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Development of Bridge Inspection Method without Temporary Scaffolding by Using Optical Measurement Techniques

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Abstract

This paper shows the development of inspecting method about bridge without temporary scaffold, using and applying the optical measurement techniques about Unmanned Aerial Vehicle and Structure from Motion. In late years UAV and SfM progress innovatively, they are becoming common techniques. SfM is a technology for building a 3D model of the target structure only images taken from multiview. By using the UAV, it is possible to acquire an image from a view point which can not be confirmed normally, it can be more effective inspection.
Thereupon authors verified their techniques at the several bridges, and summarized the measurement range, photography method, measurement precision and investigation time for future use.

1. Introduction

Japan has approximately 700,000 bridges with lengths of 2 m or more, including about 500,000 with a length of less than 15 m. In 2014, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) imposed an obligation to conduct periodic inspections of all of those bridges at a frequency of once in 5 years by proximity visual inspection. However, the reality is that adequate inspection cannot be performed because many of those bridges are managed by municipal governments which are faced with financial problems and shortages of technical personnel accompanying low birth rates, an aging population and population declines. As an additional problem, the percentage of bridges (2 m or more) with ages exceeding 50 years since construction was 20% in 2016, but this is expected to increase rapidly to 44% in 10 years. Thus, the development of more efficient bridge inspection techniques has become an urgent issue. Moreover, in proximity visual inspections by the conventional techniques, it is necessary to approach the structure closely, but this requires a bridge inspection vehicle or lift-type vehicle or temporary scaffolding and special work by rope access, and traffic restrictions must be imposed during such work (Fig. 1). In this case, reduction of inspection costs/labor is an issue.

Therefore, the authors considered the possibility of labor-saving and higher efficiency in inspections by applying SfM (Structure from Motion) technique to bridge investigations. SfM has become a general technique as a result of improvements in personal computer (PC) performance and image analysis technique in recent years. As SfM is a technique for

Fig. 1 Inspection of bridge pier by suspended scaffold and rope access

constructing a 3D model of an object structures by using only images taken from multiple views, it would appear that inspection work is possible on a PC, by indoor work, simply by photographing images with an ordinary digital camera. Although remote measurement is also possible by using a 3D laser scanner, etc., the data acquired by this method is a point group and ultimately only reproduces shape. SfM can reproduce shape, and can also acquire real color information. Since SfM can grasp damage with high accuracy, SfM would seem to be an extremely effective technique for bridge inspections.
The use of unmanned aerial vehicles (UAV) has also spread rapidly in recent years, to the point where UAV have been called an "industrial revolution in the sky." By using UAV to photograph images for SfM analysis, it is possible to acquire images from views that normally cannot be observed, and it is thought that this will enable more effective inspections.
Therefore, we verified the effectiveness of damage investigation using UAV. The object of this verification was a concrete main tower of a cable stayed bridge.

2. Applied Technologies

2.1 SfM (Structure from Motion)

SfM is a technique which makes it possible to construct a 3D model of a photographed object based on images photographed from multiple views.
Unlike conventional photogrammetry, a characteristic point on the surface of the photographic subject is taken from different directions, aiming at an overlap of 80%, and the positions of that point and the camera, in other words, 3-dimensional coordinates (X, Y, Z), are automatically assigned in succession by the stereo method from combinations of the photographed images (Fig. 2). The SfM analysis generates a triangulated irregular network (TIN) of triangular plane elements with those coordinates as the tangent points based on the point group obtained in this manner, and constructs a 3D model. Here, a "characteristic point" means a point on the image and is a point with different luminescence, i.e., color and brightness, compared with its surroundings. For characteristic points p and q in regions (i, j) on two images, SfM calculates the sum total J of their differences of luminescence T compared with the surrounding areas in the respectively regions, that is, the degree of difference in color and brightness compared with the surroundings, and the points are judged to be the same point when the value of J is within a certain judgment value (Fig. 3). Because the photographed images are linked as texture in the generated TIN, a 3D model that faithfully reproduces the photographic subject is constructed. Figure 4 shows an example of the construction of a 3D model that was generated from photographic images by SfM analysis (partial excerpt).
It is also possible to give a scale to the generated TIN by setting targets with clear coordinate values at 3 or more points in the object range, and photographing those targets in the image.

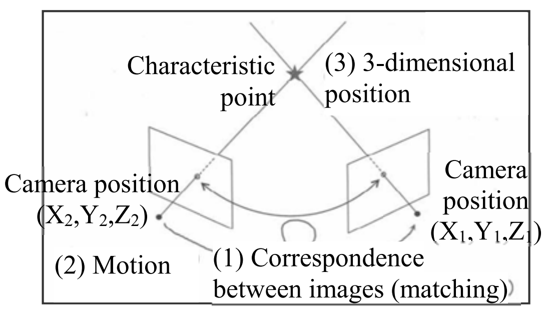
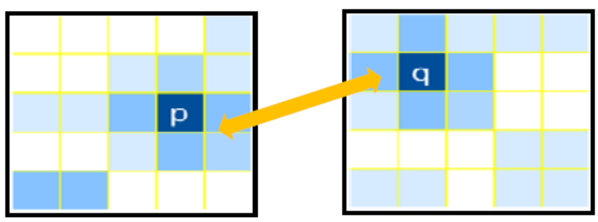


Fig. 2 Method of calculating characteristic point and camera position



$$J(p,q) = \sum_{i,j} \left| T_p(i,j) - T_q(i,j) \right|^2$$

Fig. 3 Judgment of characteristic point

Images photographed from multiple views

Result of SfM analysis

Fig. 4 Example of construction of 3D model by SfM

2.2 Comparison of Analysis Software

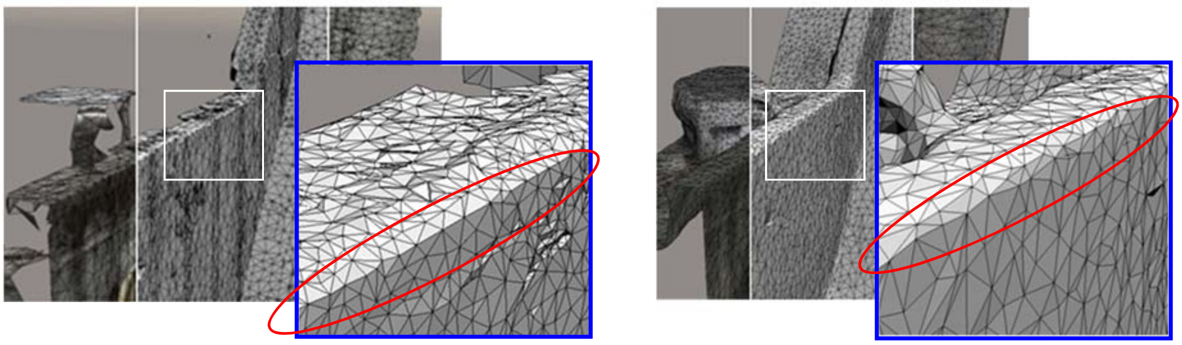
At present, several software programs which perform SfM analysis are widely used. Therefore, we compared the functions of the two types that seem to the most general, S software of A company and P software of B company. The results are summarized in Table 1. We also compared the 3D models generated by the respective programs by using the same photographed images of a concrete structure. As the result of the comparison, P software had many editing functions and high analytical flexibility, but the texture quality was somewhat low. On the other hand, S software had the minimum functions necessary for only generating models, with almost no editing functions, but a texture close with near-photographic resolution could be pasted. Furthermore, the reproducibility of the edges of the structure was also high (Fig. 5) because the TIN is generated by adjusting the edge line when performing automatic analysis. Since the priorities in bridge inspections are the reproducibility of the object structure and the degree of recognition of damage, the verification in this research was performed using the S software.

Table 1 Outline of SfM analysis software programs

Name of program	S	P
Maker	A Co.	B Co.
Principle	SfM	SfM
Camera calibration	No (parameter input is possible)	Yes
Point group editing	No	Yes
Measurement functions	Distance (viewer software)	Distance / Area / Accumulation
Ortho-image output	No	Yes
Edge line confirmation	Yes	No

TIN generated by S software

TIN generated by P software



Can adequately distinguish texture.
TIN of structure edge is generated considering edge line.

Quality of texture is somewhat low.
Edge of structure is not accurately expressed.

Fig. 5 Comparison of reproducibility of edge of concrete structure

2.3 UAV (Unmanned Aerial Vehicle)

UAV is a general name for small, unmanned aircraft. UAVs are already firmly established as a measurement technique in the fields of surveying and civil engineering, in addition to aerial photogrammetry, airborne LiDAR and ground measurements. By using UAVs, it is expected to be possible to investigate dangerous locations and the actual site immediately after disasters, which had been difficult in the past, and application to bridge inspections is also amply possible.
As shown in Fig. 6, a GPS antenna, gyro sensor and battery are mounted in a UAV, and automatic flight is possible by setting the flight path in advance. When a camera is mounted on the UAV, the operator manipulates the triaxial gimbal, which enables free vertical and lateral movement of the camera, while constantly monitoring the photographed range from the ground, and the equipment configuration makes it possible to trigger the shutter. Because the gimbal is controlled so as to automatically maintain a horizontal attitude, images that reflect the intention of the photographer can be acquired easily.
Table 2 summarizes the features of the UAV. In comparison with conventional radio-controlled aircraft, the UAV is superior in terms of compact size, light weight and stability, and safer flight is possible. Because it is motor-driven, it is comparatively quiet, but flight time depends on battery capacity and is short, at about 20 min. Although a license is not required in order to operate a UAV, the safety of UAVs has been questioned recently. As this became a social issue, Japan's Civil Aeronautics Act was revised in December 2015 so that it is now necessary to apply in advance to the Ministry of Land, Infrastructure, Transport and Tourism for flights in densely inhabited districts or over an altitude of 150 m, and for flights out of the operator's range of vision.
The verification in this research was carried out giving full consideration to the safety of the UAV, but there are also many restrictions for ensuring safe flight, as UAVs are easily affected by weather, radio waves and the like. Special care is also necessary in flights near roads, railroads, bridges, radio towers and high voltage electric power lines, and an experienced operator is indispensable.

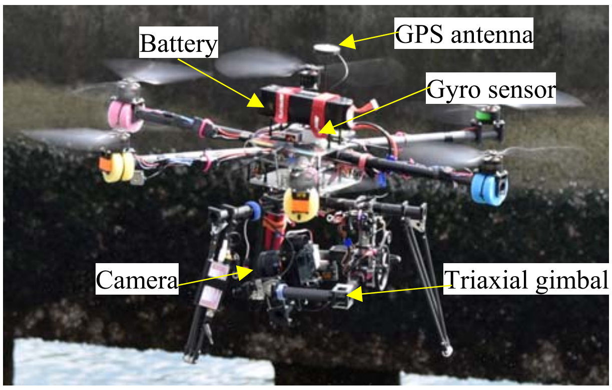


Fig. 6 Typical configuration of UAV (with camera attached)

Table 2 Features of UAV

Advantages	Compact and lightweight; easy to transport
	Operator does not require license.
	Operation is quiet (motor driven).
	Flight is stable due to large number of propeller blades.
	Easy to take aerial photographs
Disadvantages	Short flight time (about 20 min)
	Difficult to use in strong winds (10 m/s or faster)
	Approval is necessary for flights at altitudes higher than 150 m and flights in densely inhabited districts.
	Flight out of the operator's visual range is prohibited.

3. Verification at Long-Span Bridge

3.1 Outline

In bridge inspections in Nagasaki Prefecture, periodic inspections by proximity visual inspection are normally carried out once in 5 years. However, inspections of bridges which are greatly different in bridge scale or structural characteristics and inspections of bridges with a large effect on the region (priority maintenance control bridges) are also performed once a year (hereinafter, annual inspection). In annual inspections, the progress of deterioration of fixed observation points that can be observed from the ground is confirmed.

Accordingly, by using UAV-SfM in annual inspections, it is possible to confirm the condition of damage safely, quickly and at low cost, and at a wider range of points which normally can only be checked by proximity visual inspection using rope access or temporary scaffolding. In addition, since the damage assessments are performed from images, it is also possible to make quantitative judgments that are not dependent on the skill of the inspector, and comparisons over time are also easy by accumulating digital data. Moreover, if UAV-SfM can be established as a new inspection technique in place of proximity visual inspection, application to periodic inspections is also fully possible.

In this research, an investigation using SfM was performed for a concrete main tower (4P) of the Takashima-Hizen Bridge (cable stayed bridge) connecting Hoshika, Hizenmachi, Karatsu City, Saga Prefecture and Kozakimen, Takashima-cho, Matsuura City, Nagasaki Prefecture, as shown in Figs. 7 and 8. The results were compared with the existing inspection results, and the required inspection time was investigated. The following shows the data for the Takashima-Hizen Bridge.

Bridge name : Takashima-Hizen Bridge
Road name: Takashima-Hizen Line (General Prefectural Road)
Bridge length: L = 1251.00 m
Total width: W = 11.50 m
Superstructure type: 5 span continuous steel 2 main girder, 5 span continuous cable stayed bridge, 4 span continuous steel 2 main girder
Substructure: Abutments (2), piers (2)
Year constructed: 2009

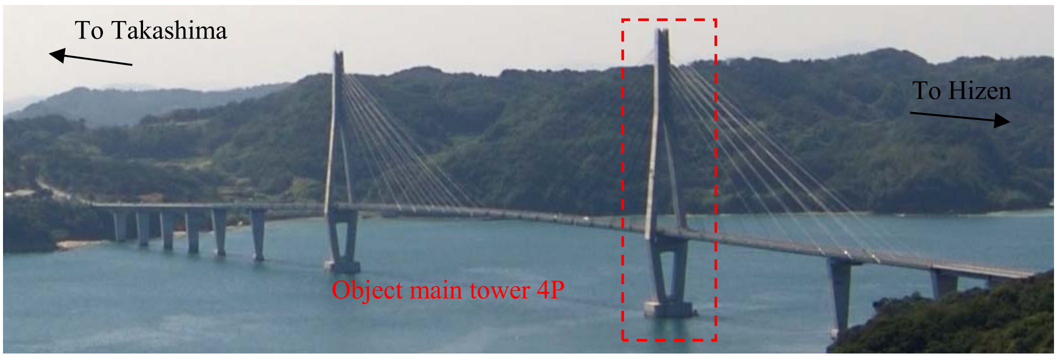


Fig. 7 Takashima-Hizen Bridge

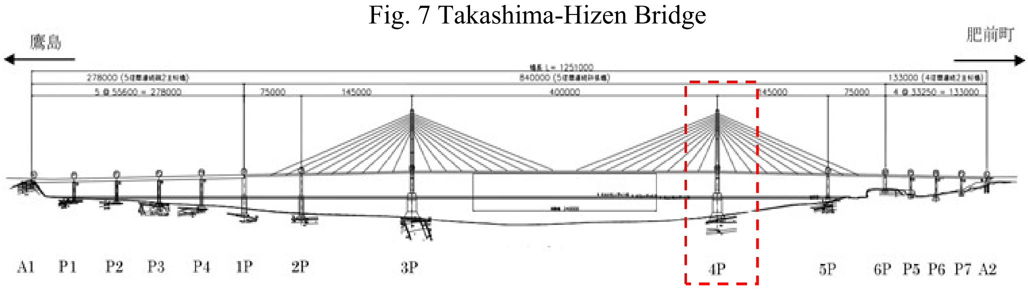


Fig. 8 Side elevation of Takashima-Hizen Bridge

3.2 Equipment Used

The specifications of the UAV and digital camera used in this research are shown in Table 3 and Table 4, respectively. The UAV used here was a Spreading Wings S900 manufactured by DJI with a maximum payload of 2.5 kg. This type was selected because strong winds were assumed above the site of the bridge, as it is possible to mount a somewhat heavy camera on the UAV, and the UAV has wind resistant stability. As the camera, a SONY mirrorless α7R was selected; this camera is equipped with a full-size sensor and enables high pixel photography (36 x 106 pixels). The photograph in Fig. 9 shows the Spreading Wings S900 with the attached α7R camera.

Table 3 Specification of UAV used

DJI Spreading Wings S900	
Payload	2.5 kg
Wind resistant stability	8m/s
Flight time	Upto 15 min
Flight distance	2 km
GPS	1 cycle

Table 4 Specification of camera used

Mirrorless SONY α7R camera	
Pixel number	7360 ×4912(36M),
Sensor size	35 mm full size
Focal length	35mm
Weight	580 g (including lens)

3.3 Content of Measurements and Work Procedure

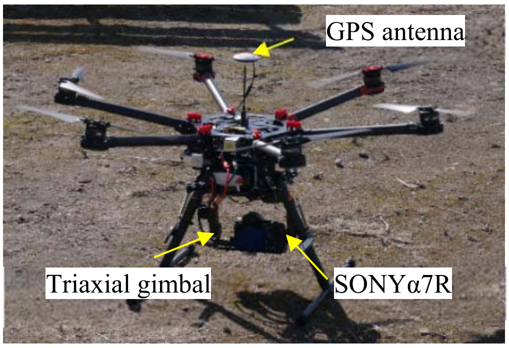
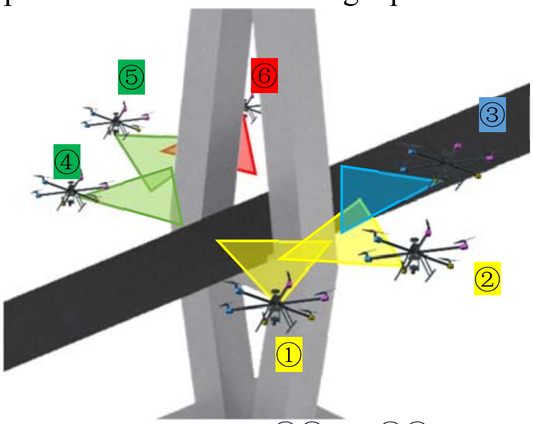


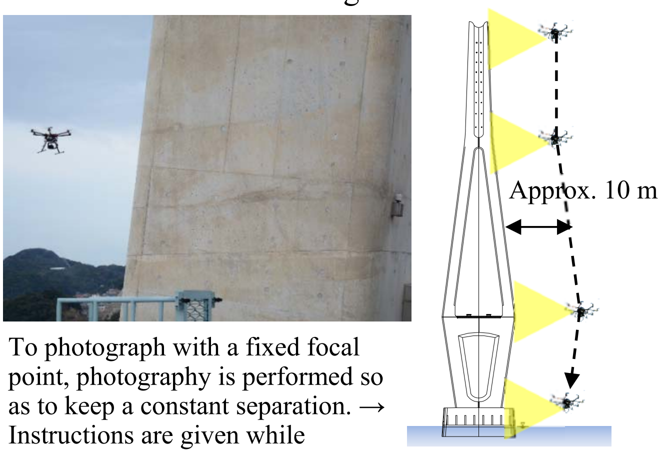
Fig. 9 UAV used

Using the UAV with the mirrorless SONY α7R camera, the sea side surface and the bridge axis side surface (45° direction) of the main tower were photographed (6 measurement lines shown in Fig. 10). Although photography with a resolution of 2 mm/pix is sufficient for capturing a crack with a 0.2 mm width on a concrete surface, the target resolution was set at 1.5 mm/pix to acquire higher resolution images. (See the statement that "In case of an image with digital resolution of 2 mm/pix, a crack with a width of 0.2 mm can be recognized on a PC monitor" in "Concrete Diagnosis Technique '16.) For photography with constant resolution, it is necessary to maintain a distance of approximately 10 m from the object surface, as shown in Fig. 11. Therefore, the UAV was flown by a 2-person team consisting of a UAV operator and an image checker. While personally confirmed the photographed images transmitted to a tablet in real time, the image checker determined the photographing distance and resolution from the size of the photographed object relative to the photographic angle of view, and gave instructions on the flight position to the operator (Fig. 12). In order to generate a 3D model from the photographed images by SfM analysis, interval photography was performed at 1 frame/sec (fps), assuming 80% overlap of all of the adjacent images. To give a scale to the generated TIN, 3D laser measurements were performed, and the coordinates of arbitrary points were used as the target points. The procedure of the work is shown in Fig. 13.



The photographs of ①② and ④⑤ were taken with single flight

Fig. 10 Image of photography (6 measurement lines of outer side of main tower)



To photograph with a fixed focal point, photography is performed so as to keep a constant separation. → Instructions are given while monitoring transmitted images.

Fig. 11 UAV flight plan

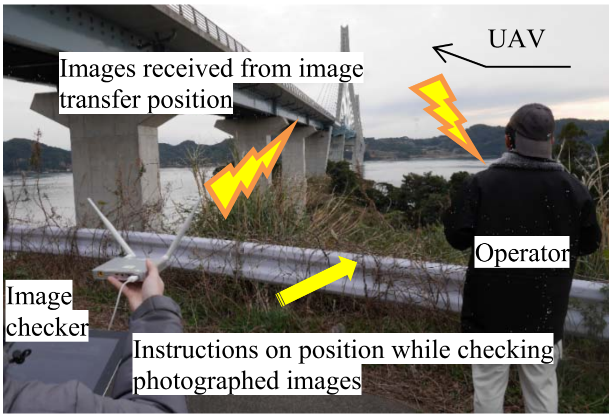


Fig. 12 System during photography

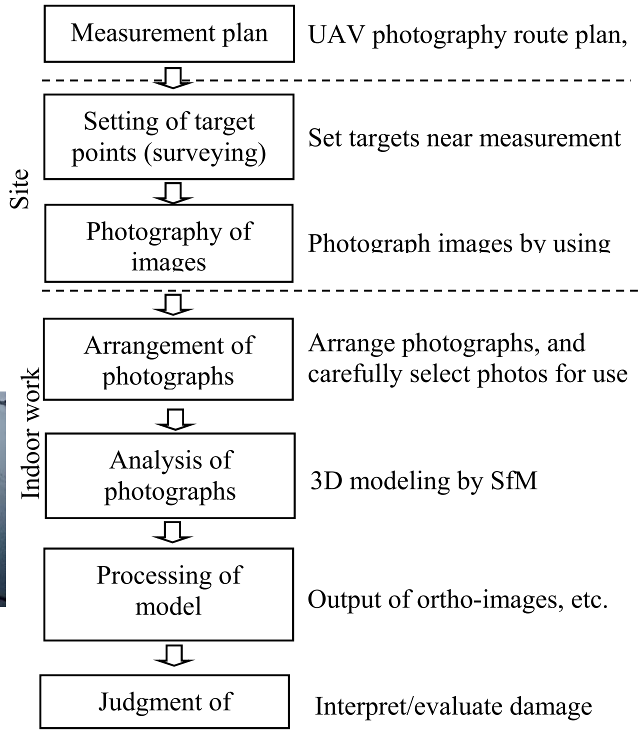


Fig. 13 Work procedure


Fig. 14 Example of photographed image

3.4 Results of Photography

A total of 4 flights were carried out to photograph the 6 measurement lines of the sea side surface of the main tower. One flight was completed in about 12 min. Because interval photography was performed at 1 fps, a total of 600 images were acquired. By using the UAV, it was also easy to obtain images of the top part of the tower, which normally can only be checked by rope access, etc., and the condition of the concrete surface could be recognized by enlarging the images. Figure 14 shows an example of a photographed image of the top part of the tower, together with an enlarged view.

3.5 Procedure from SfM Analysis to Generation of Ortho-Image

Conventional photogrammetry was extremely laborious, as it is necessary to perform manual orientation work for the enormous number of images taken by the UAV, and much time was required to match all of the images, but in SfM analysis, substantial labor-saving is possible because automatic orientation is performed using characteristic points. Furthermore, in photogrammetry, faithful reproduction of shapes with depth was difficult, but with SfM, even images photographed from multiple directions can be analyzed easily, and it is also possible to generate models of surfaces with depth.

Figure 15 shows the analysis procedure and results. First, images that are blurred due to camera shaking or are out-of-focus are eliminated from the photographed images. In UAV photography, there are a large number overlapping photographs because interval photography is performed continuously from take-off to landing of the UAV. Therefore, while eliminating poor-quality images, images that secure the proper overlap are carefully selected. Next, these carefully-selected images are analyzed by automatic orientation, and the characteristic points and camera position are calculated.

At this time, the rough shape is checked on the PC, and if a shape is not formed, the analysis is repeated several times. A TIN is then constructed based on the calculated characteristic points, and a 3D model is generated by mapping, using the photographed image as the texture. Because this model can be enlarged/reduced, moved and rotated on the PC, it is possible to examine the model from any arbitrary view. The generated model can also be exported to other CG programs (in this research, Autodesk 3dsmax was used), ortho-images can be output, and base drawings for damage investigations can be generated. The time required for generation of a model by SfM is approximately 5 days.

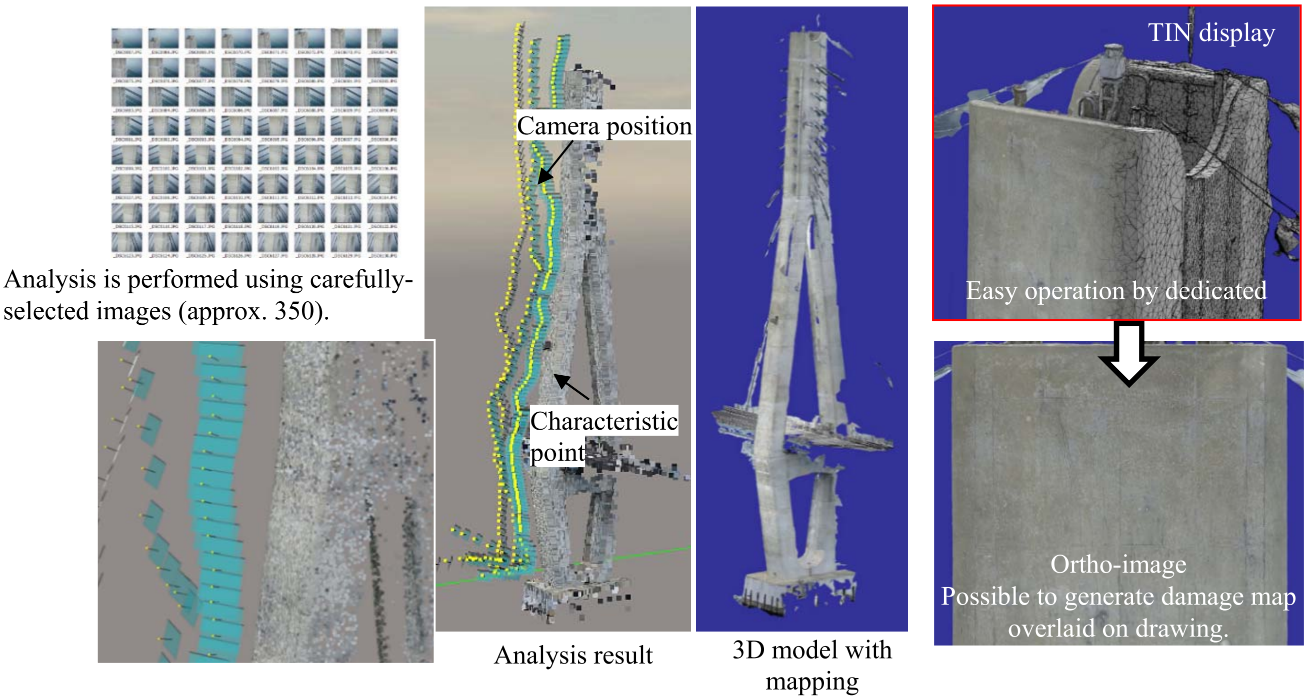


Fig. 15 Procedure from SfM analysis to generation of ortho-image

3.6 Generation of Damage Map

Ortho-images with resolution of 2 mm/pix were generated from a 3D model with mapping, which was created by SfM, and damage mapping was performed for items that could be read from the images. The object items were cracks, exfoliation and exposure of rebars, water leakage and free lime, fallen out parts, and damage of repair/reinforcing materials as shown in Periodic Bridge Inspection Procedure issued by MLIT. Among these, a tree-structure filter is sometimes used in automatic judgments of the position and width of cracks, but in this research, a Crack Position/Width Interpretation and Mapping System utilizing a Crack Index (CI) was used. This system extracts the crack position and width semi-automatically from the correlation between crack width and the total of characteristic values, CI, of the cracked part.


Fig. 16 Condition of damage extraction work

Damage interpretation is performed on multiple screens, as shown in Fig. 16. On the screen at the left, damage is extracted from the ortho-image on the lower screen, using the Crack Position/Width Interpretation and Mapping System, and this damage is described on the screen. In this process, when the image resolution is 2 mm/pix, a range of approximately 3.5 m x 1.5 m is displayed on one screen, and damage is searched in this range. At this time, a detailed interpretation is performed by enlarging the image on the PC so it is approximately on the same level as in visual interpretation. The screen at the right displays the 3D model and is used in checking the object range in 3 dimensions from various views. By searching for damage while observing the 3D model, it is also possible to check for deformation, such as differences in level and swelling, which cannot be seen in 2 dimensions. This is an extremely effective technique, in that the work be performed under calm conditions indoors. It is also possible to convert the damage shown on the screen to CAD data and transfer it to control charts, etc.

3.7 Discussion

No conspicuous damage of the main tower which was the object of this study was found as a result of checking for damage by using the photographed images and 3D model. In this, however, the SfM results were also compared with the results of visual inspection within the range possible.
In the SfM results, as shown in Fig. 17, it was possible to extract approximately the same cracks as in the visual investigation in FY 2014. However, even though fine cracks were extracted in detail in both the visual investigation and the investigation by SfM, slight differences can be seen in the positional relationship. The visual investigation was considered to be inferior in terms of positional accuracy because the results were recorded in sketches, but when using SfM, positional reproducibility was extremely high, as the images were recorded and stored at the same time. Furthermore, while all of the visual inspection results are described as 0.1 mm in width, the SfM results were generally on the order of 0.2 mm, but also included some cracks that were judged to be 0.5 mm. When cracks are extracted by using CI, there are deviations in the results due to the color or soiling of the concrete surface. While it is conceivable that the results of this study were influenced by soiling, evaluation is difficult with only this object range. For the crack width, it is considered necessary to carry out continuing verification work focusing on bridges where clear true values can be obtained, and clarify the relationship between the acquired images and crack width.
In conventional visual inspections, many parts are left to the skill and interpretation of multiple personnel, and quantitative judgment is difficult, for example, in records of the position of damage, etc. However, in investigation by SfM, quantitative judgment is possible because damage interpretation is performed based on images, and it is also possible extract 3D information such the cross section, etc. for arbitrary positions from the 3D model. Moreover, comparisons of changes over time, the progress of deterioration, and other time-related phenomena can also be checked easily by acquiring the same data periodically. Because value-added date such as 3D models, images, etc. is accumulated in this manner, it can be said that this investigation technique has great merit for future operation and maintenance.

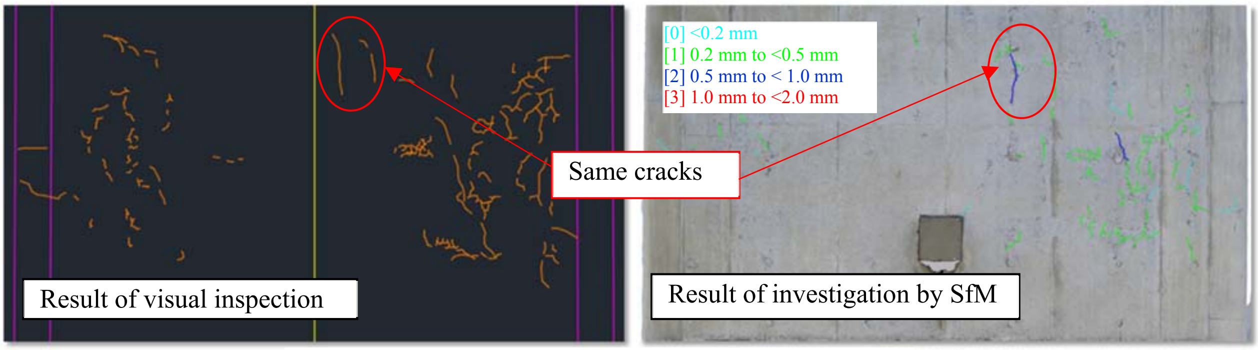


Fig. 17 Comparison of investigation results

3.8 Issues

Although investigation by UAV-SfM is an effective technique, as described above, the following issues also exist.

Adequate consideration of the safety of the UAV is necessary. Particularly when investigating a bridge, as was done in this study, it is important to be aware of weather conditions, etc., as winds blow constantly. Although a large labor-saving and low cost are possible in field work if UAV-SfM is used, the analysis work requires considerable time. Moreover, since the 3D model is constructed based on characteristic points in SfM, certain parts cannot be analyzed, for example, uniformly-painted steel structures in which extraction of the characteristic points is difficult, members with repeated patterns, thin members, etc. Furthermore, items such as lifted defects in concrete, which must be investigated by a contact technique, are difficult to interpret from images. It is thought that this is the reason why investigation by images, in its current state, has been evaluated as unsuitable as a substitute for proximity visual inspection.

4. Conclusion

Use of SfM technique to generate 3D models from images photographed employing a UAV and create damage maps is sufficiently applicable as an inspection technique, and can also realize a large labor-saving and cost reduction in comparison with investigations in which temporary scaffolding is erected. Investigation using images still has not be recognized as a substitute for proximity visual inspection because its crack width detection accuracy is insufficient and it is not possible to detect lifting, which requires investigation by a contact technique. However, a technique using images is considered effective as a primary screening method. Primary screening to select the locations where detailed inspection is necessary makes it possible to allocate time, budgets and personnel appropriately, and thus enables effective, efficient inspections.

Application of UAVs in investigations can be expected in a variety of fields (river surveys, dam investigations, etc.), and use in the rough design of countermeasures during disasters is also amply possible. However, since safety must be secured when using a UAV, from the viewpoints of safety and cost, UAVs are not necessarily effective in all cases. Depending on the required results, an appropriate plan should be prepared, and SfM analysis by manual photography, etc. should also be used effectively. Moreover, because an as-built 3D model that faithfully reproduces the present situation can be constructed by SfM analysis, expansion to BIM and CIM, while continuing the current dissemination of this technique, is considered effective.

In the future, it will be necessary to carry out ongoing verification work and clarify solutions for issues such as clarification of the relationship between crack width and photographic resolution, improvement of detection accuracy by comparison with true values, and shortening of analysis time.

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