficult due to legal restrictions. It is desired to draft the law after ensuring the accuracy and safety of each technology.

Chapter 3

Surveys on Applicability Issues of Advanced Technologies

3.1 Overview

As discussed in Chapter **2**, in the last decade, many kinds of advanced technologies have been invented for inspecting infrastructure. Nevertheless, there has not been a significantly increased number of publications in reference to the use cases of those advanced technologies. It is likely that utilizing these advanced technologies in infrastructure inspection has some limitations in application.

To understand these applicability issues, the researcher surveyed a number of workers and engineers who have been significantly engaging in technology inventing, application and policy-making. This survey targeted contractors, subcontractors, governmental officials, researchers, and so on and was based on distributed questionnaires and one-on-one interviews. This chapter presents the survey findings.

3.2 Related Research about this Survey

So far, many kinds of technologies for constructing infrastructures had been invented and used. For instance, the tunnel boring machine is one of the technologies which became a common technology. In the invention of those construction technologies, it is assumed that the similar applicability issues occurred and the research aims to clarify the applicability issues and the solutions were conducted at that time.

In 1985, Hinoshita [46] looked into the state-of-the-art technologies for construction site including a shield machine for a tunnel, concrete spraying machine, and automatically jackhammer etc.. A statement of summarized limitations was also provided out of their research which incorporates as follow; technical issues such as *mass production is difficult because the target environment is diverse*, costly issues such as *less of versatility*, *due to severe environmental conditions*, *the meter becomes high price* and systematic issues such as *few achievements in cooperation with technical groups in other fields*. In 1986, Obayashi [47] revealed that apart from the limitations from the technological perspective, social problems are likely to handicap the use of technologies as well. These technologies would have eventually been developed to deal with various construction works that are typically implemented by the human workforce. Therefore, a growing worry is the technology replacement of human beings in the typical construction sector. To effectively manage these issues, social and ethical aspects are urged to be well considered. In fact, technologies can lead to productivity gains. If used properly, technologies can also address workforce health and safety issues such as fall from a height, heat stress, crush by machines, chemical contamination, and so on. Hamada et al. [48] pointed out project success attributive to innovative technology usage is critical to any organisation that is facing opportunities and uncertainties brought up by technologies; and sometimes technology use can jeopardise competitive bidding and increase the contract price, despite this would not always be the case. A questionnaire survey on 37 technology development entities revealed that to counterbalance technology uncertainty, incentives such as financial compensation and risk transfer can be considered as effective measures to encourage more industries to use innovative technologies. Likewise, the reduction of burdens on preparing paper works by simplifying the work of the person in charge of ordering.

Asakawa et al. [49] stated some applicability issues; innovative technologies used for infrastructure project maintenance could be costly and lack versatility in terms of utilization because they are developed for specific applications. In order to overcome those applicability issues, the viable solution could be mandating technology use and reduction of the costs. As a solution, the New Technology Information System (NETIS) has been run by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) since 2006 [50]. NETIS is a database in order to inform the information about state-of-the-art technologies. The technologies registered for NETIS cleared the requirement by MLIT. Therefore that information can assist the decision to use the technologies. It has been mainly used for public works conducted by MLIT. Other applicability issues could be projecting success attributive to innovative technology usage and questionable technological reliability, as evidenced by the survey by MLIT [51]. MLIT has adopted a comprehensive evaluation bidding system from 2008, which evaluate not only the costs but also the technological advantages. However, this has been adopted only in public works, which may not effectively improve the situation across the entire industry.

From this review, the questionnaire survey is though that one of the effective ways to clarify the applicability issues. Also, there was no research which conducted the survey for different occupations workers with the same questions. Therefore, the survey subjects were decided to four types of occupations, and the survey method in this research was decided to take two-step: the first step is to conduct questionnaire surveys, and the second step is to conduct one-on-one interviews.

3.3 Survey Subjects and Survey Method

3.3.1 Profile of the Survey Subjects

In Japan, maintenance of road bridges must comply with the Road Act [2]. Under this Act, there are exhaustive technical details that have been stipulated in several technical specifications such as Bridge Inspection Manual [3] and Guideline for Periodic Road Bridge Inspection [52]. **Figure 3.1** shows three types of bridges that are typically managed by different governmental authorities [53]. Two typical working modes for bridge inspection are demonstrated in **Figure 3.2**. Those modes are that either governmental authorities conduct the work independently or outsource to third party services such as consulting firms and contractors. In addition, technology inventers, namely, tech companies, universities and research organizations, play an important role in formulating and applying advanced technologies in inspection works. Therefore, their opinions and advice should be captured in our survey. As stated in **Table 3.1**, technology inventors were included.

As shown in **Table 3.1**, the survey targeted two groups, namely, the domestic (Japan) group and the overseas group. The domestic group involved 30 governmental officials (also known as clients of the bridges), 36 technology inventers, 18 consultants and contractors/subcontractors; the overseas group involved 13 governmental officials. The government officials in the domestic group consisted of MLIT officials and prefectural/municipal governmental officials. *Contractors/subcontractors* were those who work in engineering firms such as bridge inspectors and maintenance workers.

Since 2008, Gifu University has been continuing to upskill governmental officials, engineering consultants, contractors and subcontractors. They can also be accredited by Gifu University as Maintenance Experts (ME) if all the training requirements are met [54]. The ME program educates them the skills of conducting maintenance tasks on steel bridges, concrete bridges, culverts and tunnels. The form of learning includes on-campus lectures and off-campus on-site training and typically lasts for four weeks. At present, the number of ME-qualified personnel is over 350. As professional opinions from these ME-qualified practitioners can provide unique insights and authority to our study, our survey intentionally targeted a few ME-qualified practitioners as well.

Gifu University has partnered with an institution named Japan International Cooperation Agency (JICA) [55], which is an institution that strives for promoting international cooperation as well as the development of Japanese and global economy by supporting the socioeconomic development, recovery or economic stability of developing regions. A JICA program titled *Implementation of Special Road Asset Management Program* has been established and partnering with Japanese universities since April 2018. For instance, there have been nine people that are from the countries including Egypt, Laos, Cambodia, Bangladesh, Philippines and Mongolia that have enrolled into the joint program offered by Kanazawa University, Kanazawa Institute of Technology, Gifu University, University of Tokyo, Nagasaki University, Hokkaido University and University of the Ryukyu. The forms of this program in Gifu University include classroom-based lecturing, showcasing of advanced technologies and site-based lecturing using full-scale models of tunnels, bridges and embankments at Gifu University. Thanks to this partnership, Gifu University can also reach out to overseas engineers through JICA. In this study, thirteen engineers who experienced road and bridge management from overseas were surveyed.

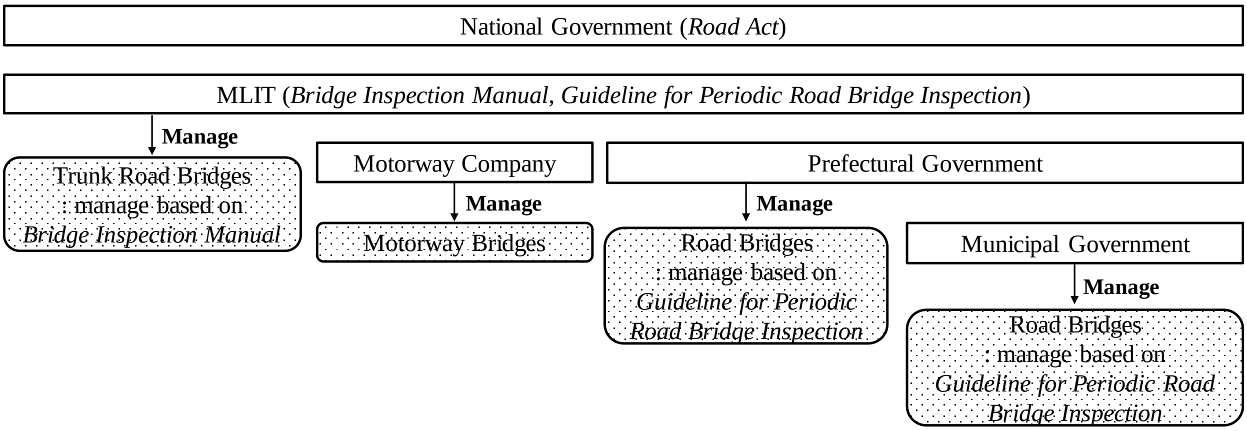


Figure 3.1 Three types of bridges managed by different governmental authorities

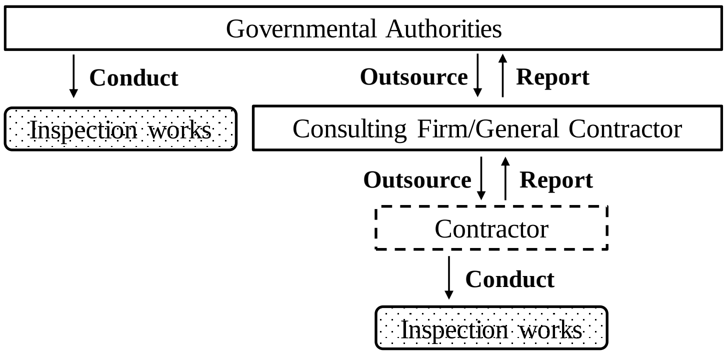


Figure 3.2 Two typical working modes for bridge inspection

Table 3.1 Profile of the survey subjects

Group	Question type	Position	Numbers	Total	Country
Domestic	Questionnaires	Government Authorities	11	34	Japan
		Tech Invention Companies	16		
		Consulting Firms/ Contractors/Subcontractors	7		
	Interviews	Government Authorities	19	50	
		Tech Invention Companies	20		
		Consulting Firms/ Contractors/Subcontractors	11		
Oversea	Questionnaires	Governmental authorities of each countries	13	13	Bangladesh/Cambodia/ Egypt(2)/Laos(3)/India(2)/ Mongolia(2)/ Indonesia/ Papua New Guinea

3.3.2 Method of Survey

The survey consisted of two steps, namely, the questionnaire step and the interview step. The questionnaire was prepared to understand the applicability issues of advanced technologies and solutions. Also, it was around advanced technologies and their use in geological survey, design, construction and maintenance. In this questionnaire, for both groups, *conventional technologies* were defined as technologies shown in current technical standards and documentation in each country. *Advanced technologies* were defined as technologies other than *conventional technologies*. Regarding *advanced technologies*, especially for the overseas group, it means not only cutting-edge technologies introduced in JICA projects in Japan but also the state-of-the-art technologies introduced in other countries. There were two types of questions in the questionnaire, including the open-ended questions (i.e. the 1st, 2nd and 6th questions) and the multiple-choice questions (i.e. the 3rd, 4th and 5th questions), as shown in **Table 3.2**. In the multiple-choice questionnaire, the respondents are required to define the most fitting selection. The question contents were prepared

After the questionnaire, the one-on-one interviews were conducted for the domestic group to understand the reasons for the selected answers. For the overseas group, the interviews were not conducted due to time constraints.

Table 3.2 Contents of the questionnaire survey

No.	Questions	Contents
1	An impression of advanced technologies	- How do you feel about utilizing advanced technologies for your work? - When you hear "advanced technologies", what comes to mind?
2	Experience in utilizing advanced technologies	- Have you ever adopted advanced technologies in your past work? - What kind of advanced technologies did you adopt? - Was the adoption success or failure? - What do you think was the reason for success or failure?

Table 3.2 Contents of the questionnaire survey

No.	Questions	Contents
3	Applicability issues of advanced technologies	- What are the reasons why you cannot or are averse to using advanced technologies? (multiple-choice question) ・ It will result in placing an order with a specific company (fairness cannot be secured). ・ I am uneasy in dealing with an accounting inspection. ・ The authorization will ultimately be given to a specific company or technology. ・ It does not completely meet the requirements of the current standards and guidelines. ・ There are no-cost benefits because it is expensive. ・ I am worried about the risks if/when trouble occurs (where responsibility lies, cost of dealing with trouble). ・ It cannot be used on-site (insufficient understanding of on-site needs). ・ I am worried about its performance and accuracy (unclear grounds and warranty). ・ I am worried about long-term technical support. ・ I will need to master advanced technology and change the system from scratch, and this will increase the burden on me. ・ The advantages and disadvantages of using advanced technologies are unclear. ・ The impact of using advanced technologies cannot be clarified.
4	Solutions to utilize advanced technologies	- What are effective solutions to make it easier to utilize advanced technologies? (multiple-choice question) ・ Obligations to obligate the introduction of advanced technologies in documentation and specifications. ・ A technical evaluation system by academic societies and industry groups. ・ Establishment of standards, guidelines, and manuals by academic societies and industry groups. ・ Technology associations organized by the personnel involved with each advanced technology. ・ Provision of application examples and specification examples of advanced technologies. ・ An evaluation system for advanced technologies by an impartial organization. ・ Establish a track record of using advanced technologies in the private sector and the semi-private sector.

Table 3.2 Contents of the questionnaire survey

No.	Questions	Contents
5	Key points in utilizing advanced technologies	- What are the key points when utilizing advanced technologies? (multiple-choice question) ・ Advantages and disadvantages with existing industries * The use of advanced technologies is welcome when it is difficult to deal with an issue using conventional technologies, but in the case of conventional technologies being replaced by the use of advanced technologies, there is strong opposition unless existing companies and industries can support the technology. ・ Consideration for local companies * There is a need for a form of utilizing advanced technologies that allow the participation of local companies, and so we ought to ensure that the use of advanced technologies does not exclude local companies. The nurturing and survival of companies connected to the local community are important for responding to disasters and securing tax revenues. ・ Other key points of note for promoting the use * There are two objectives to utilizing advanced technologies: the improvement of conventional technologies (efficiency, cost reduction) and the development of innovative technologies (innovation). It is, therefore, necessary to distinguish these two objectives. * Innovative technologies are difficult to use unless the method and impact of its use are clear. * Innovative technologies are a source of trouble if the performance and accuracy cannot be guaranteed with certainty, and so a simple and reliable inspection or confirmation method is required. * In order to promote the use of advanced technologies, many factors are relevant such as costs including LCC, standards and guidelines for road authorities, financial resources, and incentives for use, etc.
6	Others	- Free description.

3.4 Results of the Survey

3.4.1 Results of Questionnaire Survey

Figure 3.3 shows the percentages and number of the answer for Q3. For the domestic group, the highest percentage answers from *Tech Invention Companies* and *Consulting Firms/ Contractors/ Subcontractors* were *insufficient understanding of needs* and *performance and accuracy are not ensured*, respectively. About 40% of *Tech Invention Companies* and *Consulting Firms/ Contractors/ Subcontractors* chose *standards or manuals are not satisfied*, and 19% of *Government Authorities* made that choice. Therefore, preparing the standards or manuals for maintenance using advanced technology may be an effective way to overcome the applicability issues across all of these occupations. On the other hand, for *Government Authorities*, the main concerns were *fairness cannot be guaranteed,* and *explanation to account audit is a burden.* Therefore, *Government Authorities* may adopt advanced technologies if the standards or manuals are not satisfied.

58% of the overseas group chose *long-term technical support is not ensured*, and 50% chose *high cost but low merits*. In comparison with the results from the Japanese group, the percentages of the answer for *fairness cannot be guaranteed,* and *explanation to account audit is burden* was less. To the overseas group, it can be true that the applicability issue was because of not using the technologies.

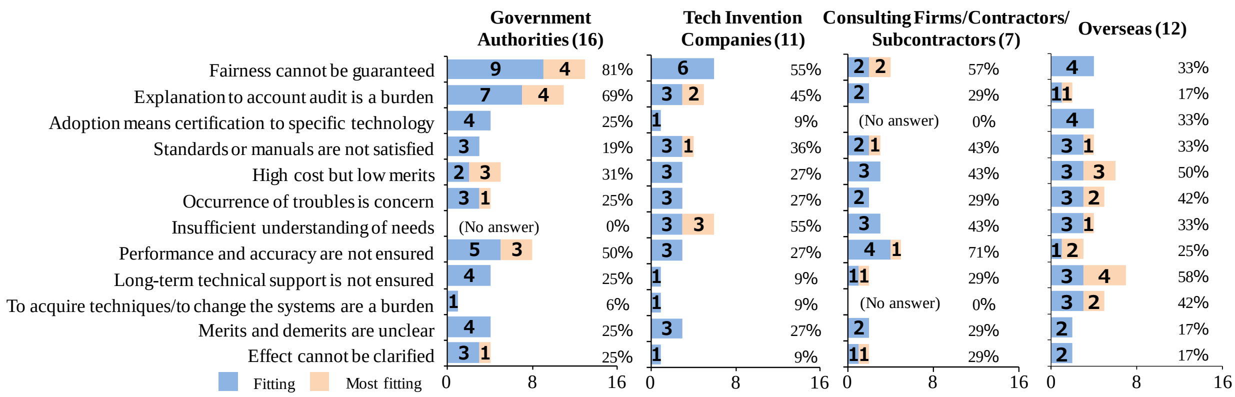


Figure 3.3 Answers for questions regarding the applicability issues

Figure 3.4 outlines the response of Q4. For the domestic group, 75% *Government Authorities*, 64% *Tech Invention Companies* and 71% *Consulting Firms/ Contractors/ Subcontractors* respondents *the manuals should specify certain advanced technologies*. The answer to this question was the highest for all occupations, so to specify certain advanced technologies by the manuals is one of the efficient solutions. However, it seems that changing the manuals is difficult. Other top answers were *provide adoption examples of advanced technology* and *create evaluation systems for advanced technologies*, chose by 64% and 45% *Tech Invention Companies* and 71% and 57% *Consulting Firms/ Contractors/ Subcontractors*. Also, 50% Government Authorities and 57% *Consulting Firms/ Contractors/ Subcontractors* chose *establishing standards and guidelines by academic societies*. Therefore, those three solutions are considered as the alternatives.

To the overseas group, 58% chose *provide adoption examples of advanced technology*. The percentage of *the manuals should specify certain advanced technologies* was 50%, in comparison with its highest ranking in the domestic group. In addition, the same percentage was observed on *create technical evaluation systems by academic societies*, *establish standards and guidelines by academic societies* and *create evaluation systems for advanced technologies*.

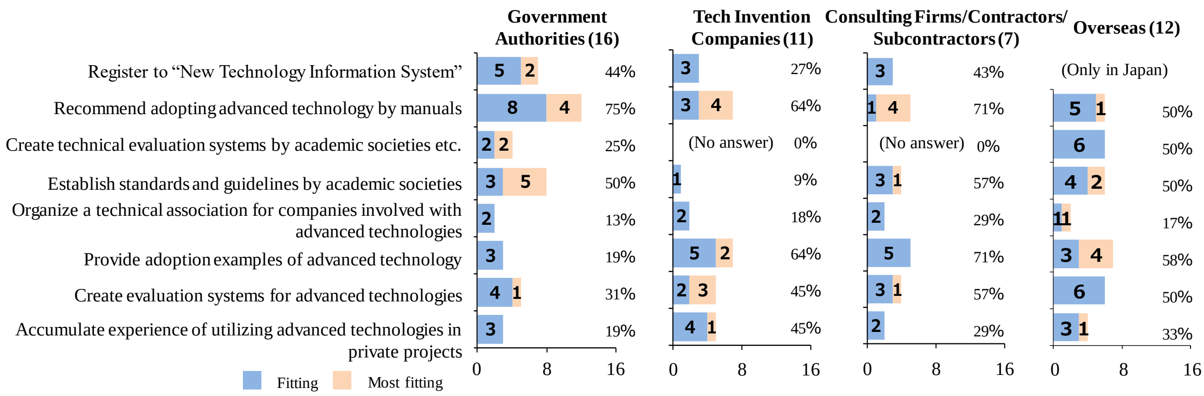


Figure 3.4 Answers for questions regarding the solutions

Figure 3.5 illustrates the percentages and number of the answer for Q5. For the domestic group, 81% *Government Authorities* and 73% *Tech Invention companies* chose *respect the participation of local companies*. Also, 75% *Government Authorities* and 71% *Consulting Firms/ Contractors/ Subcontractors* chose *note in which many factors are involved*, in contrast, only 18% *Tech Invention companies* chose it. In this questionnaire, the *many factors* mean costs including LCC, standards and guidelines for road authorities, financial resources, and incentives for use, etc.. From these results, for *Government Authorities* and *Consulting Firms/ Contractors/ Subcontractors*, one of biggest key points was shown that the concern about the many factors involved to use advanced technology. Therefore to solve and clarify those factors may accelerate the utilization of advanced technologies.

Among the answers from the overseas group, the most chosen answer was to *note in which many factors are involved,* and the percentage was 92%. Also, 67% chose *respect the participation of local companies* and *distinguish inventing and improving*. From these results, considering the local companies was pointed out as the key point in the world. Therefore, a method that can use advanced technologies with local companies may be needed.

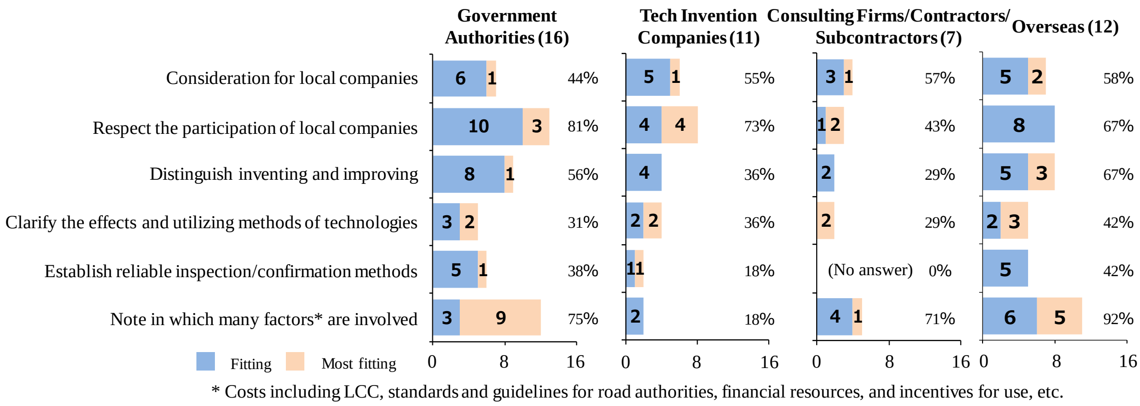


Figure 3.5 Answers for questions regarding the key points

From the answers for the Q2 (open-ended questions) of the overseas group, three of them had experiences to use the advanced technology. Two of them used a drone or a robotic camera, and they answered the utilization of those technologies was *went well*. On the other hand, another one used a database of bridge deterioration, and he/she answered the utilization was between *went well* and *did not go well*. As the reasons for this answer, he/she mentioned: lack of skills of the workers, and the director did not understand the importance of the technology.

In all questions, there were many opinions about the cost of advanced technology, e.g., the cost of utilizing them is higher than conventional methods. They also mentioned if a detailed calculation result regarding LCC is proposed, it leads to adopting advanced technologies.

The results of those questions for the domestic group will be discussed in **3.4.2** with the answers of the one-on-one interviews.

3.4.2 Results of the One-on-one Interviews

Table 3.3 shows the main applicability issues of advanced technologies for each occupation obtained from questionnaires survey and one-on-one interviews. The applicability issues which shown with blue letters in this table were not included in the contents of multiple-choice questions, i.e., those issues were obtained from open-end questionnaires and one-on-one interviews.

As shown in **Table 3.3**, the applicability issues comprise the limitation related to the technology itself, the limitation related to the work process, and the difficulty related to people's feelings. In addition, the applicability issues and the causes depended on the worker's occupations. Therefore, the solutions should be considered for each occupation.

Government Authorities are acutely aware of limitations related to the work process, such as *preparing a large number of documents* and *explaining the advanced technologies for the accounting audit* are necessary. Also, they aware of the fear to contract with a specific company having an advanced technology because *fairness should be ensured*. In addition, they feel psychological stress, such as *resistance to changes* and *anxiety over troubles due to adopt advanced technologies*. Therefore, it is important to understand the job-related and psychological limitations felt by *Government Authorities*.

For *Tech Invention Companies*, the applicability issues are primarily related to technical problems, such as *the lack of knowledge of the needs*, and the *appropriate cost for clients is unknown*. Moreover, the difficulty of making decisions to start the inventions are revealed as follow; especially about the profit, *investment recovery in a short time is difficult,* and before to start the inventions, *to understand the market* is difficult.

Consulting Firms/ Contractors/ Subcontractors feel there is no direct benefit to use advanced technologies because *technical proposals do not lead to an increase in the works*. Also, it was revealed that they fear the *significant risk arising when troubles*.

Table 3.3 Applicability issues in each occupation

Positions	Major issues	Major causes
Governmental Authorities	Attitudes of people in charge of widely varying	- The organizational mission is unclear. - There is an enthusiasm gap between head and local offices. - There is resistance to changes.
	Significant energy and effort are required for introduction	- Fairness should be ensured. - Preparing a large number of documents for account audit is necessary. - Explaining the advanced technologies for the accounting audit is necessary.
	The anxiety over troubles due to adopt advanced technologies	- Who takes responsibility is unclear. - Constant and continuing support is not assured.
Technology Inventors	Investment decision for development is difficult	- First-mover advantage from development is not assured. - Investment recovery in a short time is difficult. - It is difficult to understand the market (scale, continuity).
	Required specifications are unclear	- The lack of knowledge of the needs. - The appropriate cost for clients is unknown. - Content and period of technical support required are unknown.
	Government's situation is unknown	- Each organization and local government is in a different situation. - Method of order placing and introduction conditions are difficult to understand. - Attention to industry officials is required.
Consulting firm/ Contractors/ Subcontractor	No direct benefit	- Technical proposals do not lead to an increase in the works.
	The significant risk arising when troubles occur	- It is unclear who takes responsibility for the trouble.
	Cost of the technical proposal is high	- Needs should be understood and seeds should be collected. - Documents supporting the validity of the introduction should be formulated.

3.5 Preferred Actions for Each Occupation to Solve the Applicability Issues

From the results of this survey, the most effective solution for accelerating the adoption of advanced technologies was pointed out that *the manuals should specify certain advanced technologies*. In addition, the applicability issues and the causes lie in the worker's occupations. In order to overcome these applicability issues, the examples of preferred actions were aggregated for each worker's occupation, as shown in **Table 3.4**. In this table, the occupations of *Government Authorities* and *Tech Invention Companies* were divided into two of each by adding *Government* and *Universities* to make the differences more clear.

Government Authorities have the decision to use advanced technologies or not. Therefore, *clarifying the organizational mission to use advanced technologies* and *making performance-based contracts to adopt advanced technologies* are preferred. When utilizing advanced technology, it should be cared *to utilize a variety of advanced technologies* in order to keep fairness. Especially for *Government*, *improve the descriptions concerning advanced technologies in standards and manuals* is the biggest preferred action because they can revise the standards and manuals. Regarding the bridge inspection standards and manuals, the Guideline for Periodic Road Bridge Inspection was revised in March 2019 in Japan [56]. In this revision, since the requirement about visual inspection has been relaxed, the adoption of advanced technologies into bridge inspection becomes easier. On the other hand, not only revising the manuals but also *supporting to invent advanced technologies with a budget* such as SIP projects is preferred.

As discussed in section **3.4**, *Tech Invention Companies* faced a problem that difficulty with understanding the needs of the other occupations. Therefore, they have to communicate with the other occupations workers *to understand the needs*. In addition, since *Tech Invention Companies* clearly know the advantages and disadvantages of the invented advanced technology, it is preferred *to prepare documents which explain the technology to reduce the burden on Government Authorities*. For *Universities*, especially in the education field, *to educate maintenance engineers* and *to give lectures and seminars in adopting advanced technologies* are preferred. In addition, as the professional of infrastructure maintenance, *to offer advice on using advanced technologies to assist the decision making of Government Authorities* is one of the helpful ways. Also, as the neutral occupation of other occupations which explained above, it is preferred *to promote collaboration among local governments, industry and academia*.

Consulting Firms/ Contractors/ Subcontractors know the issues which happen in the construction site, so *providing information about the needs* is the preferred action. Also, once advanced technologies are utilized by *Consulting Firms/ Contractors/ Subcontractors*, it is thought that the limitation and needs of advanced technologies become more clear. Therefore, the proposal *to utilize advanced technology* is preferred.

From those results, it is thought that to take actions not only in one occupation but also in all occupations can lead to an acceleration in adopting advanced technology.

Table 3.4 Examples of preferred actions for each occupation

Positions		Examples of preferred actions
Government Authorities	Government	- Improve the descriptions concerning advanced technologies in standards and manuals. - Support to invent advanced technologies with a budget. - Support the development of advanced technologies by indicating clear targets.
	Others	- Clarify the organizational mission to use advanced technologies. - Make performance-based contracts to adopt advanced technologies. - Utilize a vitality of private companies to adopt advanced technologies. - Incentivize the adoption of advanced technologies.
Tech Invention Companies	Universities	- Educate maintenance engineers. - Offer advice on using advanced technologies to assist the decision making of *Government Authorities* . - Promote collaboration among local governments, industry and academia. - Give lectures and seminars in adopting advanced technologies.
	Others	- Understand the needs for advanced technologies to be developed. - Develop attractive advanced technologies. - Prepare documents which explain the technology to reduce the burden on *Government Authorities*.
Consulting Firms/ Contractors/ Subcontractors		- Providing information about the needs. - Utilize advanced technologies within the contracted work.

3.6 Summary

In this chapter, the questionnaire-based surveys and the one-on-one interviews were conducted to answer what applicability issues exist and what kinds of solutions are required to adopt advanced technologies to infrastructure maintenance. The results are summarised as follows.

(1) The distributed questionnaires indicated that the main applicability issues were *fairness cannot be guaranteed*, and *explanation to account audit is a burden* for *Government Authorities*. On the other hand, for *Tech Invention Companies* and *Consulting Firms/ Contractors/ Subcontractors, standards or manuals are not satisfied* was perceived as the main applicability issue. In addition, for the overseas practitioners, the main applicability issues were *long-term technical support is not ensured* and *high cost but low merits*. It can be said that applicability issues lie in the occupational difference.

(2) The solutions were revealed that the most effective way is for the manuals to specify certain advanced technologies *(the manuals should specify certain advanced technologies)* for all of these occupations in the domestic and overseas groups. As this solution is difficult to implement, the alternative ways were suggested, which include *providing adoption examples, creating an evaluation system for advanced technologies* and *establishing standards and guidelines by academic societies.*

(3) In order to solve the applicability issues, the preferred actions for different occupations were recommended. The results indicate that these actions should be taken by all occupations in answer to accelerating the adoption of the advanced technology.

Chapter 4

Investigation of Adopting Advanced Bridge Inspection Technologies

4.1 Overview

When the periodic inspections of bridges are conducted by advanced technologies, the technologies can lead various advantages which include; reduction of cost and traffic congestion, improvement of the safety of inspection works, and accumulation of detailed information about defects. However, the adoption has not accelerated so far.

From Chapter **3**, an effective way to accelerate adopting advanced technologies was revealed to specify certain advanced technologies by the manuals. Although this solution is difficult to implement, the alternative ways were suggested, which include: *providing adoption examples*, *creating an evaluation system for advanced technologies* and *establishing standards and guidelines by academic societies*. In this chapter, in order to implement those solutions, at first, the advanced technologies abilities were verified by field testing in three types of real bridges. Then, the *guideline*, which shows the integration methodology of the advanced technologies and human inspectors is proposed. Finally, the inspection by the advanced technology based on the proposed *guidelines* was conducted on the prestressed concrete bridge.

4.2 Outline of the Target Bridges

Gifu prefecture has many rivers in the area, that means the number of bridges is huge. The number of bridges constructed in Gifu prefecture is 5,374, and it is the fourth biggest numbers in 47 prefectures in Japan [1]. On the other hand, the number of civil engineers who work in local government is 25th in 47 prefectures [57]. It is thought that the needs for utilizing advanced technologies to help inspectors are higher than other prefectures.

Among those bridges, some of them have a serious issue to be inspected. **Figure 4.1** shows Kakamigahara Bridge which is a 10-span prestressed concrete continuous finback bridge with a bridge area of 11,200 m^2 spanning 594 m over Kiso River. The superstructure is of a box girder construction with a semicircular cross-section. The piers with an oval cross-section with no hammerhead are about 10 m from the water surface. The width of the top ends of the piers is the same as the width of the girder. The carriageway section with an average width of 7.5 m is sandwiched between 3 m-wide paths for pedestrians/bicycles (**Figure 4.2**), which is partially widened to 5 m near the P5 and P7 piers. The pedestrian/bicycle paths are designed with a special structure in which prestressed decks are supported by precast concrete brackets. In this bridge, the undersurfaces of the superstructure cannot be inspected with a general large-scale bridge inspection vehicle (BT 400) as shown in **Figure 4.3**, due to the wide paths and the presence of finback members along the edges of the carriageway. The spans above the water (P2 to P9) measuring 420m where the pier height exceeds 10 m are particularly difficult to inspect, requiring inspection with an ultra-large bridge inspection vehicle with a long projection arm of around 5 m, suspended scaffolding, ropework, etc., which would incur a high cost. **Figure 4.4** 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. Currently, it is used as a pedestrian/bicycle path. In 2008, it was recognized as one of the important cultural properties in Japan because it is a large-scale railway bridge in the Meiji period (1868 to 1912). 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 the use of materials (wrought iron) at the time of construction for repair work such as corroded members. From those limitations, the inspection costs will become higher than common bridges. In this chapter, to overcome those issues in the bridges, the utility and adoption of advanced technologies are considered.

Figure 4.1 Kakamigahara Bridge

Figure 4.2 Wide path for pedestrians/bicycles

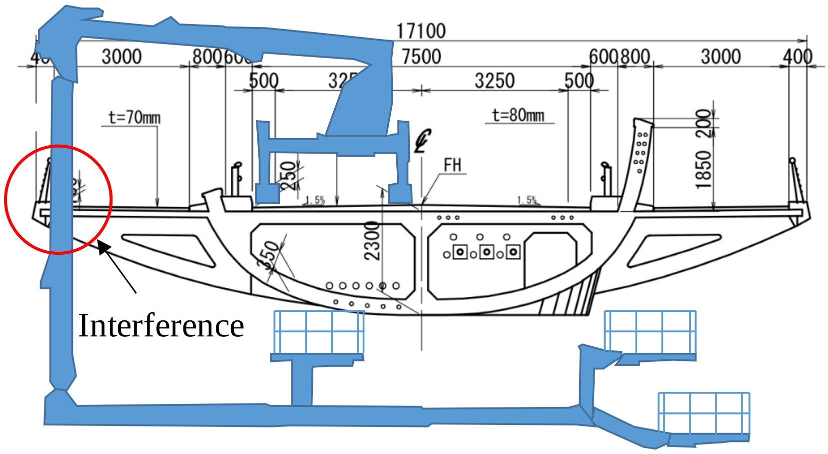


Figure 4.3 Inspection with a general large-scale inspection vehicle

(a) A view of the entire bridge

(b) Road Surface

Figure 4.4 Ibigawa Bridge

In addition, beforehand to utilize those advanced technologies, the performance of them should be well-known from users. The performance means the functions, abilities, advantages and disadvantages of advanced technologies. In order to clarify the performance of advanced technology which have been invented at the moment, field testing were conducted on three existing bridges in Gifu prefecture. In these field testing, one concrete bridge and two steel bridges were selected, which include the two bridges as mentioned above. **Figure 4.5** shows Chidori Bridge which is a 3-span steel girder bridge with a spanning 215.5 m over Nagara River. This bridge has been used from 1964 as a bridge for vehicles such as cars. In 1980, the steel box girder bridge was constructed on the upstream side, and the previous girder bridge was changed the utilize to the path for pedestrian/bicycle.

(a) A view of the entire bridge

(b) Road Surface

Figure 4.5 Chidori Bridge

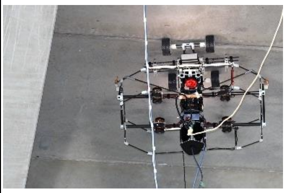
4.3 Proposal of Requirement for Performances of Advanced Technology

When adopting advanced technology into the periodic inspection of bridges, the inspection must be consistent with the *Road Act*, *Bridge Inspection Manual*, and *Guideline for Periodic Road Bridge Inspection* [2],[3],[56]. Therefore, the advanced technologies performances are confirmed by comparison with the requirements of those manuals for human inspectors.

4.3.1 Field Testing to Verify the Performances of Advanced Technologies

At first, in order to verify the performances of advanced technologies, field testing was conducted at three real bridges. The field testing was held several times from April 2017 to August 2018. **Table 4.1** shows eight technologies that were selected and verified in this thesis.

Table 4.1 Utilized advanced technologies in the field testing

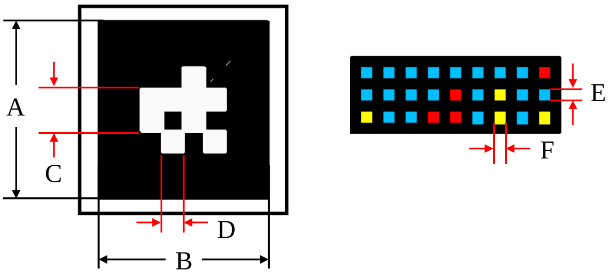
Type	Name of technology	Working	Name of technology	Working
UAV/UAS, Drone	**(1) Two-wheeled UAV with camera for bridge inspection**		**(2) Small-sized Two-wheeled UAV with camera for bridge inspection**	
	(3) UAV with a passive rotating spherical shell		**(4) Drone with controllable pitch propellers**	
Robotic Camera	**(5) Robotic camera indicating crack scale for bridge inspection**		**(6) Camera system for bridge inspection**	
Hammering Robot	**(7) Drone with wheels for visual observation and hammering tests**		**(8) Drone with hammering test equipment for bridge inspection**	

For concrete bridges, field testing was conducted at the prestressed concrete continuous finback bridge (Kakamigahara Bridge), and the six technologies which are (1), (2) and (4) to (8) as shown in **Table 4.1** were verified. The performances, especially the measurement functions, of those technologies were verified by: each *Tech Invention Company*, verification marks (**Figure 4.6**) which prepared by Gifu University SIP team, and comparison between the result of inspections by advanced technologies and visual inspection by human inspectors.

Figure 4.6 shows the verification marks prepared by Gifu University SIP team. Among these marks, there are two types of marks: the first one is the *visibility Mark* used to confirm the measurement performance for the degree of damage other than cracking (length, area, deformation, etc.) as shown in **Figure 4.6 (a)**. The measurement accuracy of length was verified by measuring the length of the sides of the squares A to F, which have different length. For the length of A and B, it was required to measure them in the accuracy of ± 50 mm. For the length of C and F, it was required to measure them in the accuracy of ± 10 mm.; The second one is the *crack Scale* which was used to confirm the measurement performance for cracking (width and length) as shown in **Figure 4.6 (b)**. The measurement accuracy of width and length was verified by measuring the six types of lines. For the width, it was required to measure them in the accuracy of ± 0.05 mm, and for the length, it was required to measure them in the accuracy of ± 50 mm. Those two marks were put on under the surface of the deck, under and the side surface of girder and side surface of the pier in order to understand those technologies performance for horizontal and vertical surfaces.

Table 4.2 and **Table 4.3** shows the results of the verifications by the verification marks for five types of technologies, No. (1), (4) to (7) as shown in **Table 4.1**. In those tables, the numbers of each cell mean the measured length or width, and the percentages mean the accuracy of those technologies. In **Table 4.2** and **Table 4.3**, the accuracy of measuring the length was calculated by the length of the marks divided measured length. For example, if the mark length was 90 mm and the measured length was 95 mm, the accuracy was $(90 \div 95) \times 100 \approx 95\%$. When the measured length was smaller than the length of the marks, the accuracy was calculated by the measured length divided the length of the marks. In **Table 4.3**, the accuracy of measuring the width was calculated based on the differences between the width of marks and measured width. **Table 4.4** shows the class of the differences and the given scores for the measured width. The accuracy was calculated by the sum of the scores divided by six. For example, if the measured width had two A classes and four B classes, the accuracy was $[(2 \times 1 + 4 \times 0.5) \div 6] \times 100 \approx 67\%$.

The accuracy of verification by the *visibly marks* (**Table 4.2**) was 59% to 100%, and the accuracy of the *crack scales* (**Table 4.3**) was 67% to 100%. Those accuracy was high, so it can be said that the advanced technologies already reached enough level to obtain the defects data when utilizing in this bridge.



(a) Visibility mark

(b) Crack scale

Figure 4.6 Verification marks

Table 4.2 Verification results of the Visibility Mark

Locations	Length (mm)	Advanced Technologies as shown in **Table 4.1**				
		(1)	(4)	(5)	(6)	(7)
Main girder V1	A 85	85	84			
	B 85	82	77			
	50mm	98%	95%	—	—	59%
	C 10	10	10			6
	D 10	10	10			6
	E 7	6	7			5
	F 7	6	8			5
	10mm	93%	97%	—	—	66%
Main girder V2	A 85			80		
	B 85			80		
	50mm	—	—	94%	—	-
	C 10			10		
	D 10			10		
	E 7			7		
	F 7			7		
	10mm	—	—	100%	—	-
Pier V3	A 85	86	87	80	70	60
	B 85	84	87	80	70	62
	50mm	99%	98%	94%	82%	72%
	C 10	10	10	10	8	7
	D 10	10	10	10	8	6
	E 7	6	9	7	5	5
	F 7	6	9	7	5	5
	10mm	93%	89%	100%	76%	68%

Table 4.3 Verification results of the Crack Scale

Locations	Width (mm)	Length (mm)	Advanced Technologies as shown in **Table 4.1**									
			(1)		(4)		(5)		(6)		(7)	
			Width	Length	Width	Length	Width	Length	Width	Length	Width	Length
Deck C4	0.05	90					B（0.2）	95	A（0.1）	95	A（0.1）	83
	0.1						A（0.2）	93	A（0.1）	95	A（0.2）	80
	0.15						A（0.2）	94	A（0.2）	95	B（0.3）	77
	0.2						B（0.4）	93	A（0.2）	93	A（0.2）	76
	0.25						B（0.4）	94	A（0.3）	93	B（0.4）	75
	0.3						B（0.5）	94	A（0.3）	92	B（0.4）	75
	±0.05mm	50mm	—	—	—	—	67%	96%	100%	96%	50%	86%
Main girder C1	0.05	90	B（0.2）	90	A（0.05）	90	A（0.1）	90			A（0.1）	72
	0.1		A（0.2）	90	A（0.1）	90	A（0.2）	90			B（0.2）	75
	0.15		A（0.2）	90	A（0.15）	90	A（0.15）	90			A（0.2）	78
	0.2		B（0.4）	90	A（0.2）	90	A（0.2）	90			B（0.4）	72
	0.25		B（0.4）	90	A（0.3）	90	A（0.3）	90			A（0.3）	73
	0.3		B（0.5）	90	A（0.3）	90	A（0.3）	90			A（0.3）	72
	±0.05mm	50mm	67%	100%	100%	100%	100%	100%	—	—	92%	82%
Main girder C2	0.05	90					B（0.2）	92	A（0.1）	90		
	0.1						A（0.2）	93	A（0.1）	90		
	0.15						A（0.2）	92	A（0.2）	90		
	0.2						A（0.2）	93	A（0.2）	90		
	0.25						A（0.3）	94	A（0.3）	90		
	0.3						A（0.3）	92	A（0.3）	90		
	±0.05mm	50mm	—	—	—	—	92%	97%	100%	100%	-	—
Pier C3	0.05	90	A（0.1）	90			A（0.1）	92				74
	0.1		B（0.3）	90			B（0.3）	92				73
	0.15		A（0.2）	90			A（0.2）	92				75
	0.2		B（0.4）	90			A（0.2）	92				75
	0.25		B（0.4）	90			A（0.3）	92				80
	0.3		B（0.5）	90			A（0.3）	92				72
	±0.05mm	50mm	67%	100%	—	—	92%	98%	—	—	-	83%

Table 4.4 Class of the differences and the given scores

Class	Differences	Points
A	Less than 0.1 mm	1
B	Between 0.1 mm to 0.2 mm	0.5
C	More than 0.2 mm	0

For steel bridges, three technologies which are (3), (5) and (6) as shown in **Table 4.1** were verified by the field testing at two types of bridges.

First, at the steel girder bridge (Chidori Bridge), one UAV type technology which has a passive rotating spherical shell (outside diameter is 96 cm) was chosen (No. 3 in **Table 4.1**). By attaching a passive rotating spherical shell, this technology enables stable flight even when bumping into a bridge member, and it allows to take images by a close distance which is up to approximately 50 cm to the inspection object. In this field testing, taking an image from a close distance to the object was possible even when there was an attachment of the bridge such as shown in **Figure 4.7**. In addition, the degradations map was created by detected defects such as cracks, as shown in **Figure 4.8**. Therefore, this technology was assessed that it had applicability of steel bridges inspection.

Second, at the steel truss bridge (Ibigawa Bridge), the two robotic camera technologies that are installed and used on the upper surface of the bridge were selected (No. 5 and 6 in **Table 4.1**). This bridge locates close of the railway, for safety, the drone technology that requires flying was not selected. The purpose of this field testing was to verify the applicability of advanced technologies in the following four contents: (I) Application to bridges with complex structures; (II) Detection of defect such as corrosion and cracks in coating; (III) Detection of falling bolts and rivets etc.; and (IV) Application to the area in river. Regarding the two technologies used in this field testing, *(5) Robotic camera indicating crack scale for bridge inspection* detected the defects of diagonal member and upper chord of truss, and *(6) Camera system for bridge inspection* detected the defects of the lower chord, floor assembly members and RC slabs. At first, (I) Application to bridges with complex structures was verified. *(5) 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 acquired. By this method, the camera can be inserted into the truss even it has complex structures, and acquires the images as shown in **Figure 4.9**. Also, using the function to zoom up the images as shown in **Figure 4.9 (b)**, it can be possible to detect small defects. Furthermore, even for the complicated structure of the panel point as shown in **Figure 4.10**, it was able to obtain an image that can detect the defects sufficiently by the zoom up function explained above. *(6) 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 to acquire the image from a close distance. By this technology, the images as shown in **Figure 4.11** can be obtained, and it was shown that this technology can detect the defects of the lower surface of the bridge such as lower chord. When using such an arm-type technology in a truss bridge, the works to insert and remove the arm between the diagonal members can be time-consuming. On the other word, if the working times to insert and remove the arm can be reduced, it can lead to effective inspection. In this field testing, the time from positioning on the bridge surface to completion of arm insertion under the girder is about 5 minutes, and the arm movement between the truss panels is about 12 minutes. The working time was early enough to conduct the inspection. Next, about (II) Detection of defects such as corrosion and cracks in coating and (III) Detection of falling bolts and rivets etc., were investigated. In both technologies, it is possible to detect defects such as corrosion and coating cracking over a wide range, as shown in **Figure 4.9** and **Figure 4.11**. In addition, by using the zoom up function as shown in **Figure 4.9 (b)** and **Figure 4.11 (b)**, local corrosion such as at rivets in a narrow area could be detected with a precise image. In the case of bridges which are constructed over the river, inspection scaffolds can only be installed during dry periods when there is little rain because it can disturb river flows. Therefore, in order to confirm whether the inspection scaffolds are required, (IV) Application to the area in the river was investigated. Both technologies are utilized by installing on the bridge surface and the scaffolds were not required, so the application enabled. From the above reasons, it was verified that these two technologies have applicability in the four contents.

Figure 4.7 Narrow space in steel girder by attachments

Figure 4.8 Created degradations map

(a) Wide view image (b) Zoom up view image

Figure 4.9 Images obtained by *(5) Robotic camera indicating crack scale for bridge inspection*

Figure 4.10 Panel point of the truss bridge

(a) Wide view image (b) Zoom up view image

Figure 4.11 Images obtained by *(6) Camera system for bridge inspection*

4.3.2 Defining the Requirement for Performances of Advanced Technologies

Defining the performance requirements for advanced technology is difficult because advanced technologies have not been applied to periodic inspection of bridges. The unclear performance requirements make it difficult to set a goal of the technologies performances for those inventors. In addition, when considering to use advanced technologies, the users have to select which technology is useful for the target bridge. However, there are no criteria which can compare with the requirements by Bridge Inspection Manual [3] and Guideline for Periodic Road Bridge Inspection [52],[57]. Therefore, the requirement for performances of advanced technologies is defined in this section.

In section **4.3.1**, the advanced technologies functions for concrete and steel bridges were verified. Based on these results, the requirements for functions of advanced technologies were defined. The defined requirements were aggregated as shown in **Table 4.5** and **Table 4.6**. Those requirements are based on the performances whereby a soundness class of "II or higher" can be judged for each member in order to properly determine the need for preventive maintenance as shown in Bridge Inspection Manual [3]. The accuracy of the measuring function specified in **Table 4.5** and **Table 4.6** was determined to refer to Gifu Prefecture's Bridge Inspection Manual [58]. The tolerances were determined to refer to the results of the field testing which explained in section **4.3.1** as well. **Table 4.5** shows the requirement for advanced technology when utilizing at Kakamigahara Bridge, which is a concrete bridge. **Table 4.6** shows the requirement for advanced technology when utilizing at Chidori Bridge or Ibigawa Bridge, which are steel bridges. For steel bridges, the biggest difference with concrete bridges is the necessity to approach narrow areas, and the requirements for performances were defined as the operability of advanced technologies for each type of bridge structure such as Girder/Box Girder, Deck and Through bridges. However, **Table 4.6** is based on the performance of current technologies. It is presented as an initial value, so the criteria in steel bridges should be continued examining and updating in the future.

Table 4.5 Requirements for performances of advanced technology (Concrete bridge)

<table>
<tr><th colspan="3">Requirements</th><th>Verification</th></tr>
<tr><td rowspan="5">Detection of defect</td><td>Presence and type</td><td>Defect can be detected and classified.</td><td rowspan="5">Pictures and sketches of defect 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.</td></tr>
<tr><td>Location</td><td>Defect can be detected in a manner to allow sketching of defect portions in relation to other members.</td></tr>
<tr><td>Size</td><td>The overall image can be obtained to judge whether the defect is localized or extensive.</td></tr>
<tr><td>Direction and pattern</td><td>The direction (horizontal, vertical, diagonal, longitudinal or transverse to reinforcement, etc.) and pattern (map cracking, etc.) of defect can be detected.</td></tr>
<tr><td>Water penetration paths</td><td>The source and path of water ingress can be detected regarding defect involving water, such as water leakage and free lime.</td></tr>
<tr><td rowspan="3">Measurement of defect</td><td rowspan="2">Size</td><td>Crack width:
The crack width of 0.2 mm or more can be measured with an error margin of 0.0 to + 0.1 mm.</td><td rowspan="3">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.</td></tr>
<tr><td>Crack length, peeling, rebar exposure, leakage, etc.:
The size can be measured with an error margin of 5 cm.
(Length: L = XX cm, Area: A = XX cm × XX cm)</td></tr>
<tr><td>Displacement</td><td>The displacements of expansion gaps and bearings can be measured with an error margin of 10 mm.</td></tr>
</table>

※ The following performance is required so that there can be no omission of cracks with a width of 0.3 mm or more.
For a crack width of 0.2 mm, it is acceptable to output a measurement result of 0.3 mm (0.2 mm + error 0.1 mm) to be on the safe side.
For a crack width of 0.3 mm, it is not acceptable to output a measurement result of 0.2 mm (0.3 mm - error 0.1 mm) on the dangerous side.

Table 4.6 Requirements for performances of advanced technology (Steel bridge)

<table>
<tr><th colspan="3">Requirements</th><th>Verification</th></tr>
<tr><td rowspan="3">Operability</td><td>Girder/
Box girder</td><td>The technology can freely pass through an area around 1m×2m vertically.</td><td rowspan="3">Conducting a field test on actual bridges or structural model bridges.</td></tr>
<tr><td>Deck bridge</td><td>The technology can freely pass through an area about 3m×5m vertically and horizontally.
(In truss bridge etc.)</td></tr>
<tr><td>Through bridge</td><td>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.)</td></tr>
<tr><td rowspan="5">Detection of defect</td><td>Presence and type</td><td>Defect can be detected and classified.</td><td rowspan="5">Pictures and sketches of defect 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.</td></tr>
<tr><td>Location</td><td>Defect can be detected in a manner to allow sketching of defected portions in relation to other members.</td></tr>
<tr><td>Size</td><td>The overall image can be obtained to judge whether the defect is localized or extensive.</td></tr>
<tr><td>Direction and pattern</td><td>The d irection (horizontal, vertical, diagonal, longitudinal or transverse to reinforcement, etc.) and pattern (map cracking, etc.) of defect can be detected.</td></tr>
<tr><td>Water penetration paths</td><td>The source and path of water ingress can be detected regarding defects involving water, such as corrosion and deterioration of the paint.</td></tr>
<tr><td rowspan="3">Measurement of defect</td><td rowspan="2">Size</td><td>The deformations can be measured with an error margin of ± 10mm.</td><td rowspan="3">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.</td></tr>
<tr><td>The defects can be measured with an error margin of ± 50mm.</td></tr>
<tr><td>Displacement</td><td>The displacements of expansion gaps and bearings can be measured with an error margin of 10 mm.</td></tr>
</table>

4.3.3 Comparison of the Data Obtained by Human Inspectors and Advanced Technologies

In order to confirm the advanced technologies performances, the data obtained by those technologies were compared with visual inspection results conducted by human inspectors. These comparisons were conducted based on the requirements criteria defined in section **4.3.2**.

For concrete bridges, the data were obtained from the prestressed concrete continuous finback bridge (Kakamigahara Bridge), and the created deformations maps were compared. **Figure 4.13** shows an example of overlapped deformations maps which obtained by human inspectors and by the technology, *(1) Two-wheeled UAV with camera for bridge inspection*. From this map, the location and width of cracks were almost matched, so it is found that the technology has almost the same accuracy to create the deformations map. In bridge inspections, it is important to detect all defects because the overlooking of defects can lead a serious deterioration. **Table 4.7** shows the numbers of each defect detected by human inspectors and advanced technologies. From this result, the number of detected defects by advanced technologies were far higher than the defects by human inspectors, but there were a few overlooking. However, because all obtained data can be saved, it is thought that to reduce the risk of overlooking is possible by checking the obtained data several times or using some defect detection technologies such as image processing, etc.. Regarding the width of the detected cracks, there were fourteen overestimation results in the superstructure, but the underestimation was only one in the substructure. Therefore, it is thought that those advanced technologies have enough accuracy in detecting the width of cracks.

Table 4.8 lists the key results of assessments for the performances of advanced technologies in each inspection segments at Kakamigahara Bridge. In this table, the performances were assessed by three levels, A: It has enough applicability, A+: It has an extra function, A-: A revaluation is needed, B: There are some requirements to use the technology, and C: It does not have enough applicability. This table reveals that it is currently difficult to carry out inspection of all segments by a single technology. Therefore, when to formulate an inspection plan for Kakamigahara Bridge by advanced technologies, it was considered to combine multiple technologies to accomplish the inspection.

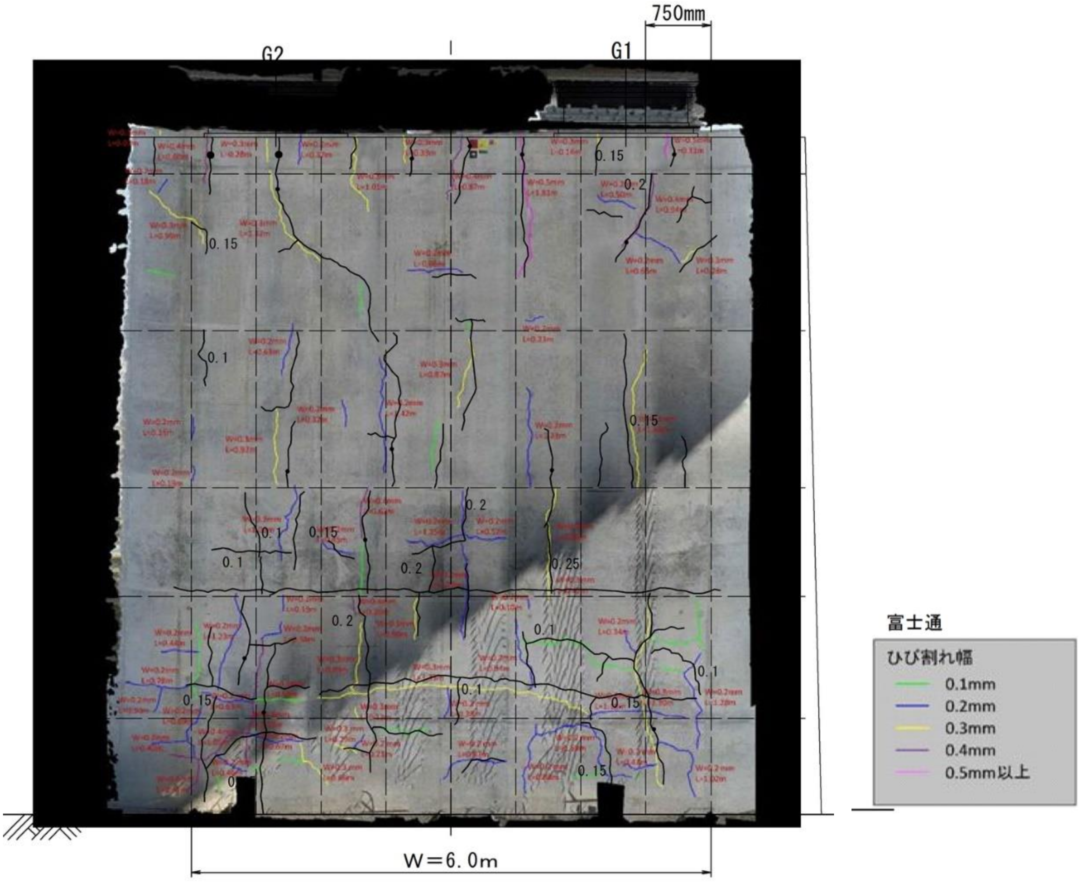


Figure 4.12 Overlapped deformations maps

Table 4.7 Numbers of each defect detected by human inspectors and advanced technologies

	Inspection conductor	Contents	Cracks	Water leaking & Free lime	Spalling	Others
Superstructure	By advanced tehcnologies	Detected defects	269	168	17	25
		Overlooking	2	3	0	4
		Incorrect detection	6	0	4	1
	By human inspectors	Detected defects	90	26	6	24
Substructure	By advanced tehcnologies	Detected defects	374	4	0	9
		Overlooking	0	0	0	0
		Incorrect detection	0	0	0	0
	By human inspectors	Detected defects	56	4	0	0

Table 4.8 Organized and assessed key results of required performance for technologies

The subject of inspection segments in Kakamigahara Bridge	Assessment of the applicability for Kakamigahara bridge	Operating by drone engineer			Operating by inspection engineer	
		Drone with wheels for visual observation and hammering tests	Two-wheeled drone with camera for bridge inspection	Drone with controllable pitch propeller	Robotic camera indicating crack scale for bridge inspection	Camera system for bridge inspection
Spans in the river	A : Applicable B : With requirements	B (Using a boat)	B (Using a boat)	B (Using a boat)	A	A
Bottom surface deck	A : Applicable B : With requirements C : Not applicable	A (+) (Hammering test)	A (-) (Revaluation)	A	A	A
Girder (Side surface)		B (Only upper part)	C (Except for curved surface)	A	A	A
Girder (Bottom surface)		A	A (-) (Revaluation)	A	A	B (Except for centre part)
Beam		C (Unavailable)	C (Unavailable)	A	B (Only side surface)	A
Bracket		B (Only lower surface)	A	A	A	A
Bearing		C (Unavailable)	A	A (-) (Revaluation)	B (Except for between piers)	B (Except for between piers)
Drainage pipe & metal fitting		A	A	A	A	A
Substructure (Top surface)		C (Unavailable)	A	A (-) (Revaluation)	C (Unavailable)	C (Unavailable)
Substructure (Side surface : Top to the surface of the water)		C (Unavailable)	A	A	C (Unavailable)	C (Unavailable)

For steel bridge, the data were obtained from the steel truss bridge (Ibigawa Bridge), and the diagnosed soundness class were compared. As the diagnosis by advanced technology, the data obtained by *(5) Robotic camera indicating crack scale for bridge inspection* was used. In this field testing, the soundness was diagnosed for the superstructure; diagonal member, vertical member, upper chord, lateral bracing, portal bracing and panel point. As a result of this diagnosis, the soundness classes of the target members were judged as II or III. **Table 4.9** shows the comparison with the result of the visual inspection by human inspectors which conducted at one year before this field testing. According to **Table 4.9**, the image quality obtained by this technology was almost equivalent to the images obtained by human inspectors, and the diagnosed soundness classes were the same in each. Besides, the types of detected defects were similar such as corrosion or deformation for diagonal members. From those results, it is thought that the diagnosis based on information obtained by advanced technology is possible.

Table 4.9 Comparison with the diagnosis based on visual inspection

	Panel point	Diagonal member	Vertical member
Diagnosis based on information obtained by human inspectors	III	III	
			
Diagnosis based on information obtained by advanced technology	III	III	III
			

4.4 Proposal for Guideline to Inspect by Advanced Technologies

When considering to utilize those technologies, the adoption is difficult because there are no manuals or guidelines on how to utilize advanced technologies to bridge inspections. In order to solve this issue, the *guideline*, which shows how to utilize advanced technologies in concrete bridge inspections, is proposed based on the verified performances in previous chapters.

4.4.1 Inspection Flow by Advanced Technology

In this guideline, it was proposed to carry out two-step investigations as shown in **Figure 4.13**. In the first step, a *preliminary inspection* is carried out by advanced technology prior to the close visual inspection by human inspectors as a support to them. Because the advanced technologies still have a few overlooking of defects and the way to deal with those overlooking is not clarified, it is thought that to inspect by only advanced technology contain some risks. Therefore, in the *guidelines*, advanced technologies play a role to support visual inspections. Besides, it is expected to reduce the worries of users by utilizing those technologies as supports, and it might accelerate the use of advanced technologies. In the second step, a *visual inspection* is conducted on the whole bridge with the results of the *preliminary inspection*. The second step inspection is conducted by engineers who have expert knowledge about bridge inspections. It can lead to more effective work for the *visual inspection* because the inspector will be able to confirm by intensively observing the members and ranges.

The two-step investigations can lead to reducing the overlooking of defects by inspecting twice; by advanced technologies and human inspectors. Also, the *preliminary inspection* has a possibility to reduce the pressures of human inspectors. In general, the inspection work is conducted with strict time limits and the inspectors are required a perfect job with no overlooking of defects. If the inspectors can obtain the defects information before to inspect, it might reduce their pressures. For those reasons, the two-step investigations are thought that an effective way not only accelerating to use advanced technologies but also reduce the risks in inspections.

Regarding the specific process flow, extra time was planned between the *preliminary inspection* and the *visual inspection* to allow for research/investigation of questions arising from respective defects recognized during the *preliminary inspection* and preparation for appropriate operation during the *visual inspection*.

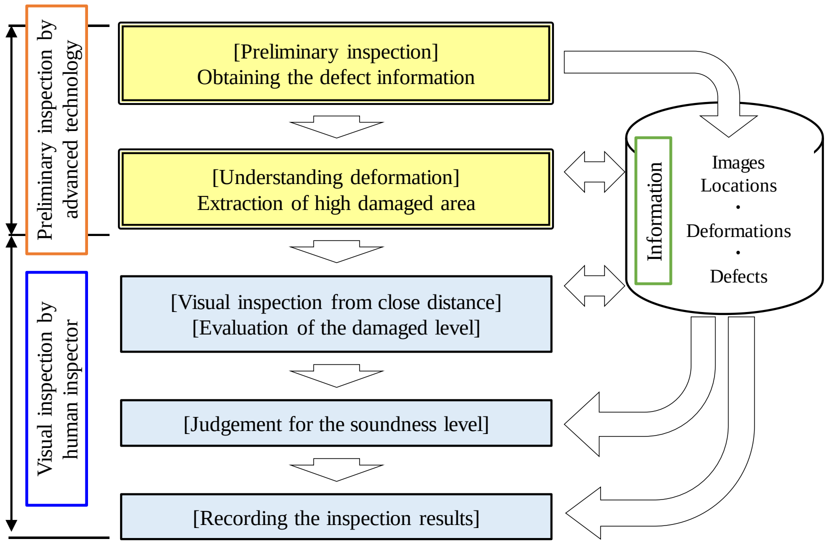


Figure 4.13 Two-step investigations flow

4.4.2 Defining the Required Information

When utilizing advanced technologies for bridge inspections, it is expected to many kinds of data are output as the results, i.e., images of defects with/without location information, sound waves obtained by hammering test, three-dimensional models with defects information, etc.. Therefore, to define the minimum required information is needed in order to deal with the data effectively. As the required information, the following five contents were defined; 1. The inspection information, 2. The recorded inspection information, 3. The prepared paperwork information in order to extract the area where need to conduct *visual inspection* carefully, 4. The prepared paperwork information in order to write the inspection reports and 5. The saved condition information of the entire bridge. Therefore, for advanced technologies, the performances to obtain the above five information are required.

Regarding the details of required performances, it is thought that the requirements depend on the target bridges as discussed in section **4.3.2**. Besides, the detailed requirements for advanced technologies are not defined in the *guideline*. In order to deal with each bridge, it is thought that to propose the *standard* which focuses on the target bridge, and it shows the detailed requirement for advanced technology is one of the solutions.

4.5 A Periodic Inspection on Concrete Bridge by Advanced Technologies

Based on the *guideline*, a periodic inspection on Kakamigahara Bridge, which is a concrete bridge, was conducted from July 2018 to February 2019.

4.5.1 Preliminary Inspection

As discussed in chapter 4.3.3, it was thought that to conduct the inspection by one technology is difficult (**Table 4.8**). Therefore, the inspection method to combine the six types of technologies which are (1), (2) and (4) to (8) listed in **Table 4.1** was proposed for the *preliminary inspection*. **Figure 4.14** shows the role allotment of each advanced technology for members in the *preliminary inspection*. The following three types of inspections were proposed and conducted so that advanced technology could be well utilized; Narrow-area inspection, Wide-area inspection and Hammering test. The narrow-area inspection was conducted for detecting various defects including cracks 0.2 mm or more in width. The technologies used in the narrow-area inspection satisfied the performance requirements as shown in **Table 4.4**. The wide-area inspection was conducted for ascertaining the state of the entire bridge by capturing various defects excluding small defects and their location information. Also, some technologies created orthophotographs and 3D models of the bridge by the wide-area information. The shooting range was around 5 m by 3.4 m, and the resolution was around 0.84 mm/pixel to be capable of detecting cracks with a width of around 0.3 mm. In the wide-area inspection, the high speed of drone-type robots demonstrated the character, and it led curtailing the time of work on site.

The hammering tests by advanced technology were conducted on segments where is thought that there are delamination or blistering of concrete. Those areas were extracted by wide and narrow-area inspection. In this inspection, the hammering tests by advanced technologies were conducted only on Pier P9 and the superstructure of Span P7-P8, due to the work efficiency and available time limitations of the technologies. Therefore, the hammering tests to other segments were only conducted by the *visual inspection*.

		A2	A2–P9	P9	P9–P8	P8	P8–P7	P7	P7–P6	P6	P6–P5	P5	P5–P4	P4	P4–P3	P3	P3–P2	P2	P2–P1	P1	P1–A1	A1
Preriminary Inspection	Wide-area	(4)																				
Preriminary Inspection – Narrow-area	Superstructure		(5)		(5)		(6)		(4)		(4)		(6)		(6)		(6)		(5)		(5)	
Preriminary Inspection – Narrow-area	Bearing			(1)		(1)		(1)		(1)		(1)		(1)		(1)		(1)		(1)		
Preriminary Inspection – Narrow-area	Substructure			(1)		(1)		(4)		(4)		(4)		(1)		(1)		(1)		(1)		
Preriminary Inspection – Narrow-area	Hummering test	Superstructer (7) , Substructure (8)																				
Human Visual Inspection		Inspection vehicle						Wide Zone / Rope work		Inspection vehicle		Wide Zone / Rope work		Inspection vehicle								

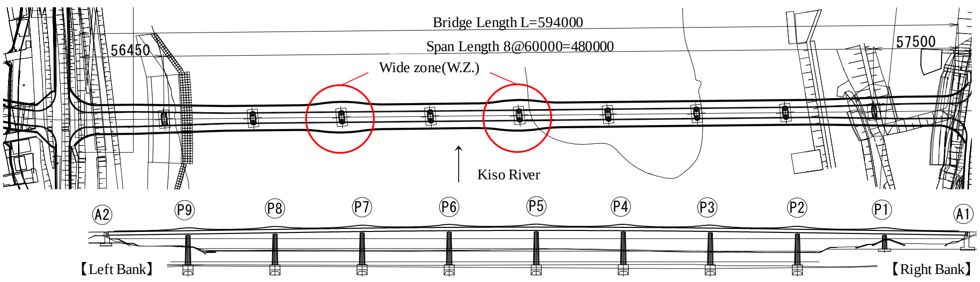


Figure 4.14 Combination of advanced technologies

4.5.2 Results of Preliminary Inspection by Advanced Technologies

By the results of the *preliminary inspection*, the deformations map was created for reference to the *visual inspection*. The deformations map was overlapped on the orthophotographs created based on the wide-area inspection to facilitate understanding of the positional relations between defects and the structure. Furthermore, by the advanced technology which is the (1) as shown in **Table 4.1**, a 3D structural model was created and displayed on a tablet as shown in **Figure 4.15** to show the position of each detected defect. This structural model was also connected with images. It makes the soundness diagnosis easier along with enhancing the work efficiency in the *visual inspection*.

According to the advanced technology which is the (2) as shown in **Table 4.1**, the orthophotograph of each structural unit (a span in the superstructure and a pier in the substructure) divided into 5m×5m mesh was created as shown in **Figure 4.16**. Each mesh unit is connected to original images as well. In the original images, to mark the defect, to note entering and to enlarge the images can be done. This functions significantly facilitated confirmation of defects on the desk and preparation of information for planning subsequent the *visual inspection*.

Figure 4.17 shows the comparison between the images acquired by the wide and narrow-area inspection. It revealed that cracks with a width of approximately 0.3 mm can be detected by either area inspection. Therefore, it was thought that the advanced technologies employed in the wide-area inspection are more effective for preliminary inspection. Furthermore, the enhancement of camera functions, such as resolution, the photographing accuracy is expected to close the accuracy of narrow-area inspection, and it can further increase the efficiency of preliminary inspection.

The *preliminary inspection* by advanced technologies enabled to know the types and positions of defects before to conduct the *visual inspection*, thereby it can narrow down the areas and segments where to be inspected carefully. As a result, the number of days required for *visual inspection* using the ultralarge inspection vehicle on Kakamigahara Bridge was significantly reduced to four days, which would otherwise have been ten days by conventional methods. The reduction of inspection time leads to reduce inspection costs. From this result, it is thought that the proposed inspection method, the two-step investigations, is one of the efficient methods.

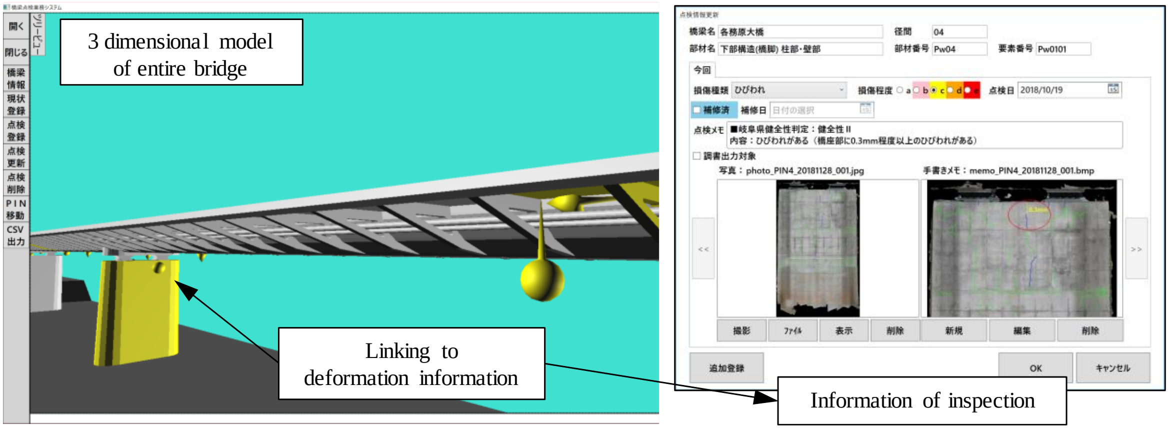


Figure 4.15 Connect defect maps of 3D structural models with images

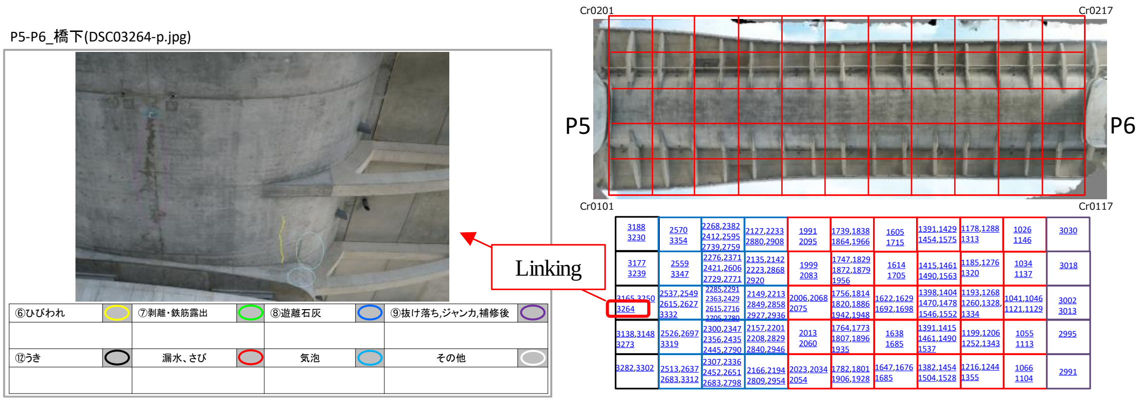
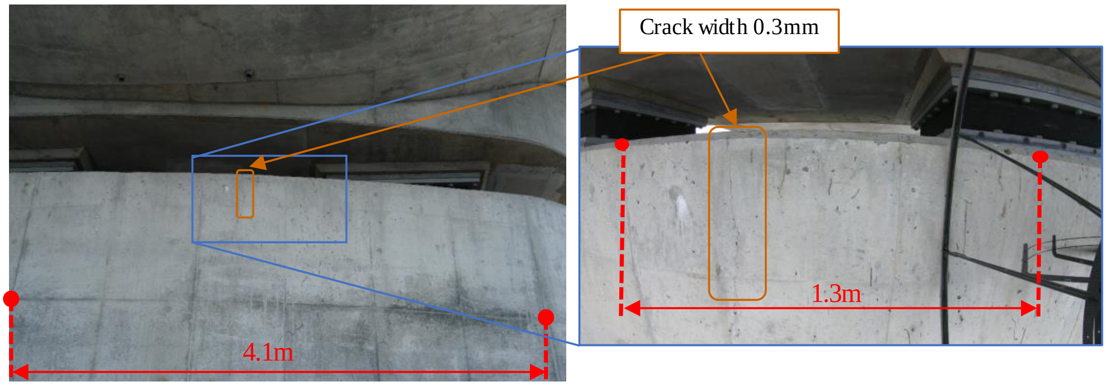


Figure 4.16 Results of wide area survey



(2) Drone with controllable pitch propellers
(6000×4000pixcel, Resolution 350×350dpi)

(1) Two-wheeled drone with camera for bridge inspection
(3840×2160pixcel, Resolution 96×96dpi)

Figure 4.17 Comparison between the images acquired by the wide and narrow-area inspection

4.6 Discussions for Promoting the Utilize of Advanced Technology

Based on the above-mentioned implementation of advanced technology for preliminary inspection activities, the newly recognized problems, advantages of using advanced technology, and points of note and ideas regarding the use of advanced technology were presented as follows.

First, regarding to how to use the advanced technology, it is thought that include the following three types; (1) Using exclusively for segments that have not been covered by the conventional inspection, (2) Using for preliminary inspection and (3) Using for screening survey. The using type of (2) was conducted in this chapter. It can increase the efficiency of visual inspection by making use of the results of the preliminary survey. The using type of (3) means to carry out research beforehand through the eyes of a technology to narrow the areas requiring confirmation, followed by close visual inspection. There may be sound bridges requiring no close visual inspection. From now on, it is thought that the following procedure is effective in appropriately ascertaining and recording the condition of a bridge; For the first inspection, carry out preliminary inspection using advanced technology, followed by overall close visual inspection. For subsequent inspections, limit the ranges of close visual inspection based on the screening survey by advanced technology.

Next, it is thought that the presentation of performance requirements for advanced technology is necessary. The administrator of a bridge should present reasonable performance requirements in specific terms for advanced technology to be used (**Table 4.4** and **Table 4.5**, for instance). The performance requirements to be presented should specify the defect-detecting accuracy just enough for judging the soundness class. Excessively demanding performance requirements should not be presented. If excessive-performance to measure extremely fine crack width is required, for instance, then a significantly large number of photographs becomes necessary to ensure the image resolution. This will complicate the subsequent image processing and data management, possibly reducing the work efficiency of judging the soundness class based on the images. Care should be exercised to present performance requirements in consideration of efficient data processing while ensuring the minimum qualifications required of information acquired by advanced technology. Judging from the results of the close visual inspection conducted following the preliminary survey, the performance requirements for advanced technology given in **Table 4.4** and **Table 4.5** were appropriate. In addition, whether or not the advanced technology to be employed meets the performance requirements specified by the administrator of a bridge should be verified. For the verification method, the following three methods are presented; (1) Performance verification by field testing, (2) Verification by actual use experience under control of other bridge administrators and (3) Verification by catalogues, etc., issued by public organizations such as MLIT. Since there have only been limited examples of performance verification by field testing so far, it is considered advisable to select (1) as a standard for the time being. Note that it is desirable to standardize the marks for verification to ensure generality of field testing. In performance verification, it is also advisable to confirm the operability of the function for measuring the length of defects and crack width, in consideration of the research results being used later.

Next, regarding the points of use the advanced technology, the works on the water should be considered. The

Civil Aeronautics Act limits the flight of a drone to visual flying. Operation of a drone on a boat may be necessary when inspecting a bridge crossing a wide river. Postural stability of the robot operator should be ensured when the river flows fast or when the water is shallow with a risk of the bottom of the boat coming in contact with the riverbed. In addition, safety solutions for utilizing drone-type inspection technology should be considered as well. When using drone-type inspection technology, safety solutions which are different from them for conventional inspection are required. For instance; (1) Ensuring safety in the event of radio wave disturbance, (2) Ensuring the safety of road users and (3) Supply and backup of a substitute drone. About (1), when the drone control signals are disrupted by obstacles or radio wave disturbance occurs due to interference, measures should be taken to prevent runaway of the drone. Regarding (2), safety solutions should be taken to protect the road users (vehicles and pedestrians) on the bridge from being injured by an out-of-control drone, even when the operation is carried out under the bridge. Permission for road occupancy or road use should be obtained depending on the methods of work. And about (3), since an inspection technology is a precision machine, a supply system for a substitute drone should be established in case of trouble, such as malfunction.

Next, regarding the data obtained from those technologies, the arrangement and storage of research results should be considered. The results of inspection using advanced technology can be systematized in the following forms; (1) Defect maps of 2D drawings and photograph files (conventional technique), (2) Connect defect maps of 2D images with images, (3) Connect defect maps of 3D structural models with images and (4) Connect defect maps of 3D images with images. Though (4) is the targeted form, the present results were summarized in the forms of (2) and (3) due to the processing capacity of computers. It was then judged that the form of (3) is desirable for close visual inspection in view of the ease of reference to the results of preliminary inspection and modifiability. The following three storage systems are conceivable for inspection results; (1) Storage by each bridge administrator, (2) Storage at the data centre, etc., of each municipality including prefecture and (3) Storage at the national data centre. In consideration of the risks including earthquakes, the storage system (3) is desirable with the advantage of standardizing the format of the research results.

4.7 Summary

In this chapter, in order to adopt advanced technology into bridge inspection, at first, the advanced technology performances were verified by field testing in three types of real bridges. Then, the *guideline*, which shows how to utilize advanced technologies, was proposed. Finally, a periodic inspection by the advanced technology based on the proposed guidelines was conducted on the prestressed concrete bridge. The results are summarized as follows.

(1) Performance requirements for advanced technologies were defined, and the performances of advanced technologies were verified in comparison with visual inspection results conducted by human inspectors. Those requirements are based on the performances whereby a soundness class of "II or higher" can be judged for each member in order to properly determine the need for preventive maintenance.

(2) The *guideline,* which shows how to utilize advanced technologies in concrete bridge inspections, was proposed. In this *guideline*, as the inspection flow by advanced technology, the two-step investigations were proposed. The first step is the *preliminary inspection*, which is conducted by advanced technology, and the second step is the *visual inspection* from a close distance by human inspectors, which is carried out for the entire bridge based on the *preliminary inspection* results.

(3) The periodic inspection by advanced technologies was conducted on Kakamigahara Bridge, which is a long-span prestressed concrete bridge with a large cross-section, based on the proposed *guideline*. As a result of the two-step investigations, it can reduce the number of days required for the *visual inspection*.

(4) It was shown that to propose the *guideline* is one of the efficient ways to adopt advanced technology for bridge inspection. In addition, it was clarified that the invented technologies already have enough performances to support bridge inspection.

Chapter 5

Classification for Images of Corroded Steel by Image Processing Technology

5.1 Overview

From the above chapters, the obtained data by advanced technologies is expected that the images of the bridge's surface. Regarding the detection of the defects from the images, the image processing technology has been tentatively used. In particular, the research about detecting and assessing the cracks on concrete bridges [6],[59],[60], the paint deterioration of steel bridges [9], and the deterioration patterns of the rust formed on weathering steel bridges [10]-[12] based on image processing have been conducted. On the other hand, the research to detect carbon steel's deterioration based on the images of exterior appearance are still few. The reasons are expected that the relation between the deterioration and exterior appearance on carbon steel has uncleared.

Carbon steel is one of the common materials to construct the bridges. Normally, they are used by painting to prevent corrosion deterioration. However, in the aggressive environments such as exposed to high temperature, high humidity, or high concentrate of chloride by air-born sea salt or deicing materials etc., those paints are broken and corrosion is occurring. For instance, the corrosion process under a wet condition can be represented as the following reactions [61]-[63] . First, the Fe becomes an ion, Fe^{2+}, and e^- is generated (**Equation 5.1**). Then, the reactions as shown in **Equations 5.2** or **5.3** are occurring by the generated e^-. As shown in **Equation 5.4**, the iron ion reacts with OH^- and generates $Fe(OH)_2$. The generated $Fe(OH)_2$ reacts with O_2 as shown in **Equation 5.5**, and FeOOH is generated. Then, FeOOH becomes Fe_3O_4 under the low O_2 environment by reduction (**Equation 5.6**), and the Fe_3O_4 becomes FeOOH again under the high O_2 environment by oxidation (**Equation 5.7**). Those corrosion are categorized into general corrosion or localized corrosion. For steel structures, the local corrosion is a big issue because it has high corrosion rate. In order to maintain the steel structures properly, understanding the corrosion type and the rate is important.

$$Fe \rightarrow Fe^{2+} + 2e^- \quad \text{Equation 5.1}$$

$$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^- \quad \text{Equation 5.2}$$

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad \text{Equation 5.3}$$

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \quad \text{Equation 5.4}$$

$$4Fe(OH)_2 + O_2 \rightarrow 4FeOOH + 2H_2O \quad \text{Equation 5.5}$$

$$Fe^{2+} + 8FeOOH + 2e^- \rightarrow 3Fe_3O_4 + 4H_2O \quad \text{Equation 5.6}$$

$$3Fe_3O_4 + \frac{3}{4}O_2 + \frac{9}{2}H_2O \rightarrow 9FeOOH \quad \text{Equation 5.7}$$

Under those situations, this chapter tries to assess the carbon steel's corrosion deterioration through the images. First, the corrosion tests are conducted to obtain the images of corroded carbon steel and to understand the corrosion products characterization. Then, an image processing is conducted by formulating the Convolutional Neural Network classifier that can effectively identify deterioration patterns of rust from raw images.

5.2 Outline of the Image Processing

Image processing is the application of a set of techniques and algorithms to a digital image to analyse, enhance, or optimize image characteristics such as sharpness and contrast [64]. Regarding conducting the image processing, the utilization of deep learning is getting great attention in recent year. **Figure 5.1** shows the category of Artificial Intelligence (AI) [65]. From this figure, it is shown that deep learning is categorized in Neural Network (NN). For the image processing, the Convolutional Neural Network (CNN) analysis which is included in the NN analysis is one of the common methods [11],[66]. In this chapter, the CNN analysis was selected to assess the conditions of corroded carbon steel.

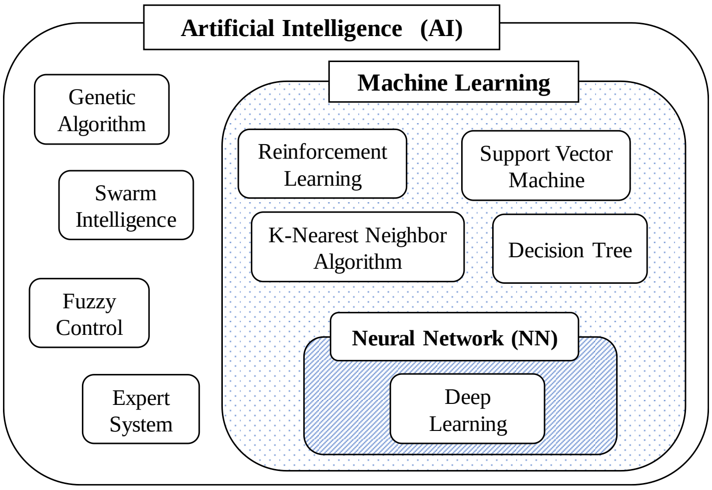


Figure 5.1 Categories of the Artificial Intelligence (AI) [62]

5.3 Corrosion Tests

5.3.1 Test Method and Environment

As the specimens, the carbon steel (SS400) with dimensions of 60 mm × 60 mm × 2.3 mm were used. The specimens were sandblasted as shown in **Figure 5.2**. The specimens were soaked into the liquid cup, which contained sodium chloride (the concentration is 3%) for one minute during each day (**Figure 5.3**).

Regarding the corrosion products, the producing speed and the types are relying on the exposed environment [67]. The bridges are constructed and exposed in various environments, which means, the obtained images of the bridge surfaces show the various types of corrosion products. In order to obtain the images of steel corrosion which produced under various environment, nine corroded specimens were produced by the corrosion tests in three different controlled environments as shown in **Figure 5.4**. In the environment A, at first, the relative humidity (RH) was maintained between 50-60% and the temperature between 10-30 degrees during Day 1 to Day 74; second, the RH was maintained above 74% and temperature between 10-30 degrees during Day 75 to Day 384; and third, the RH was maintained above 74% and the temperature at 40 degrees from Day 385 to Day 490. In the second environment, the RH was maintained above 74% and the temperature at 40 degrees from Day 1 to Day

325. In the third environment, the RH was maintained above 74% and the temperature at 5 degrees from Day 1 to Day 275. About the humidity, in order to accelerate to corrode, the RH was controlled above 74%, which is the critical relative humidity of sodium chloride [68].

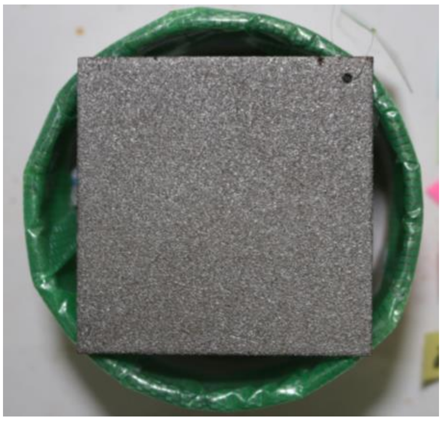


Figure 5.2 Sandblasted specimen

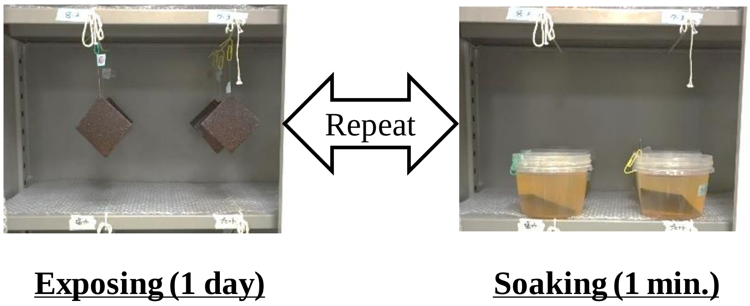
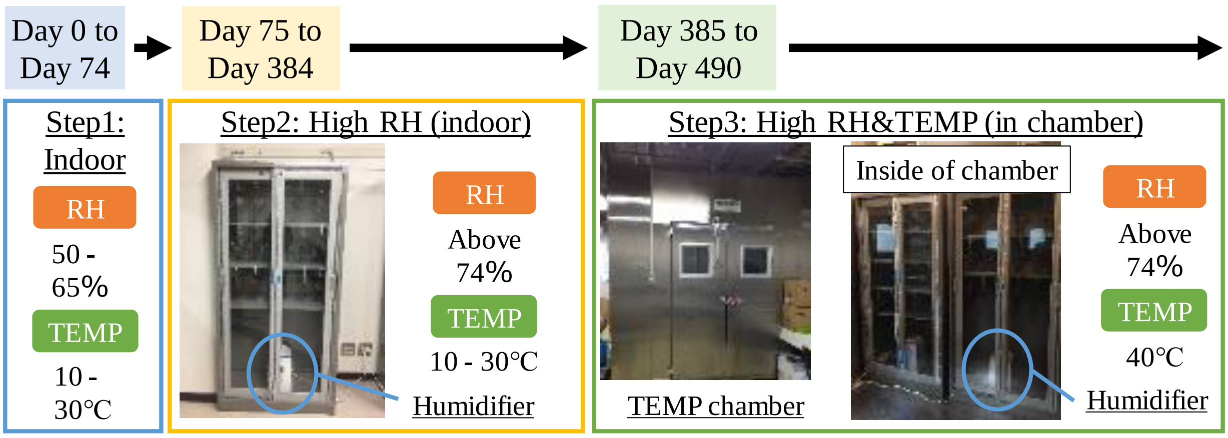
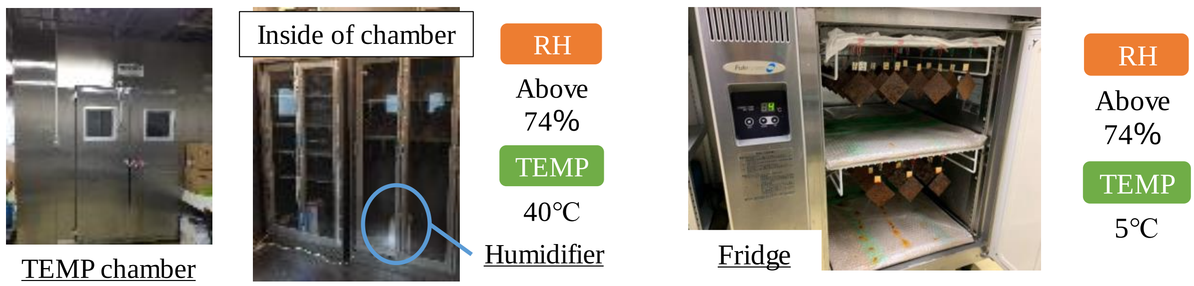


Figure 5.3 Method of the corrosion test



(a) Environment A: Changing environment for three steps



(b) Environment B: High TEMP and high RH

(b) Environment C:Low TEMP and high RH

Figure 5.4 Three types of test environments

5.3.2 Gained Weight due to the Corrosion Products

As the assessment method of the steel deterioration by corrosion and the corrosion products, the loss of corrosion [69] and the gained weight of the corrosion test specimens, the thickness of the rust [70], and the composition of the rust [62],[71],[72] have been proposed and used. Regarding the gained weight, **Figure 5.5** shows the model of corrosion procedures under the atmospheric environment with a drop of water [73]. As shown in this figure, the volume of the original steel will be reduced because steel becomes an ion, Fe^{2+}, and the produced corrosion products will remain on the surface. In usual, the loss of steel specimens weight is used to assess the corrosion [69]. When to measure the loss of corrosion, this measurement requires to remove all of the corrosion products. So that the continuous measurement on the one specimen is difficult. In order to measure the temporal change of corrosion, the gained weight of specimens due to corrosion was focused on. **Table 5.1** shows the main corrosion products produced under atmospheric environment [73],[74] and the molar mass of each corrosion product. Assuming 20% of the original steel become FeOOH, the weight of the specimen can be calculated to be around 112% of the original weight because the corrosion products remain the surface. Before to start this corrosion test, the weight of dropped corrosion products into the solutions was measured. As a result, the dropped corrosion products weight was far smaller than the gained weight of the corroded specimens. Thus the gained weight due to the corrosion products was used to assess the corrosion.

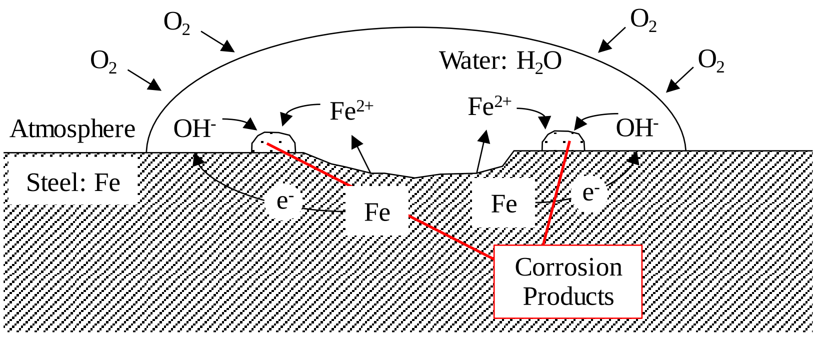


Figure 5.5 Model of corrosion procedures

Table 5.1 Corrosion products and the molar mass

Corrosion products	Characteristics	Molar mass (g/mol)
α-FeOOH (goethite)	Electrochemically inactive and it has a high protective ability.	89.8
β-FeOOH (akageneite)	Formed in the presence of chloride. Accelerate corrosion.	
γ-FeOOH (lepidocrocite)	The initial stage of corrosion. Accelerate corrosion.	
Fe_3O_4 (magnetite)	If it exists with β-FeOOH or γ-FeOOH, it accelerates corrosion.	77.1 (Fe= 1mol)

* The molar mass of Fe is 55.8 g/mol

Figure 5.6 and **Table 5.2** show the changing of the gained weight due to corrosion in each environment. In the figure and table, the results of two specimens in each environment were shown. Another one specimen in each environment were used to analyse the rust composition by the Fourier transform infrared (FT-IR) spectroscopy analysis. In this analysis, the corrosion products were drilled, so the analysed specimens were removed from the figure and table. From those results, the specimens produced in the environment B had the highest speed to corrode. Also, in the environment A's third step and environment B, which were the same environment in temperature and humidity, the gradients were almost the same. The result means even the specimens were already corroded as shown in the environment A, the corrosion rate was accelerated by changing the exposed environment to high temperature and humidity. The differences in the corrosion rate in these three controlled environments followed the relation between temperature and the corrosion rate [67].

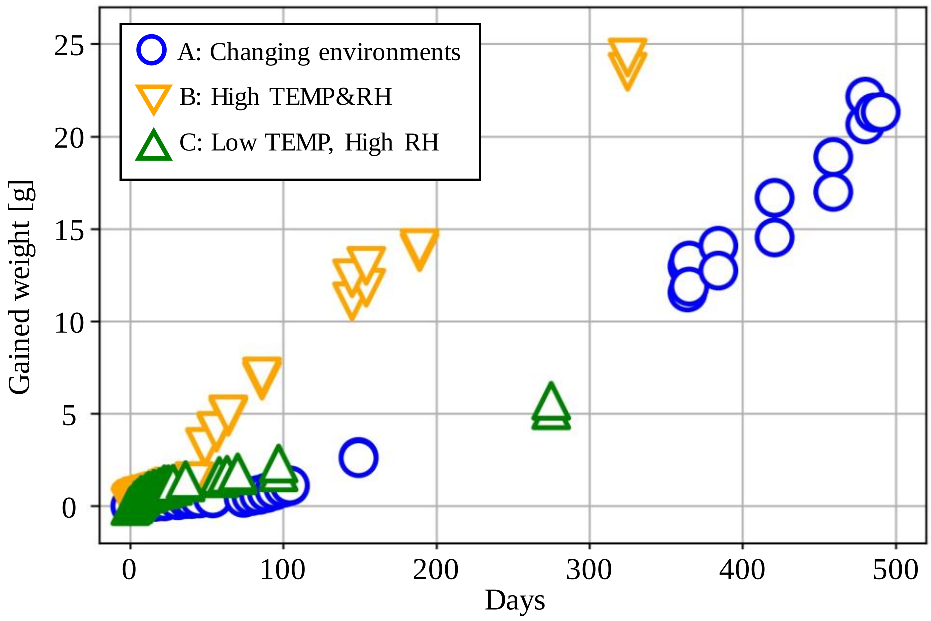


Figure 5.6 Changing of the gained weight

Table 5.2 Gained weight results in each environment

Environment	Days	Specimen 1 [g]	Specimen 2 [g]	Average [g]
A: Changing Environments	480	13.102	12.093	12.598
B: High TEMP & High RH	325	23.502	24.288	23.895
C: Low TEMP & High RH	275	5.187	5.720	5.454

5.3.3 Images of Corroded Steel Exterior Appearance

The images of corroded steel specimens were taken for each environment specimen. For all specimens, solid corrosion products were produced on the surfaces. **Figure 5.7** to **Figure 5.9** shows the examples of images of the specimen's exterior appearance obtained from the environment A to C.

According to the results of environment C, which had the lowest corrosion rate, the corrosion producing procedure can be explained as follow: first, the corrosion produced as small dots on the specimen; next, the dots integrated to cover the entire surface with the light brown colour; next, the colour of corrosion products became darker; then, after the entire surface covered by the dark brown corrosion products, local corrosion was produced. For environment A and B, those procedures occurred in rapid than environment C in the same procedures. In this section, those images are used for image processing analysis.

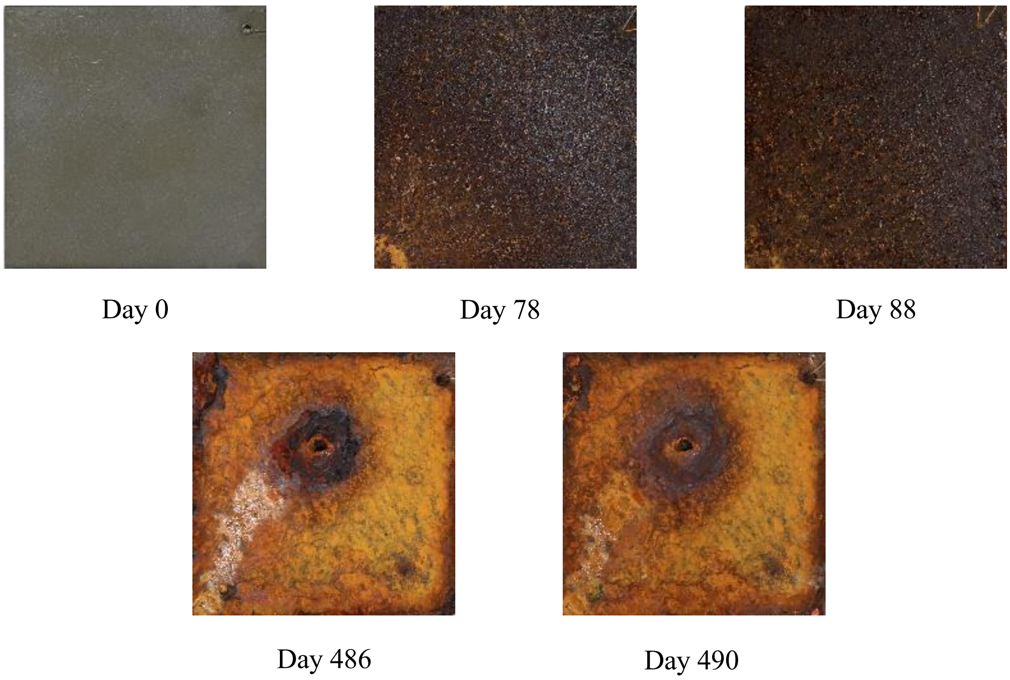


Figure 5.7 Exterior appearance of specimens produced in the environment A
(changing the environment for three steps)

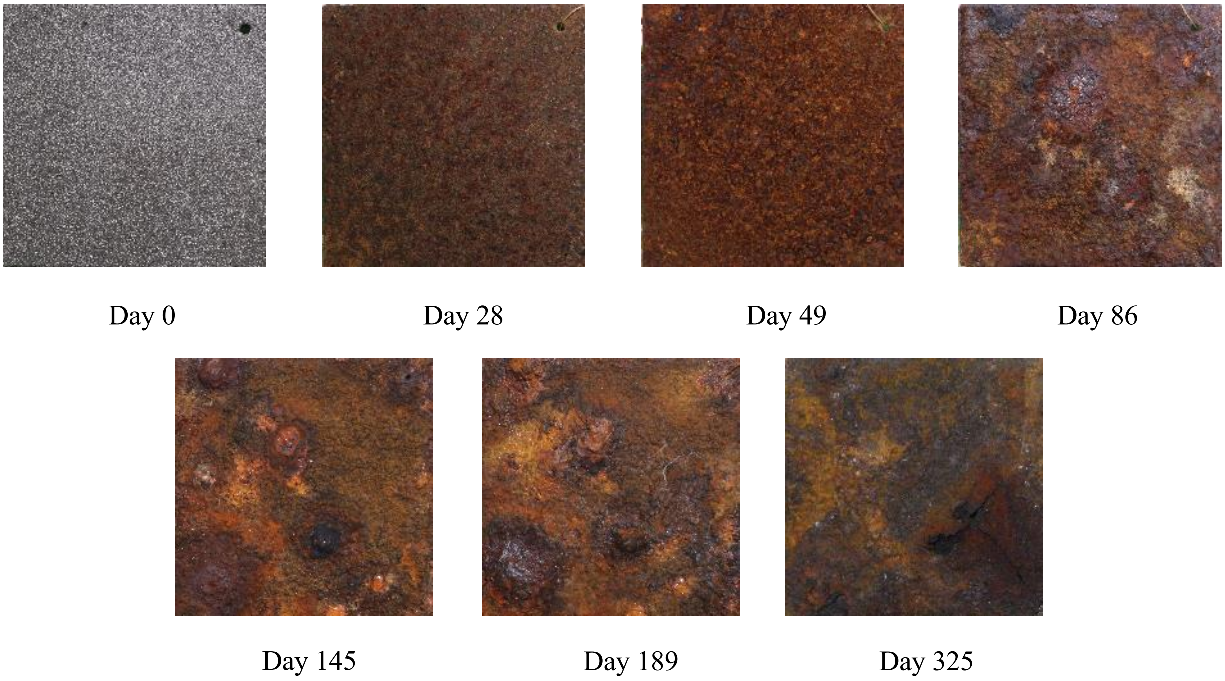


Figure 5.8 Exterior appearance of specimens produced in the environment B
(high temperature and high humidity)

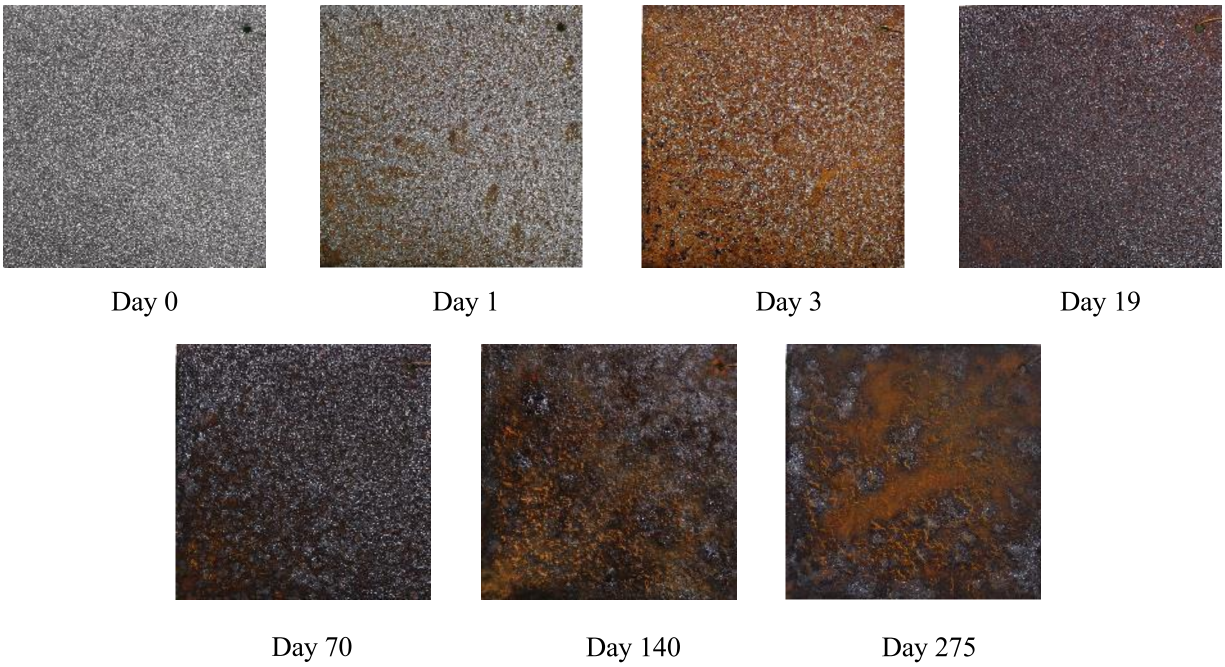


Figure 5.9 Exterior appearance of specimens produced in the environment C
(low temperature and high humidity)

5.3.4 The Relations Between the Gained Weight and the Exterior Appearance

As the assessment methods for steel corrosion deterioration by images, classification based on image processing techniques were considered. For classifying the images of corroded steel specimens which produced under different environments, the same criteria for each environment are needed. In this thesis, the gained weight is focused on as the criteria, and the relations between the gained weight and the exterior appearance images is investigated.

So as to understand the relations, the obtained images from the corrosion tests, as shown in **Figure 5.7** to **5.9**, are classified by two types of classifications: (1) classifying based on the gained weight by a human; (2) clustering by k-means clustering algorism. The clustering is one of the unsupervised learning algorisms, and the k-means clustering is a method commonly used to partition a dataset into k groups automatically [78]. In this thesis, the numbers of groups (k) are defined as the same numbers of groups in classification (1). These classifications mean that the closer of the results of these two classifications, the stronger of the relations.

In order to classify the images based on the gained weight, the classifying category was decided as shown in **Table 5.3**. This category was decided based on the differences of exterior appearances on each specimen.

Table 5.4 shows the results of k-means clustering. As the result, 78% of the images in Group 0 were clustered into Group E, and 22% of them into Group A. For the images in Group 1, they were clustered into Group A and E in 50% of each. Which means, the images of the steel which has the general corrosion on almost of all surface were clustered into same groups of the not-corroded specimens images. Therefore, the not-corroded specimens images (Group 0) and general corrosion of almost all surface (Group 1) have the possibility to be recognized and classified as the different corrosion deterioration. On the other hand, the most of images in Group 2 to 5 were clustered into the same group, group D. Which means after the corrosion was occurring on all surface, to detect the differences is difficult. However, the images clustered into group C, 35%, were consisted of only Group 4 images in environment A (**Figure 5.7**). Those specimens have a big local corrosion. Thus, there is the possibility to recognize and classify such a big local corrosion.

From those results, the clustering was not completely the same as the classification based on the gained weight. However, the differences in not-corroded specimens, specimens have general corrosion of almost all surface, and specimens have a big local corrosion can be recognized base on images even non-supervised learning clustering. Therefore, Convolutional Neural Network, which is one of the supervised learning methods, is conducted for those images.

Table 5.3 Classifying categories based on the gained weight

	Categories	
	Gained weight	Condition
Group 0	$x = 0\ [g]$	Before the test
Group 1	$0\ [g] < x \leq 0.3\ [g]$	General corrosion
Group 2	$0.3\ [g] < x \leq 5.0\ [g]$	
Group 3	$5.0\ [g] < x \leq 10.0\ [g]$	Local corrosion
Group 4	$10.0\ [g] < x$	

Table 5.4 The results of classification and clustering for the images from all environments

		Clustered by images				
		A	B	C	D	E
Gained Weight	Group0	22%				78%
	Group1	50%				50%
	Group2	8%	28%		64%	
	Group3	45%			55%	
	Group4	20%		35%	45%	

5.4 Classification by Convolutional Neural Network Analysis

5.4.1 Outline of Convolutional Neural Network

In order to classify the images of corroded steel, an image processing is conducted by Convolutional Neural Network (CNN) analysis. A Neural Network (NN) is a type of machine learning which models itself after the human brain. **Figure 5.10** shows an example of NN [78] . The layer consisted of neurons, and the working flow of the neuron is; to receive the input data; to conduct the processing as shown in **Figure 5.11**; to output the processed data. In this process, all input data (u) is calculated by the input data (x_i), the weight of the network (w_j) and the bias of the network (b) as shown in **Equation 5.1**. Then, the output data is calculated by the activation function (f) as shown in **Equation 5.2**.

$$u = w_1x_1 + w_2x_2 + w_3x_3 + w_4x_4 + b \qquad \text{Equation 5.8}$$

$$z = f(u) \qquad \text{Equation 5.9}$$

This procedure is called *learning*, and when using the big amount of the layers for learning, it is called *deep learning*. In NN, the input data should be one-dimensional data. For instance, assuming the input image has the size with 10 × 10 pixels and the colour RGB information, which means three-dimensional data, it can be written as (10, 10, 3). When inputting this data into NN, the shape becomes changing into (300) as the one-dimensional data, and the information of images will be lost. In order to overcome this issue, the Convolutional Neural Network (CNN) was developed. CNN is especially useful to conduct image identification and classification. **Figure 5.12** shows an example of CNN classifier model. The network consists of combinations of five types of layers including an input layer, convolutional layers, pooling layers, a fully connected layer and an output layer. **Figure 5.13** shows an example of processing in the convolutional layer. Convolutional layers look at spatially local patterns by applying the same geometric transformation to different spatial locations in an input data [78]. **Figure 5.14** shows an example of processing in the pooling layer, and it is the max-pooling processing. Max-pooling consists of extracting windows from the input feature maps and outputting the max value of each channel [78]. By this process, the feature maps are downsampled.

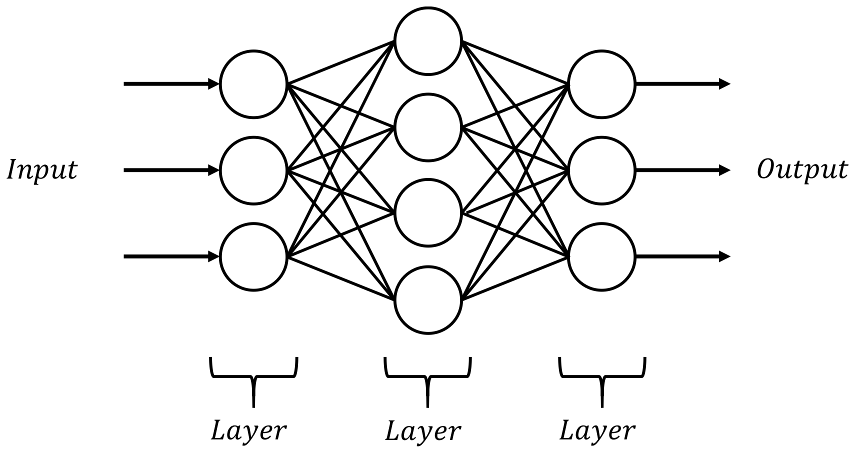


Figure 5.10 Example of Neural Network [76]

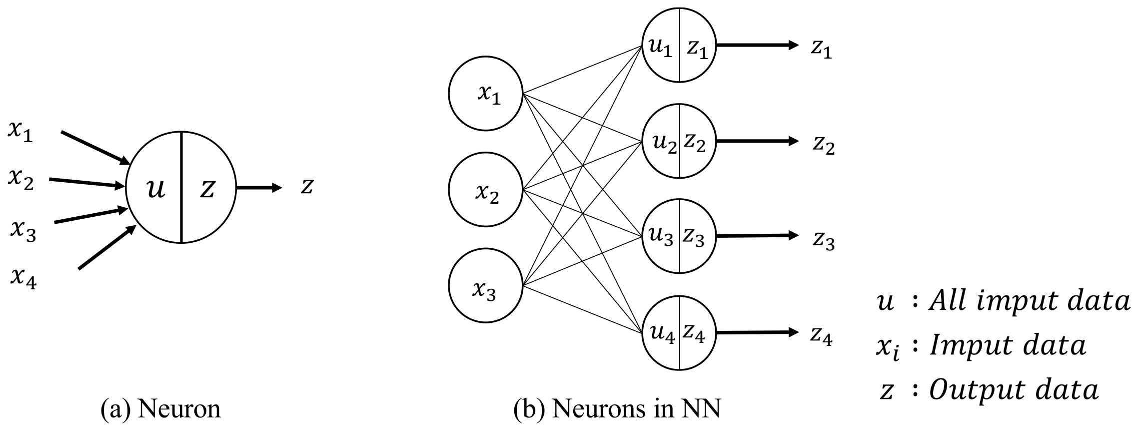


Figure 5.11 Example of the neurons working flow in Feedforward NN[76]

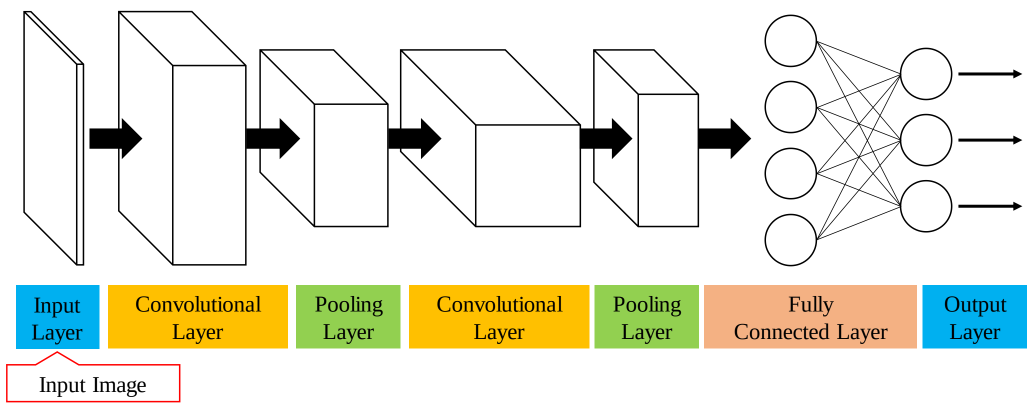


Figure 5.12 Example of Convolutional Neural Network

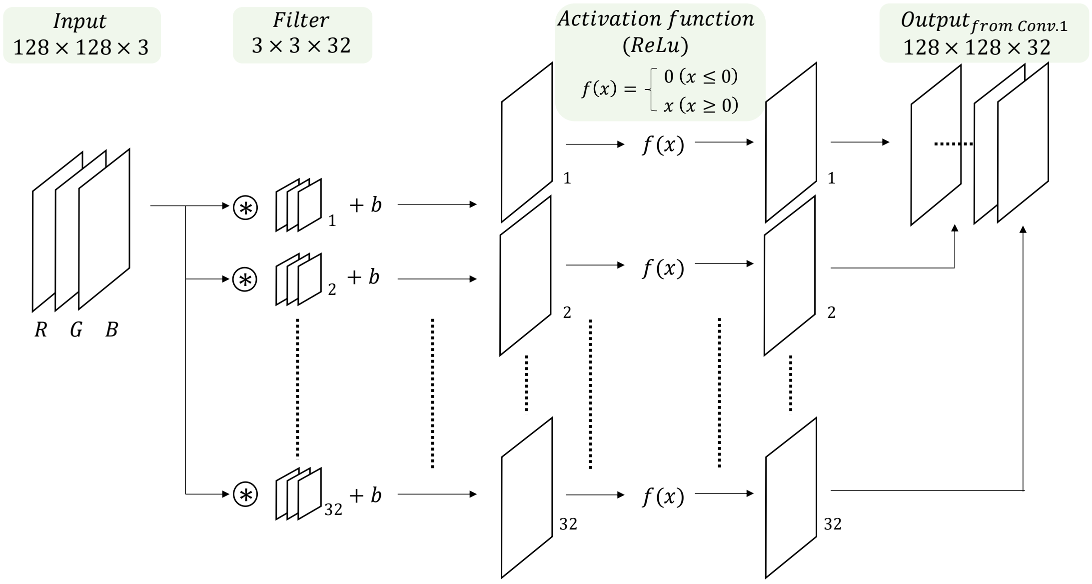


Figure 5.13 Example processing of convolutional layer

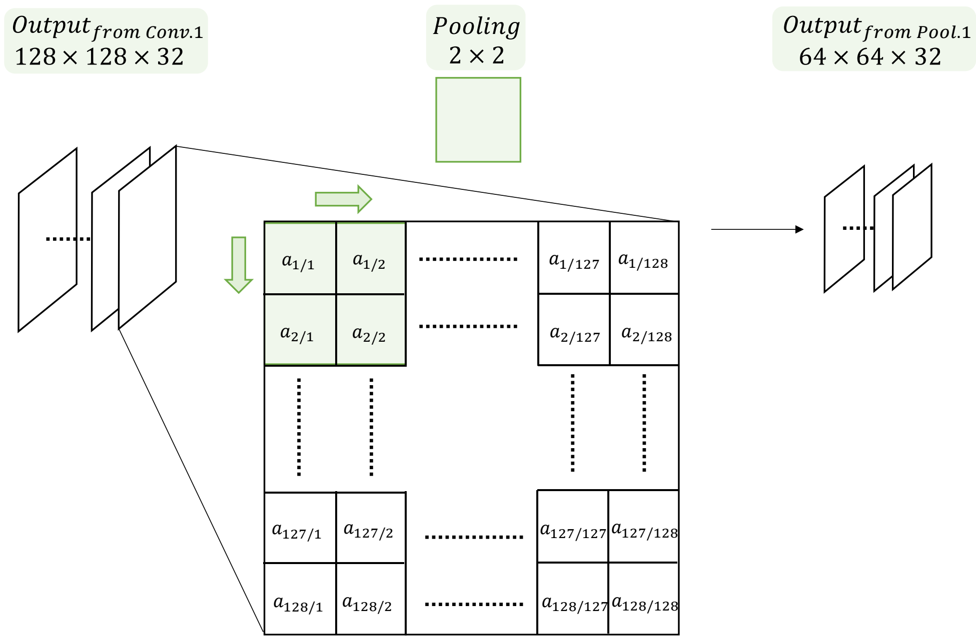


Figure 5.14 Example processing of pooling layer (max-pooling)

5.4.2 Procedures for Utilizing CNN

Figure 5.15 shows a flowchart of using CNN. The procedures consist of three parts; making the input datasets, training and verification of the classifier model, and classification prediction by the verified classifier model.

At first, the three types of input datasets, which are the training, the validation and the test dataset, were prepared. For the training and validation datasets, the images should be classified by human or machine learning, such as unsupervised learning [78], because the CNN classifier model will learn the correct and incorrect answers through those datasets. Next, the CNN classifier model was made. Many kinds of classifier models have been proposed and the accuracy was verified in one of the biggest competition, the ImageNet Large Scale Visual Recognition Challenge (ILSVRC) [79]-[83]. In this research, the existing classifiers [82],[84] were compared and used by modifying to suit the input datasets.

Second, the made classifier model was trained and verified by the prepared datasets. **Figure 5.16** shows the flow of training by the environment A dataset. At first, the training dataset is input, and it goes through the filters in the network by conducted each processing. Next, the results obtained through the classifier model are compared with the true results, which were already given in the dataset, and the accuracy and the loss are calculated. The loss means the differences between the true results and the obtained results. Then, those obtained comparison results were propagated to layers in order to get the minimum loss by updating the weights in each layer. By repeating this process using the same images in the training dataset, the classifier model is trained to obtain high accuracy and low loss of the classification. At the same time of the training process, the trained classifier model is verified by verification dataset, which consisted of the other images of the training dataset. In the verification, it takes the almost same procedure of training excepts to update the weights. In other words, in the verification, the process is only to calculate the accuracy and the loss, and it makes to monitor the classifier model accuracy and loss. After the training and verification process, if the results of accuracy and loss were not enough to classify, the classifier model, the datasets or both of them should be modified.

At last, the classification prediction was conducted by the trained classifier and the test dataset. **Figure 5.17** shows the flow of the prediction. To predict the class, the test dataset, which consisted of the other images of the training and verification dataset, is input to the trained classifier. The input images go through the classifier model by conducted each processing, and the outputs are the prediction results. In the prediction process, accuracy and loss are calculated as well.

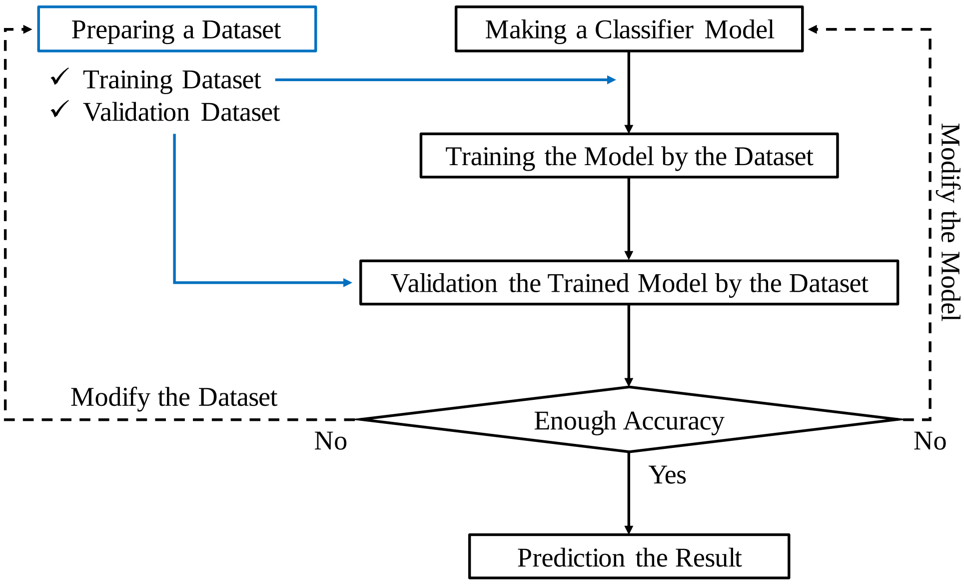


Figure 5.15 Flowchart of using CNN

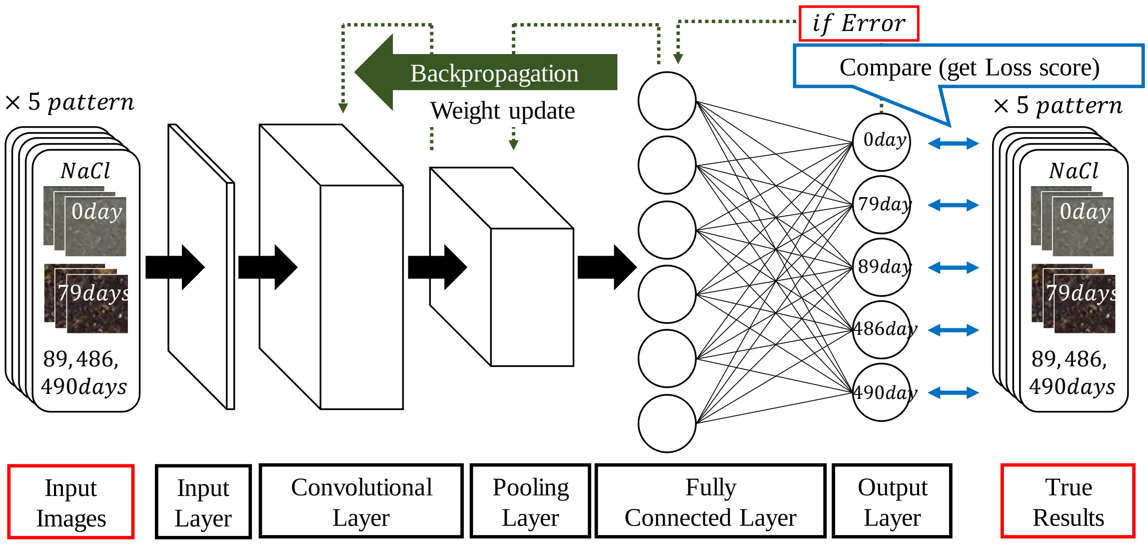


Figure 5.16 Flow of the training on CNN

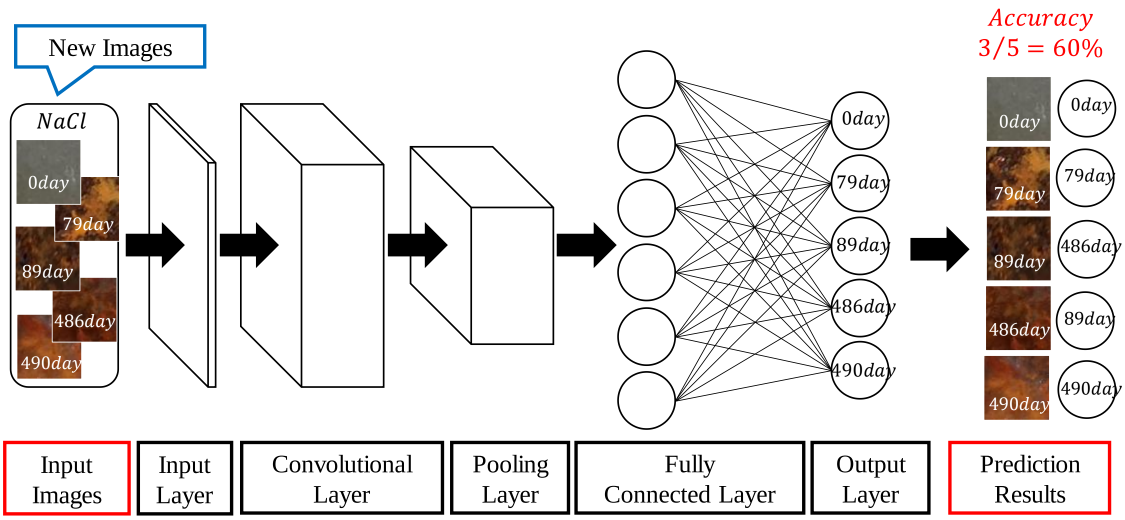
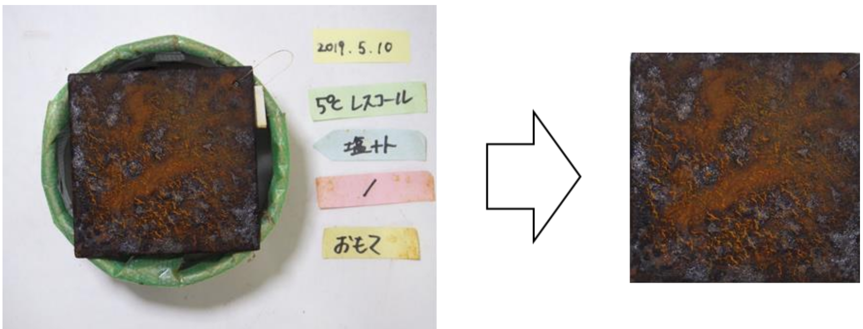


Figure 5.17 Flow of the prediction by CNN

5.4.3 Making the Input Datasets

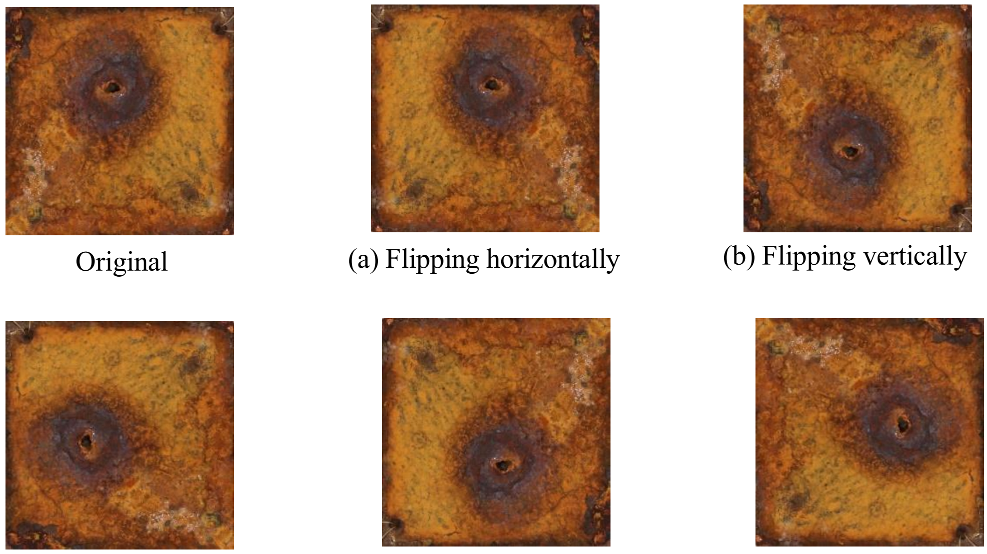
The images which were obtained from the corrosion test (**5.3**) had various pixel sizes. Also, the images include background images as shown in **Figure 5.18 (a)**. In order to remove the unnecessary information to conduct CNN analysis, the images were trimmed as shown in **Figure 5.18 (b)**. In this processing, the specimen was extracted and the pixel size of image height and width were aligned in each image because the input data of CNN is required the aligned pixel size of images.

When considering to use CNN, usually, a large number of images are required to obtain high accuracy classification results. However, the number of images obtained from corrosion tests is limited because it depends on the number of specimens. In this corrosion test, the numbers of specimens were three for each environment, and the images were taken from the front surface and back surface. In order to increase the number of images, the images were flipped and rotated as shown in **Figure 5.19**. In addition, the differences in the numbers of validation data are investigated. From those images, seven types of datasets are made as shown in **Table 5.5**.



(a) Before trimming (b) After trimming

Figure 5.18 Trimming the images



Original

(a) Flipping horizontally

(b) Flipping vertically

(c) Rotating 90°

(d) Rotating 180°

(e) Rotating 270°

Figure 5.19 Flipped and rotated the images

Table 5.5 The input image datasets

Augmentation method	Used dataset	Env.	Name	Number of images														
				Group 0			Group 1			Group 2			Group3			Group 4		
				Train.	Valid.	Test	Train.	Valid.	Test	Train.	Valid.	Test	Train.	Valid.	Test	Train.	Valid.	Test
Original		Env.: A	Dataset A	4	1	1		-		9	2	1		-		6	1	1
Filliping/ rotating	Dataset A/B	Env.: A	Dataset B	32	2	2		-		68	2	2		-		44	2	2
Filliping/ rotating	Dataset A/B	Env.: A	Dataset C	28	6	2		-		56	14	2		-		37	9	2
		Env.: B	Dataset D	28	6	2		-		47	11	2	23	5	2	71	17	2
		Env.: C	Dataset E	28	6	2	56	14	2	85	21	2	28	6	2		-	
		All env.	Dataset F	84	18	6	56	14	2	188	46	6	51	11	4	108	26	4

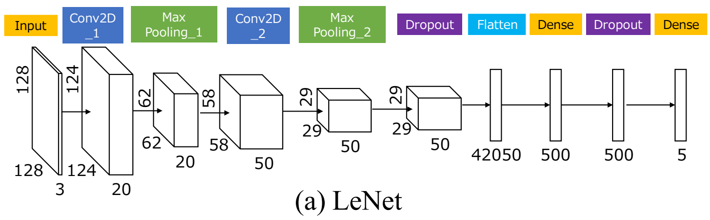
5.4.4 Training and Verification of the Classifier Model

As shown in section **5.4.2**, many kinds of CNN classifier models have been developed in the ILSVRC competition [77],[78]. In this chapter, two existing CNN classifiers, which are LeNet [80] and VGG19 [82], were employed to classify these images, then the accuracy and the loss were compared to choose more accurately classifier.

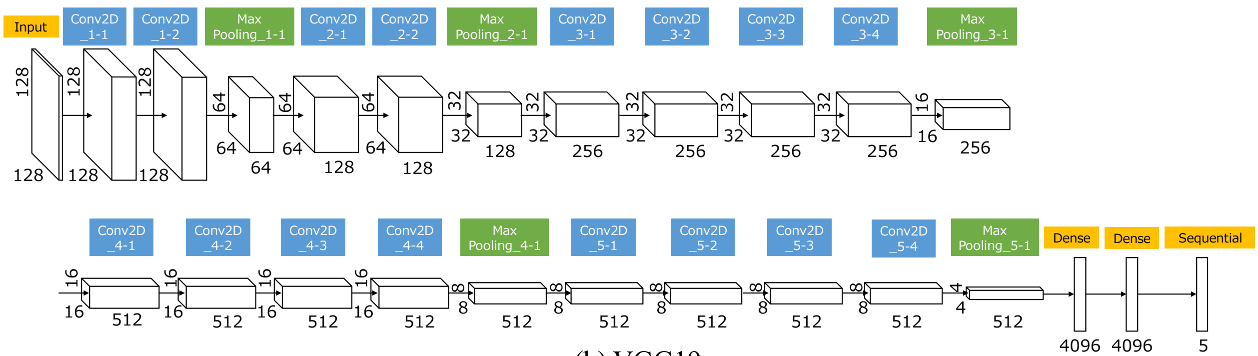
The network architecture of them is shown in **Figure 5.20**. In this comparison, Dataset A and Dataset B (**Table 5.8**) are used. **Figure 5.21** and **Figure 5.22** show the accuracy calculated by training dataset and loss calculated by training and validation dataset. The left vertical axis shows the value of accuracy, the right vertical axis shows the value of the loss, and the horizontal axis shows the numbers of epochs. As shown in **Figure 5.21**, for the small number of images, LeNet shows higher accuracy than VGG19. As shown in **Figure 5.22**, the accuracy was increased in VGG19 by augmenting the images. From the results, for Dataset B, these two classifiers did not have a big difference. In order to classify a more detailed class, VGG19 classifier was selected. Also, by comparison of **Figure 5.21** and **Figure 5.22**, the accuracy of Dataset B, which is the image augmented dataset, is higher than that of Dataset A. Thus, the augmentation by this method was effective in this dataset. In machine learning, overfitting is one of the biggest problems. The occurring of overfitting is judged by the gaps in training loss and validation loss. In the above results, there were not occurring overfitting.

In order to understand the effects caused by the differences in the numbers of images on validation datasets, the CNN analysis is conducted by VGG19 for Dataset C. In Dataset C, the validation data was set about 20% of the training data. **Figure 5.23** shows the accuracy and loss, and there was not a big difference between Dataset B and Dataset C.

From those comparisons, the VGG19 classifier was selected and the numbers of validation data were set about 20% of training data in this chapter.

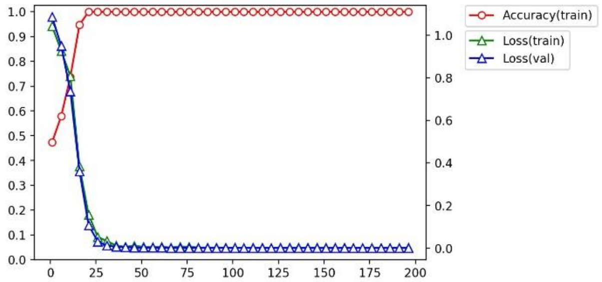


(a) LeNet

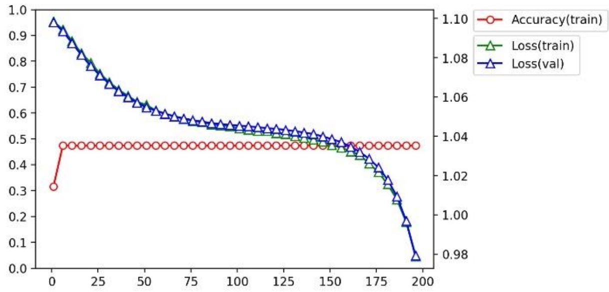


(b) VGG19

Figure 5.20 CNN architecture

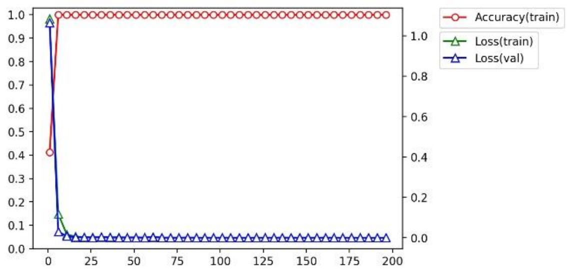


(a) LeNet

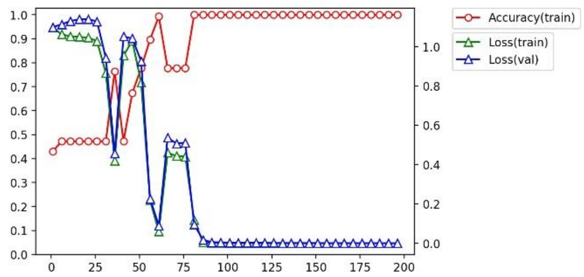


(b) VGG19

Figure 5.21 Training and validation result of Dataset A



(a) LeNet



(b) VGG19

Figure 5.22 Training and validation result of Dataset B

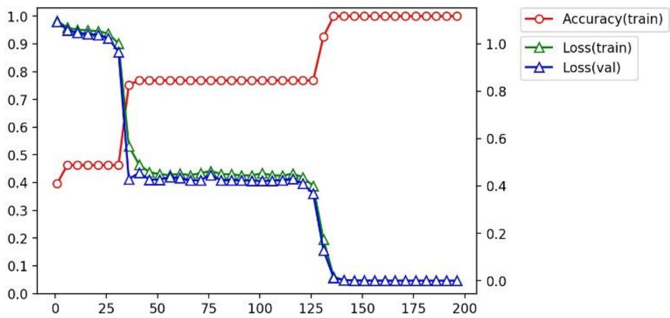


Figure 5.23 Training and validation result of Dataset C by VGG19

5.4.5 Comparison of the Classifiers Made by the Images from Different Environments

As discussed in **5.3.4**, the obtained images were classified based on the gained weight of the specimens, and the specimens were produced in three different environments. In order to formulate the CNN classifier, two types of input images datasets are considered: the classifier I to III based on the images obtained from each environment, which means, three classifiers are formulated based on Dataset C, Dataset D and Dataset E; the classifier IV based on the images obtained from all environments, which means, one classifier is formulated based on Dataset F.

Figure 5.23 to **Figure 5.26** shows the accuracy and the loss of these classifications. As shown in those figures, the overfitting was occurring only the classifier IV based on the images from all environment, as shown in **Figure 5.26**. Regarding the accuracy and loss calculated by test datasets, the results were as follow: for the classifier I, accuracy was 100% and loss was 0.03; for the classifier II, accuracy was 86% and loss was 0.35; for the classifier III, accuracy was 75% and loss was 0.33; and for classifier IV, accuracy was 87% and loss was 0.88.

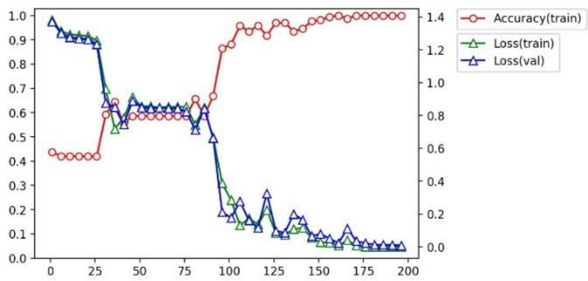


Figure 5.24 Training and validation result of Dataset D

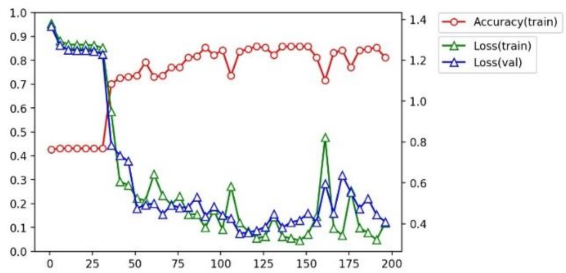


Figure 5.25 Training and validation result of Dataset E

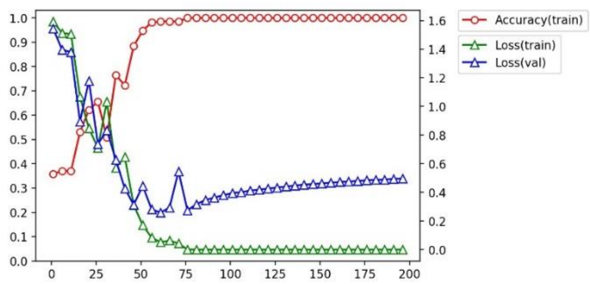


Figure 5.26 Training and validation result of Dataset F

The accuracy and loss were calculated by the test datasets. The test dataset contains the images obtained from the same environment of the training and validation datasets. Thus, the applicability for the images obtained from other environments is assessed by calculating the accuracy, precision and F-measure based on the other environments images datasets. For the classifier IV based on the images obtained from all environments, this calculation was not conducted because all environment's images were already used. In order to calculate the accuracy, precision and F-measure, the classification results were sorted by the four types as shown in **Table 5.9**, and the details are explained as follow: TP (True positive) is the correct classification; FP (False positive) is the wrong classification but it is classed for the safe side, i.e., the true result is Group 2 (the gained weight is 0.3 g < x < 5.0 g) but the classification result is Group 0 (the gained weight is 0 g); FN (False negative) is the wrong classification and it is classed for the dangerous side, i.e., the opposite of TP; and TN (True negative) does not occur in this classification. From the numbers of TP, FP and FN, the accuracy, precision and F-measure are calculated by **Equation 5.3** to **Equation 5.6**. **Table 5.10** shows the calculation results of accuracy, precision and F-measure for each classifier. For the classifier I to III, the accuracy for classifying the images from other environments was low. Therefore, the classification based on images is concluded as difficult for steel corrosion deterioration.

Table 5.6 Confusion matrix

		Actual	
		Positive	Negative
Predicted	Positive	TP (True Positive)	FP (False Positive)
	Negative	FN (False Negative)	TN (True Negative)

$$Accuracy = \frac{TP + TN}{TP + FP + FN + TN}$$ Equation 5.10

$$Precision = \frac{TP}{TP + FP}$$ Equation 5.11

$$Recall = \frac{TP}{TP + FN}$$ Equation 5.12

$$F - measure = \frac{2 \cdot Recall \cdot Precision}{Recall + Precision}$$ Equation 5.13

Table 5.7 The calculation results of accuracy, precision and F-measure for each classifier

	Classifier I	Classifier II	Classifier III
Accuracy	0.250	0.571	0.357
Precision	0.444	0.615	0.625
F-measure	0.400	0.727	0.526

5.5 Summary

This chapter aimed to assess the steel deterioration through the images, the corrosion tests and image classification by Convolutional Neural Network (CNN) analysis were conducted. The results are summarized as follows.

(1) From the corrosion tests results, there was a relationship between the exterior appearance and the gained weight of the corroded steel specimens. Therefore, the classification was conducted based on the gained weight of the specimens.

(2) CNN analysis was conducted by VGG19 classifier. Regarding the input datasets, the dataset contained the images obtained from different environments had the highest accuracy, 86.7%.

(3) On the other hand, to classify the images obtained from other environments by one classifier, the accuracy was low. Therefore, the classification based on images is concluded as difficult for steel corrosion deterioration.

From this chapter, in order to adopt to real bridges, the images used to construct the classifier should be obtained from each bridges for suiting to each environment.

Chapter 6

Conclusions

6.1 Conclusions

This thesis aimed to formulate an efficient method of utilizing advanced technology for bridge maintenance. Conclusions of each chapter are described as follows:

Chapter 2 reviews the state-of-the-art technologies that have been used in bridge inspection and identifies the ability of those technologies. The main concerns about applying novel technologies into the bridge inspection field are inspection quality (i.e. assessment accuracy), fieldwork efficiency and inspectors safety. Regarding the inspection quality, the inspection by advanced technologies reached the same or higher quality of that by human inspectors. As to use the technology for supporting human inspectors, there are benefits of utilizing advanced technologies. Also, many of the research is focusing on inventing new technologies to detect concrete cracks, rather than steel structure corrosion and fatigue.

Chapter 3 reports the implementation of distributed questionnaires and one-to-one interviews. The survey was conducted to identify the most effective way to adopt advanced technologies into bridge maintenance. The applicability issues were revealed as fairness cannot be guaranteed, explanation to account audit is a burden, and long-term technical support is not ensured. For addressing the issues, specifying certain advanced technologies in the inspection manuals, providing adoption examples, creating an evaluation system for advanced technologies, and establishing standards/guidelines by academic societies were clarified as the solutions via this survey. Also, it was revealed that even for similar applicability issues, the solutions are totally different which relying on the engineers' occupations.

Chapter 4 proposes a two-step investigation guideline, with which the procedures of implementing the advanced technologies in bridge inspection are clarified. The first step is a preliminary inspection by the advanced technology as the support to the second step, and the second step is a visual inspection from a close distance by human inspectors. At the preliminary inspection, the wide-view and narrow-view inspection were suggested to obtain the information for assessing the deterioration of the bridges. Also, performance requirements for advanced technology were defined, and the performance of the six types of technologies were verified in comparison with conventional visual inspection. With the proposed guideline, an inspection is conducted by six types of technologies on the prestressed concrete bridge. As a result of the two-step investigations, it can reduce the number of days required for the visual inspection.

Chapter 5 aims to assess the steel deterioration through the images, the corrosion tests and image classification by Convolutional Neural Network (CNN) analysis were conducted. From the corrosion tests results, there was a relationship between the exterior appearance and the gained weight of the corroded steel specimens. Therefore, the classification was conducted based on the gained weight of the specimens. CNN analysis was conducted by

VGG19 classifier. Regarding the input datasets, the dataset contained the images obtained from different environments had the highest accuracy. The prediction accuracy achieved 86.7%, thus, formulating the CNN classifier by the exterior appearances images based on the gained weight was one of the assessing methods which has high accuracy.

6.2 An Efficient Method of Utilizing Advanced Technology

6.2.1 Selecting the Advanced Technology for Utilizing Bridge Inspection

When considering to utilize the advanced technologies into bridge inspection, the advanced technologies which suit for the object bridge must be selected. In order to select the best technologies for the object bridge, the selecting method is suggested based on the findings of this thesis as follow.

Before to select the specific technology, defining the following information is recommended: the main material of the object bridge; the structure type (especially for steel bridge, the girder bridge or the truss/arch bridge); the technology type (the UAV/UAS, the robotic camera or others). Based on those information, the most suiting advanced technology is selected. For selecting the technology, the following three methods are suggested: first, to refer the verification results of six types of advanced technologies which used in this thesis and select the most suiting technology from these six technologies; second, to verify the advanced technology abilities by users based on the performance requirements which proposed in this thesis and the Inspection guideline [17]. As the verification method, conducting the field testing was suggested in Chapter 4; third, to select the technology from the catalog which published by Ministry of Land, Infrastructure, Transport and Tourism (MLIT) [82]. This catalog shows the performances of advanced technologies which verified by invention companies; fourth, to verify the advanced technology abilities by users based on the guideline published by MLIT [83].

6.2.2 Suggestion of the Method for Utilizing Advanced Technologies

From the findings of this thesis, an efficient method of utilizing advanced technology for bridge maintenance is suggested as shown in **Figure 6.1**. First, selecting the technology which used to inspection based on the methods suggested in **6.1.1**. Next, conducting the bridge inspection based on the two-step investigations which proposed in this thesis: the first step is the preliminary inspection by advanced technologies; the second step is the visual inspection by human inspectors. Finally, assessing the defects based on the images obtained from the two-step investigations by conducting image processing.

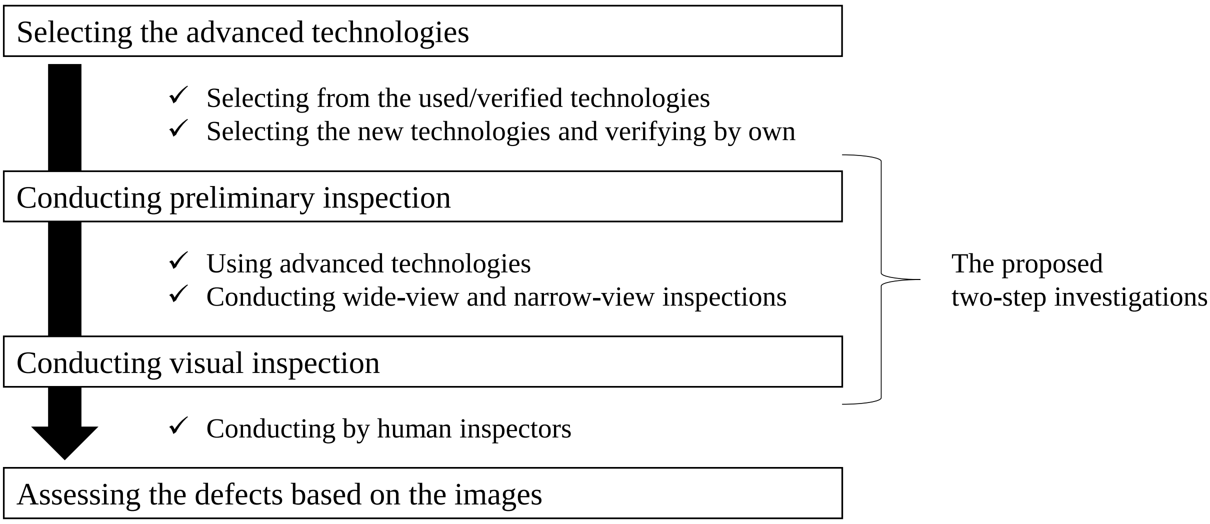


Figure 6.1 Suggested method for utilizing advanced technologies

6.3 Future Works

In this thesis, an efficient method of utilizing advanced technology for bridge maintenance was formulated. However, the ability of advanced technologies is still not enough as the alternative way to human inspectors. Regarding the assessment method for corroded steel, it was only based on the corrosion test specimens. In order to utilize this method for real bridges, the CNN classifier which can classify the corrosion on real bridges is required. In addition, the prediction method for future deterioration based on the assessment by the advanced technologies is desired. Therefore, the following researches are recommended to achieve more efficient bridge maintenance.

1. Investigating and enhancing the advanced technologies abilities

The abilities of advanced technologies which had investigated are still not enough as the alternative way to human inspectors, and they have some limitations to conduct bridge inspections. For example, the UAV/UAS cannot be used under the GPS-denied environment or unfavorable weather conditions because to keep stabling is difficult. Thus, the research to overcome those limitations are recommended. Also, formulating standards has been conducted, but it is thought that not enough yet. In order to accelerate the utilization of advanced technologies, changing or formulating the inspection standards should be conducted.

2. Formulating CNN classifier for real steel bridges

In order to utilize the CNN classifier for real bridges, the formulated classifier should be updated. As the updating method, to conduct the exposer test of steel specimens at the real bridges, and to obtain the images from both of the specimens and bridges. By adding those images, the CNN classifier model is expected that it will be more robust and will make more accurate predictions.

As the problems to obtain and use the images from real bridges, there is the difficulty to control and keep the same brightness of images. Therefore, not only utilizing raw images and colour information but also conducting the image preprocessing should be considered for adopting real bridges. The image preprocessing is a method to emphasize the characterization of images and to remove some noise in images. In previous researches about detecting the paint deterioration or weathering steel deterioration, the following two methods were considered: *median filter* [12] and *image thresholding* [86]. This method automatically calculates a threshold value from image histogram for a bimodal image, which is an image whose histogram has two peaks [87]. In order to utilize the CNN classifier for real bridges, conducting such image preprocessing is recommended.

3. Utilizing the rust composition information

In this thesis, the assessment method which classifies the images of corroded steels was conducted based on the gained weight of corrosion test specimens. The gained weight is one of the important information about corrosion deterioration, though it can be obtained from only specimens. Instead of the gained weight, utilizing the rust composition information is considered. The rust composition can show the progress of corrosion, e.g., γ-FeOOH is produced at the first step, β-FeOOH is produced in the presence of chlorides, and over time, both of them become α-FeOOH which is stable rust, etc. [68]. Regarding the analysis methods of rust composition, there are some methods: the Fourier transform infrared (FT-IR) spectroscopy analysis [66], X-ray Diffraction (XRD) analysis [71], and Raman spectroscopy analysis [88]. Among them, the FT-IR has the potential to analyse the rust composition of the corrosion products produced on the real bridges because the analysis requires only a small amount of rust.

In order to utilize the rust composition information to assess and predict the deterioration of steel bridges, formulating the following two methods are recommended: first, the method which can obtain the corrosion products produced on the real bridges by human inspectors or advanced technologies; second, the method which can assess the rust composition based on the images.

4. Formulating the prediction method based on the information obtained by advanced technologies

So far, the deterioration of bridges has been predicted based on the deterioration curve (**Figure 1.3**). This prediction method is based on the information which can be obtained by human inspectors. On the other hand, as shown in this thesis, the more detailed information on the bridge's deterioration will be obtained in the future with advanced technologies. Therefore, the prediction method based on more detailed information is desired. Regarding the prediction methods for bridge deterioration, the research using Markov process and Markov chain have been conducted [89]-[91]. In order to enhance those prediction methods, the utilization of the information obtained by advanced technologies should be considered and the research to formulate the more accurate prediction methods is recommended.

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