

Can technology improve routine visual bridge inspections?

McRobbie, Wright and Chan

<http://dx.doi.org/10.1680/bren.12.00022>

Paper 1200022

Received 19/09/2012

Accepted 10/10/2014

Keywords: bridges/field testing & monitoring/
maintenance & inspection

ice | proceedings

ICE Publishing: All rights reserved

ice
Institution of Civil Engineers

publishing

Can technology improve routine visual bridge inspections?

- 1 **Stuart G. McRobbie** MSc, CPhys
Researcher, Technology Development, TRL, Wokingham, UK; PhD Student, School of Civil Engineering, University of Birmingham, Birmingham, UK
- 2 **M. Alex Wright** BSc, PhD, CPhys
Group Manager, Technology Development, TRL, Wokingham, UK

- 3 **Andrew Chan** Eurlng, MPhil, PhD, MBCS, CEng, FEANI, FHEA
Professor, School of Civil Engineering, University of Birmingham, Birmingham, UK; now Deputy Dean of Information Technology and Engineering, Federation University, Australia



This paper discusses the role of visual inspections in the UK highways bridge inspection regime, and how current practice results in inspection data that are less reliable than they could, and should, be. Evidence that visual inspections in general are not totally reliable is discussed. Similar problems have been overcome in other areas, such as pavement inspection, by using technological aids during the data collection and inspection process. It is hoped that better bridge condition data could be obtained by making use of technology to assist the visual inspection process on bridges. Some of the ways in which images could be recorded to make the inspection process more reliable and reproducible are discussed, and a prototype system that has been developed with the aim of providing a full, high-resolution image record of the visual condition of a bridge, which is suitable for use, is presented.

1. Introduction

Until the 1960s it was typically assumed that bridges required little maintenance or inspection. However, a number of high-profile bridge failures focused attention on the issue, and led to calls for the development of routine inspection procedures and equipment.

In the 1970s the Organisation for Economic Co-operation and Development (OECD) concluded that, in many countries, the process of bridge inspection had only recently been formalised and regulated (OECD, 1976). The OECD Bridge Inspection Group proposed an inspection regime that was adopted by many countries. This introduced a step change in the way bridge inspections were planned and performed. However, reviews of current inspection practice across a range of countries (Bevc, 2002; Bevc *et al.*, 1999; Moore *et al.*, 2001b; PIARC, 2011), suggest that little has changed in inspection regimes since then, and the recommendations made in the 1970s still form the basis of many current bridge inspection philosophies, including the UK. The precise details of the inspection frequency and thoroughness vary by country and sector, but generally the regimes are based on relatively frequent visual inspections and less frequent detailed

testing where visual inspections have identified a potential problem.

Visual inspections are a relatively cost-effective and simple approach to collecting information about the condition of a structure. A good inspector can identify many types of defect before the integrity of the structure is compromised. However, there is a wealth of evidence, from civil engineering (Moore *et al.*, 2001a), and other sectors (Spencer, 1996), to suggest that the objectivity, reliability and reproducibility of visual inspections is not as high as would be desirable.

A range of approaches have been proposed to improve the quality of data from visual inspections. These include training of inspectors and additional quality controls on the inspection results, but could also include alternative inspection approaches and the use of technology.

Technological approaches have been successfully adopted in many areas, including the inspection of railway sleepers (Yella *et al.*, 2009), the detection of defects in ceramic tiles (Elbehery *et al.*, 2005) and the automated assessment of road pavements

Offprint provided courtesy of www.icevirtuallibrary.com
Author copy for personal use, not for distribution

(Ferne *et al.*, 2003) using devices such as the Highways Agency road research information system shown in Figure 1, which can measure, at traffic speed, a range of pavement condition parameters.

Knowledge and techniques already exist for using technological means to improve the quality and reliability of data that were previously collected using traditional visual inspection methods. This paper will discuss some of the problems with visual inspections as a means of collecting bridge condition data, and the potential for making use of technological approaches as used in other sectors to produce more reliable and objective visual inspection data.

2. Role of visual inspections in bridge inspection regime

The need for bridge inspection and maintenance is not only constrained to highways bridges; for example, similar inspections are required on rail bridges. The research described in this paper has been carried out specifically considering the inspection regulations for, and problems facing, visual inspections on the UK Highways Agency network. Inspectors undertaking inspections in other sectors may be operating under different regulations and requirements, but the basic issues and problems with visual inspections will be similar, and there is no reason why methods developed for use on highways bridges cannot be applied on bridges over waterways or railways.

The requirements for inspecting highway bridges on trunk roads in England are defined in Volume 3, Section 1, Part 4 of the *Design Manual for Roads and Bridges* (BD 63/07) (Highways Agency, 2007). This gives details of the different levels of inspection to be used on trunk road structures. The five inspection levels are summarised in Table 1.

Visual inspection is the key component of general and principal inspections. These inspections are required to detect and record defects and changes in the condition of the bridge, enabling the condition of the structure to be monitored. Clearly, such inspections only detect visible defects, or visible manifestations of hidden defects. Special or assessment inspections, or alternative forms of structural condition monitoring, may detect defects that cannot be detected visually, but these inspections will only be undertaken when the visual inspection has identified that there may be something worth investigating.

To understand how useful general inspections (GIs) are felt to be, and how the guidance is applied in practice, engineers responsible for bridge inspections and maintenance were consulted about a number of issues affecting the collection and use of visual bridge inspection data. The consultation took the form of a number of face-to-face interviews as well as a questionnaire that was distributed by email. In total 42 responses were received during the consultation and interview process. Table 2 shows some of the results of the consultation.

It can be seen that almost 80% of the consultees either 'agreed' or 'strongly agreed' that GIs were the primary source of information about the visual condition of the bridge, although only 50% 'agreed' or 'strongly agreed' that a GI would record all the visual defects that were of interest, leaving a significant gap of engineers who agree that GIs are the main source of information, but who do not feel confident that they provide information on all the defects of interest. In fact, the data in Table 2 show that over 80% of consulted engineers 'agree' or 'strongly agree' that GIs sometimes fail to spot defects. Over 55% of engineers would accept a GI that did not fail to detect cracks wider than 0.4 mm. In addition, only 50% of engineers in the consultation 'agree' or 'slightly agree' that the results of GIs are consistent from inspector



(a)



(b)

Figure 1. Survey vehicles for high-speed condition measurement of pavement surface condition: (a) HARRIS1 and (b) HARRIS2

Offprint provided courtesy of www.icevirtuallibrary.com
 Author copy for personal use, not for distribution

| Inspection | Interval | Purpose and description |
|----------------|----------------------------------|---|
| Safety | Typically weekly | A cursory check of those parts of any structure that are visible from the highway to identify obvious dangers and deficiencies. Inspections are often carried out from a moving vehicle as part of an inspector's other duties. |
| General (GI) | Every 2 years | A visual assessment of the condition of the structure performed without any special access equipment or traffic management arrangements. Reports on what can be seen from relatively accessible parts of the structure. |
| Principal (PI) | Every 6 years | Require the inspector to get close access to all parts of the structure, enabling the inspector to touch the structure and examine it from a variety of angles and directions. |
| Special | When GI or PI indicate necessity | There is no 'standard' special inspection: each one is tailored to the needs of the particular structure or element being inspected. These inspections are carried out when a need is identified. |
| Assessment | When necessary | Performed to collect the information required to undertake a structural assessment. |

GI, general inspection; PI, principal inspection

Table 1. UK Highways Agency bridge inspection regime

to inspector, and 57% agreed or strongly agreed that the results of GIs were statements of fact, not opinion.

there are concerns that the data may be incomplete, inconsistent and subjective.

These findings give credence to the idea that visual inspections play a key role in the bridge management process, but that there are concerns about the data they produce. Specifically,

Further questions dealt with the process of undertaking an inspection and found that, broadly speaking, the inspection process has three phases: planning; inspection; reporting.

| General inspections ... | Strongly disagree | Disagree | Slightly disagree | Neither agree nor disagree | Slightly agree | Agree | Strongly agree |
|--|-------------------|----------|-------------------|----------------------------|----------------|-------|----------------|
| ... are the primary source of information about the visual condition of the bridge | 0.0 | 7.1 | 3.6 | 0.0 | 10.7 | 28.6 | 50.0 |
| ... record all visual defects that may be of interest to the engineer | 3.6 | 7.1 | 14.3 | 0.0 | 25.0 | 42.9 | 7.1 |
| ... sometimes fail to spot small defects that are not close to the inspector | 0.0 | 3.6 | 3.6 | 3.6 | 7.1 | 60.7 | 21.4 |
| ... provide consistent data (you would expect separate inspections of the same bridge, by separate inspectors to produce similar inspection reports) | 0.0 | 7.1 | 10.7 | 3.6 | 28.6 | 39.3 | 10.7 |
| ... provide objective data (the findings in the inspection report would be statements of fact, not opinion) | 0.0 | 3.6 | 7.1 | 3.6 | 28.6 | 50.0 | 7.1 |
| What is the largest crack width that it might be acceptable to fail to detect in a general inspection (in mm)? | 0.2 | 0.4 | 0.6 | 0.8 | 1 | 2 | 4 |
| | 33.3 | 11.1 | 18.5 | 11.1 | 18.5 | 7.4 | 0.0 |

Table 2. Consultation results

Offprint provided courtesy of www.icevirtuallibrary.com
Author copy for personal use, not for distribution

Before going on site, the consultees indicated that it is standard practice to familiarise themselves with the type, layout and history of the bridge, and examine available inspection reports for the structure. The consultees indicated that photographs would be taken while on site in almost all inspections, but that usually fewer than 20 photographs would be taken. There is no official guidance on the number of photographs to be taken during an inspection – generally the inspectors try to take ‘enough’ photographs, which will depend on the size, type and condition of the bridge. The consultees were asked how frequently they would use tools to provide a better view. Over 73% of respondents stated that they would use such tools less than 60% of the time, with almost 40% of the responses indicating that they would either never use such tools or use them in fewer than 20% of their inspections. Bearing in mind that the consultees indicated they would accept a system that detected all cracks wider than 0.4 mm, then the authors contend that there will be large parts of bridges in which this is not possible due to viewing distances and lighting conditions, coupled with the lack of special access arrangements.

The inspector completes an inspection report, including the location, type, severity and extent of any detected defects, as well as the overall bridge condition, and uses the photographs taken on site to illustrate the report. The photographs, however, only show what the inspector deemed worthy of photographing during his or her visit to the site, and are not a complete record of the bridge condition.

In summary, visual inspections are a key component of the UK highways inspection regime. Most of the information available to the engineers regarding the condition of their bridges comes from such inspections, and it is these data that are used to determine whether or not additional more specialised testing or inspections are necessary. The consultation process established that engineers accept photographic evidence to assist in determining the condition of a structure. However, the photographic evidence is currently being recorded and presented to the engineers in an unsystematic manner. Among other things, this produces only a partial image record of the structure, and makes it difficult to compare photographs from successive inspections, as changes in the images may arise from changes in the condition or differences in the way the image was taken. The value of the inspection data is largely derived from the engineers applying their knowledge and experience to the data presented to them, and it is therefore vital to ensure that these data are collected as consistently, accurately and objectively as possible.

3. Problems with visual inspections

Visual inspections are common in numerous fields including aviation (Spencer, 1996), electronic engineering (Schoonard *et al.*, 1973) and telecommunications (Jamieson, 1966). The reliability of inspection data has been extensively investigated

over many years. These investigations include many studies that have considered the factors that influence the quality of visual inspection data.

Inspectors performing bridge inspections have to be able to detect a relatively large number of potential defects, which are often only subtly different in appearance from the background conditions. It is known that the number and varieties of potential defects for which the inspector must look can influence the success of the inspection, as can the clarity of distinction between sound elements and defects. Thus, if the inspector has only to look for a single type of defect that is clearly and obviously distinct from the background then it is an easy task to perform (Megaw, 1979). This is not the case in bridge inspections. Gallwey and Drury (1986) performed a study investigating the effect of the number of distinct defect types that the inspector must consider during an inspection. They agreed with the conclusion of Megaw (1979) that, as the number of potential defects increases, the reliability of the inspection decreases. In addition, bridge inspections must often be undertaken from a distance, under variable lighting and environmental conditions.

The studies referenced above concerned themselves with issues affecting the reliability of visual inspections in general, or in industries other than civil engineering, but their findings can be applied to other areas where visual inspections are used. Other studies (Lea, 2005; Rens and Transue, 1998) have more explicitly considered the problems with collecting bridge condition data, a number of which have identified the need for inspector training (Estes, 1997; Purvis, 1988).

Training can help inspectors recognise the importance and implications of different defects in different locations, and how these might differ from structure to structure, but it is not a panacea. Moore *et al.* (2001a) undertook a large-scale trial involving 49 practising bridge inspectors inspecting a series of test bridges. The study focused on the two most common types of inspection undertaken in the USA, routine inspections (analogous to UK GIs) and in-depth inspections (UK principal inspections). During the routine inspections the bridges were assessed using the standard condition rating guidelines in the Federal Highway Administration (FHWA) *Bridge Inspector's Training Manual* (FHWA, 1995). The study found that the spread of condition ratings reported (from none to nine) across the routine inspections showed a normal distribution. On average, each assessed element of the bridges had somewhere between four and five condition assessment ratings assigned to it, with a maximum spread of six.

Inconsistent, variable inspection results make it hard to know the relative condition of different bridges inspected by different inspectors, and also make it hard to monitor changes in bridge

Offprint provided courtesy of www.icevirtuallibrary.com
Author copy for personal use, not for distribution

condition over time. The inspectors taking part in the Moore study were all trained, and yet still produced widely variable results. It is clear that delivering consistent visual inspections is not straightforward, particularly when multiple defect types may be present, and when these defects are not clearly distinguished from the background conditions, as is often the case on bridges.

4. Potential technological solutions

Technological techniques are often adopted in cases in which the repeatability, reproducibility and objectivity of a measurement need improvement. There have been calls (Middleton, 2004; Woodward, 2006) for the use of such technology in bridge inspection. Technological techniques are widely accepted in other areas of bridge condition monitoring, such as ground penetrating radar, or acoustic monitoring (Chang *et al.*, 2003). Research into the use of technology in various aspects of bridge condition assessment seems to have overlooked the problem of collecting routine visual inspection data, and has instead focused on more complicated and specialised applications (Uhl *et al.*, 2011). Given that visual inspections are the foundation on which bridge condition knowledge is based, and are likely to remain so for the foreseeable future, the use of technologies that could improve the inspections should be explored. Such approaches could be applied to the bridge inspection process at various levels and stages, from data collection to data presentation and interpretation. However, what technological assistance or automation is available for routine visual bridge inspections?

Technology to aid in the collection of visual inspection data is likely to be based on the collection of images of the structure in a methodical manner at a resolution that would enable defects to be reliably identified within the images using either manual or automated analyses. Previous work on the collection of image data has concentrated on the development of methodologies and platforms to help collect the images of the structure. A variety of approaches have been tried, including systems mounted on aerial imaging platforms (Metni and Hamel, 2007; Woo, 1995), vehicles (McCormick *et al.*, 2013), booms (Oh *et al.*, 2009) and robotic platforms (Lim *et al.*, 2011). Other work has looked at the development of robotic inspection systems, which climb over the structure and collect data from close to the surface (Kim *et al.*, 2005; Murphy and Sitti, 2007). Other, possibly simpler, approaches have considered the use of tripod-mounted cameras (Sites, 2010), or CCTV type cameras mounted permanently in place on the structure (Jahanshahi *et al.*, 2011).

Aerial platforms can use GPS to follow pre-programmed flight paths. However, the accuracy limit of GPS introduces problems with the precise positioning of the imaging platform when collecting data. In addition, GPS reception can be poor in the environments where bridges are located, especially under

the bridges themselves. There are also legislative and regulatory issues affecting the ease of obtaining permission to fly a remote control aircraft carrying a high-resolution camera close to houses or live traffic. As a result, imaging systems mounted on aerial platforms generally focus on the collection of images at specific locations or parts of a structure (Metni and Hamel, 2007). Therefore, although they enable views to be obtained of parts of structures that may otherwise be very difficult to access, they are currently unsuitable for use for performing routine GIs or principal inspections of an entire structure.

The most promising vehicle-mounted system developed to date (Difcam) has been developed for use in rail tunnels (McCormick *et al.*, 2013). This system uses cameras and lasers to record condition data as the vehicle moves along the tracks through the tunnel, and can identify changes in the measured condition between successive surveys. Because the system operates at a speed of approximately 1 m/s the system requires a closure of the track in order to operate safely. The Difcam system is highly promising, but at present the high system cost, need for closures and difficulties in collecting data on parts of the structure that do not present perpendicular faces to the track mean that it is unsuitable for routine GIs.

Boom-mounted systems provide excellent access to parts of a structure, particularly the underside of the deck, but require special access arrangements and road closures. While under-slung boom systems providing human inspectors with a viewing platform from which they can make a visual inspection have been in use for years, newer systems are being designed with a camera at the end of the boom (Oh *et al.*, 2009). These camera systems can either be used to assist the inspector performing the inspection on site (using the images as they are filmed), or they can be more robotic, systematically recording a series of images of the whole of the underside of the bridge for later analysis. Boom-mounted systems, particularly those that systematically collect a full image record of the soffit, are able to provide excellent condition information for the underside of a deck, but leave other parts of the structure uninspected.

Systems making use of permanently installed cameras either require that the cameras are already in place (i.e. for security or traffic monitoring) or must have cameras installed specifically for the purpose of performing remote inspections. These cameras cannot move around the structure, but can be panned, tilted and zoomed into features on the bridge, either following a predetermined path, or being 'driven' remotely by an inspector. Jahanshahi *et al.* (2011) have proposed a system that enables an inspector to watch the camera output while controlling the camera over the internet. If a feature of interest is seen, an image can be recorded and stored for later analysis, including comparison against images recorded during previous inspections. This enables the changes in individual defects to be monitored. If a structure is

Offprint provided courtesy of www.icevirtuallibrary.com
Author copy for personal use, not for distribution

equipped with sufficient cameras of a high quality it would be possible to perform a full visual inspection using this information. However, each bridge would require several high-quality cameras, internet access, control systems, etc. This may be prohibitively expensive for routine installation and so such a solution is best suited to select bridges with very specific requirements.

A relatively simple approach of a camera and a tripod can provide a stable viewing platform, where the position of the camera at any time can be tightly controlled and known. With suitable lenses such a system can provide detailed images of all visible parts of a structure. If there is somewhere from which the pictures can be taken without hindrance from or to traffic then there is no need for a closure or special access arrangements. One example is the ScanSites system (Sites, 2010), which uses lenses with focal lengths of up to 2000 mm. The system claims to be able to detect 0.1 mm wide cracks from a distance of 300 m. However, like some of the previously discussed systems, the ScanSites system does not routinely collect a full image record of the whole bridge. Instead it enables an inspector to watch images from the camera, and can record images as and when something of interest is noted. In addition, the camera does not scan over the surface of the structure automatically, but must be manually panned and tilted. With careful operation this could be done systematically and methodically, but there is a risk that parts of the structure would be missed due to operator error.

It is apparent that there is interest in the idea of using image data to monitor aspects of bridge condition, but it is also apparent that there are currently no fully developed collection systems suitable for routinely providing image data. Many of the existing systems do not collect a full image record of the bridge, or do not meet the requirements for minimal additional traffic management (i.e. little more than that which would normally be required for a GI). The one system that might provide this (permanently installed, remotely accessed and controlled cameras) would be prohibitively expensive to fit to many bridges.

Consultations with practising engineers, consideration of the problems faced by bridge inspectors, and review of the existing systems suggest that a suitable system would need to satisfy a number of minimum requirements, including the following.

- The collection of full colour high-resolution images, which
 - have a resolution that enables visual defects to be identified on the structure surface
 - cover all visible parts of the surface of the structure that would be normally inspected in a GI
 - are collected and labelled, to enable the accurate location of any image in relation to any other image

- ideally will operate systematically to collect images over the whole structure with minimal operator input.
- Have the ability to display and analyse the image data to provide a condition record that is comparable to that achievable using a standard inspection.
- Have the ability to be used within practically achievable access limitations and traffic management requirements.
- Have an acceptable level of cost, in the context of current costs of visual inspections.

Meeting these requirements will be challenging. Initial practical investigations have been carried out into the type of equipment that could be used to satisfy them. Please note that the system described is an exploratory prototype and not a finished system, and does not meet all the requirements for routine use, but is useful in illustrating the types of issue that will have to be overcome if a suitable system is to be developed.

5. Developing automated bridge inspection

To explore the potential of this approach a prototype system has been developed that attempts to satisfy the above requirements. This prototype system enables an exploration of the issues of image collection, processing, alignment and display, and investigates the potential usefulness of image-based inspections. This paper presents the concept of an image-based inspection system as an aide to inspectors, and a means to overcome some of the problems affecting traditional visual inspections. The prototype system discussed is merely a means to present the issues and potential solutions and is not a finished system.

The system (Figure 2) uses a standard camera and lens, and an automated GigaPan pan-tilt unit (GigaPan, 2009) mounted on a tripod. The tripod provides a stable viewing platform and can be located on a standard footway or verge without requiring a road closure (bridges with no suitable footway would require traffic management, but this would also be the case for traditional visual inspections). The GigaPan unit is a commercially available, automated, motorised mount, which enables the creation of large, highly detailed panoramic image-sets. GigaPan is a small, battery-operated device that costs only a few hundred pounds, making the system portable, affordable and able to operate where no power source is available.

For the purposes of image collection and display, the bridge is considered as a set of individual and distinct surfaces (i.e. west abutment, east abutment, soffit, ...). Large surfaces may require more than one image collection position, and the tripod and system must be moved manually between these positions. In order to provide images of all parts of the bridge a number of locations are required for the tripod, around and under the bridge.

Offprint provided courtesy of www.icevirtuallibrary.com
 Author copy for personal use, not for distribution



Figure 2. Prototype image collection system showing camera mounted on GigaPan unit

Bridge dimension information is used to identify the required lenses and the number and location of tripod positions. The locations are determined on the basis that each set of images collected at that location will have a minimum resolution of 1 mm/pixel on the structure surface.

Once on site the tripod is moved to the first imaging position and the system is set up. The image acquisition process is fully automated, with the GigaPan unit controlling the camera orientation and triggering. The GigaPan unit is mounted on the tripod, and following some initialisation, automatically calculates the number and position of images required to provide full coverage of the area of interest, and the required camera orientation for each image. The system then adjusts the camera orientation, following the path shown in Figure 3, triggering the image collection process at appropriate points, and producing a series of images covering the area of interest. Once all images at an imaging position have been collected the system can be moved to the next location.

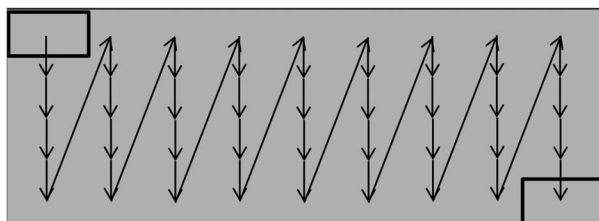


Figure 3. Path taken by GigaPan during collection of images

The entire structure is imaged from a number of discrete imaging positions, each one chosen to provide the optimum view of an element of the bridge, while maintaining the required image resolution. The camera is not fixed in place, but is moved around the structure as required to ensure detailed images are recorded on the whole structure.

The approach described will provide images at a consistent level of detail over the whole surface of the structure, but does have the disadvantage that any part of the bridge that is behind an immovable obstruction will not be imaged. A traditional inspector may be able to look behind some obstructions, and may be able to see higher levels of detail on some parts of the bridge where close access is easy, but they will see less detail on parts of the structure that are hard, or impossible, to get close to, such as tops of abutments, soffits or parapets over the live carriageway. If the inspector is more than a few metres away from the bridge or element in question, the images will present more detail.

The set of images is then tessellated onto a plane surface so that large areas of the bridge can be inspected at a time. Information about the camera orientation is used to align the individual images (Figure 4(a)). The initial alignment is then refined by selecting small overlapping areas of the images and performing image cross-correlation on the selected image samples to determine improved image alignment information (result shown in Figure 4(b)). In theory, it should be possible to align the images using only the image features. However, this relies on images having distinct and unambiguous features. In practice an image of part of a concrete abutment can look very similar to an image of another part of a concrete abutment. Combining the orientation information with the image correlation data delivers much better results.

Once the system hardware is correctly located and set up, the entire image collection, processing and alignment process is automated. The processing is not fast, but can be run overnight and requires no input. Advances in computer processing mean that what is time consuming now will not be in the near future.

Once processed and aligned an inspection can be carried out on the images. To explore the usefulness of the method an approach has been developed in which the inspector can zoom in and out of the images and record the location and type of any identified defect by clicking on the defect in a computer display. This allows the whole surface of a bridge to be inspected at a resolution of 1 mm/pixel. The inspector does not have to view all the data in high detail – just as in a traditional GI the inspector can scan large areas of the structure looking for likely defects, and only zoom in for a closer look when it is felt appropriate. The way the data are recorded means that the position of any feature on the bridge is known to within a few

Offprint provided courtesy of www.icevirtuallibrary.com
Author copy for personal use, not for distribution

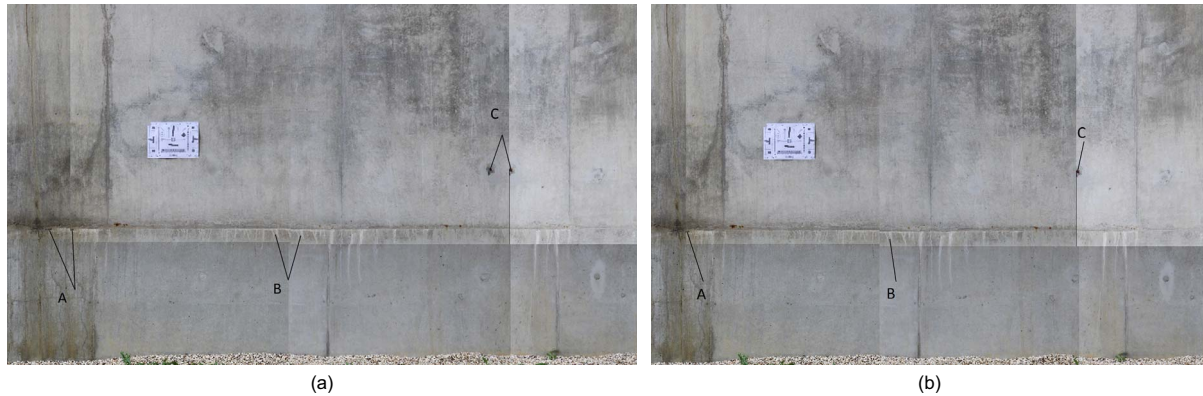


Figure 4. Image alignment (a) without and (b) with the refinements obtained by image cross-correlation. Note the features that are repeated in the original alignment, and that are now correctly aligned after the use of image cross-correlation

centimetres. A ‘defect map’ is produced by such an inspection, at whatever resolution is deemed appropriate, which can be used to identify areas of the structure that may require further investigation or attention. Figure 5 shows an example of such a defect map, showing the locations of potential defects seen during an image-based inspection. Features that may appear to be interesting at this level of detail can easily be investigated further and either recorded or ignored as appropriate, in the same way as an inspector performing a traditional inspection may see something of potential interest, but discover on closer inspection that it is not a problem. However, unlike a traditional inspection the full image record can be stored for the future, when any part of the bridge can be revisited or re-inspected if a defect later becomes apparent.

The prototype system presented includes no automated defect detection or identification, but such work is under investigation



Figure 5. Example of a defect map overlaid on image, showing location and type of defect

(Abdel-Qader *et al.*, 2003, 2006; Chang *et al.*, 2003; Jahanshahi *et al.*, 2009; Li *et al.*, 2013; Moon and Kim, 2011; Oh *et al.*, 2009). Indeed, more work appears to have been done on the automatic analysis of images of bridges than has been done on the systematic collection and inspection of the images themselves. One of the prerequisites of any automated image analysis and defect detection system is that images are available at adequate resolution.

5.1 Experience

The development of the prototype system has addressed a number of the requirements of image-based visual inspections. It collects in a structured way a full image record of the bridge, which can be easily aligned and displayed for analysis. The images are of high resolution and the collection apparatus is low cost, simple to operate, and has no need for traffic management or road closures. The images and display tools developed have been found to be useful and enable the completion of image-based inspections in a safe, controlled, comfortable environment to a level broadly comparable to UK highways GIs (McRobbie *et al.*, 2007). Even with the current limitations of the prototype, it is apparent that the systematic collection of images of a structure for the purposes of undertaking visual inspections has significant potential. In addition, with suitable images, there is scope for automation of the inspection process itself.

The authors are working with a number of Highways Agency maintaining agents and local authorities to develop and explore the capabilities of the techniques. Feedback from the inspectors has indicated that looking at a series of flat images is less intuitive than looking at a three-dimensional (3D) structure. To recover some of the lost context and provide a more intuitive

Offprint provided courtesy of www.icevirtuallibrary.com
Author copy for personal use, not for distribution

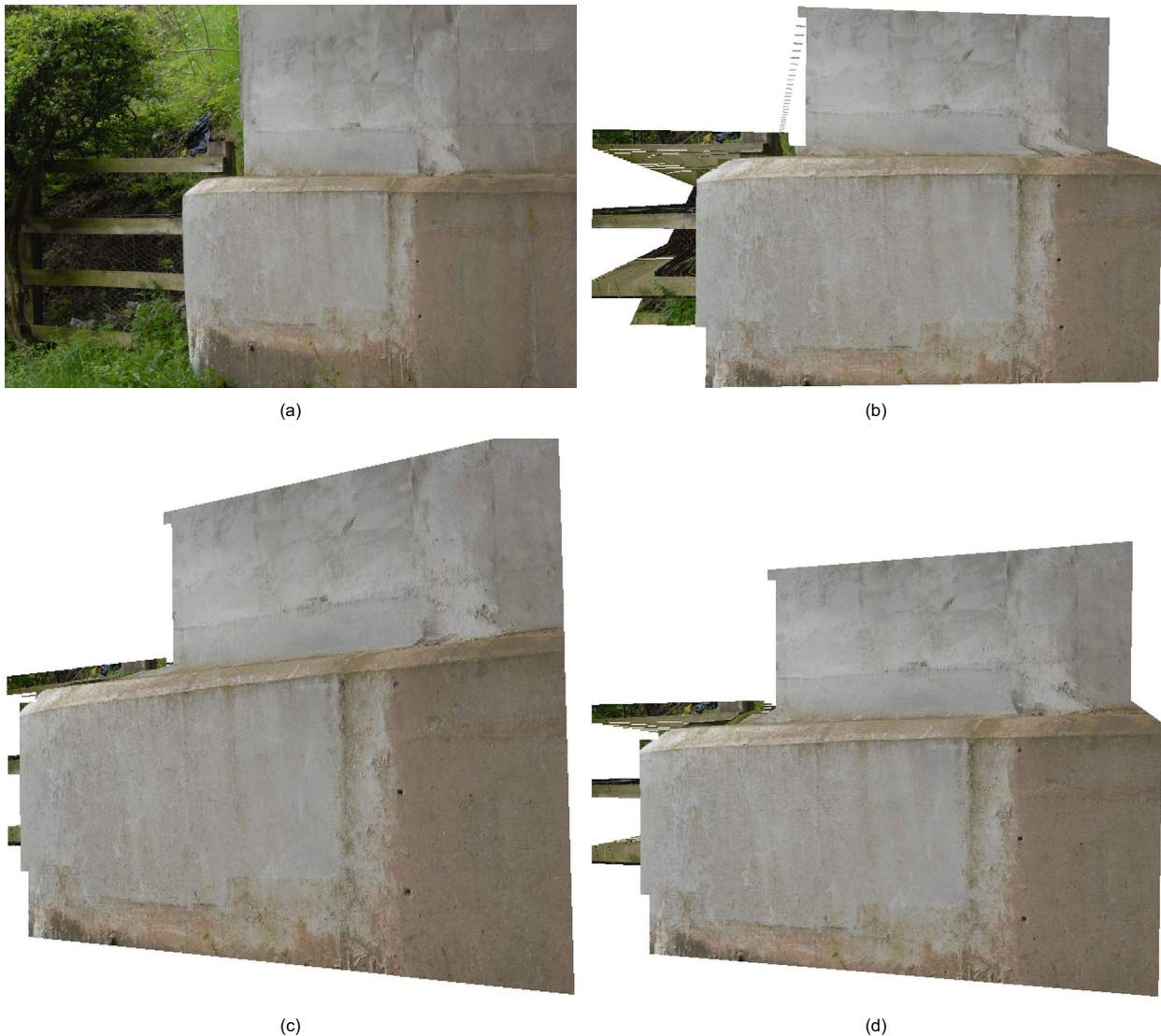


Figure 6. (a) Original 2D image; (b–d) three rotated 3D reproduced views created from original image and depth data

inspection experience methods of producing 3D models by combining images and laser measurements are being investigated (Figure 6).

6. Conclusions and recommendations

The situation has moved a long way from that of 40 years ago when routine visual inspection was seen as unnecessary, to one in which it is now a key part of infrastructure asset management. However, there is a substantial body of evidence showing that visual inspections are subjective, variable and non-reproducible. In spite of this they are still the main way of collecting bridge condition data.

Although engineers accept photographic evidence to support visual inspection reports, these photographs are currently provided in an ad hoc manner, with no clear guidelines on the collection of images or how many images to collect. It is apparent that introducing technology to improve the reproducibility of the data collection, and provide a full image record of the bridge, would be useful.

An increasing amount of technology is used to assist in the collection of condition data on structures. Although much of this is targeted on non-visual defects, systems for the collection of image data are becoming available. However, these are not

Offprint provided courtesy of www.icevirtuallibrary.com
Author copy for personal use, not for distribution

yet able routinely to provide images of entire structures in a practical manner. The authors have investigated image collection of a structure by means of the construction of a simple motorised image collection system.

The major potential benefits of the system include the delivery of a full image record, the consistency of the level of detail available over the whole bridge, the ability to compare images directly from successive inspections and compare defect conditions over time, and the ability to undertake the inspections in a safe, comfortable environment where consultation with others and obtaining second opinions is easy.

Owing to the wide variety of bridge sizes and types in the UK (and elsewhere) GIs are not always particularly useful in obtaining condition data. Just as GIs are not necessarily suitable on all bridges, it is likely that no single technology-based inspection system will be suitable for all bridges. However, the use of images to facilitate the performance of routine visual inspections appears to be an idea worth investigating further, with a view to one day developing systems that are capable of quickly, safely and repeatably collecting high-resolution data suitable for either human or computer inspections. This may be the first step in a long journey, but it is, the authors believe, a journey worth taking.

Acknowledgements

The authors would like to acknowledge the advice and support of Professor Chris Page and Dr Michael Burrow and thank them for many useful discussions regarding the research.

REFERENCES

- Abdel-Qader I, Abudayyeh O and Kelly M (2003) Analysis of edge-detection techniques for crack identification in bridges. *Journal of Computing in Civil Engineering* **17**(4): 255–263.
- Abdel-Qader I, Pashaie-Rad S, Abudayyeh O and Yehia S (2006) PCA-based algorithm for unsupervised bridge crack detection. *Advances in Engineering Software* **37**(12): 771–778.
- Bevc L (2002) *Inspection of Highway Structures – A European Perspective*. Institution of Engineers of Ireland (IEI), Dublin, Ireland, Assessment of Bridges and Highway Infrastructure Seminar. Dublin, Ireland, pp. 53–64.
- Bevc L, Mahut B and Grefstad K (1999) *Review of Current Practice for Assessment of Structural Condition and Classification of Defects*. BRIME (Bridge Management in Europe) Project Deliverable D2, project funded by European Commission.
- Chang PC, Flatau A and Liu SC (2003) Review paper: Health monitoring of civil infrastructure. *Structural Health Monitoring* **2**(3): 257–267.
- Elbehriy H, Hefnawy A and Elewa M (2005) Surface defects detection for ceramic tiles using image processing and morphological techniques. *Proceedings of World Academy of Science, Engineering and Technology*, ISSN 1307-6884, pp. 158–162.
- Estes A (1997) *A System Reliability Approach to the Lifetime Optimization of Inspection and Repair of Highway Bridges*. PhD thesis, University of Colorado, USA.
- FHWA (Federal Highway Administration) (1995) *Bridge Inspector's Training Manual*. Federal Highway Administration, Washington, DC, USA.
- Ferne B, Wright A and Pynn J (2003) *The Development of HARRIS – A System for Road Surface Condition Monitoring at Traffic Speed*. TRL, Crowthorne, UK.
- Gallwey T and Drury C (1986) Task complexity in visual inspection. *Human Factors* **28**(5): 595–606.
- GigaPan (2009) *About Gigapan*. See <http://www.gigapan.org/about/> (accessed 24/08/2010).
- Highways Agency (2007) *Design Manual for Roads and Bridges*, Volume 3, Section 1, Part 4, Inspection of Highway Structures, BD 63/07. The Stationery Office, London, UK.
- Jahanshahi MR, Kelly JS, Masri SF and Sukhatme GS (2009) A survey and evaluation of promising approaches for automatic image-based defect detection of bridge structures. *Structure and Infrastructure Engineering* **5**(6): 455–486.
- Jahanshahi MR, Masri SF and Sukhatme GS (2011) Multi-image stitching and scene reconstruction for evaluating defect evolution in structures. *Structural Health Monitoring* **10**(6): 643–657.
- Jamieson G (1966) Inspection in the telecommunications industry: a field study of age and other performance variables. *Ergonomics* **9**(4): 297–303.
- Kim S, Asbeck AT, Cutkosky MR and Provancher WR (2005) *SpinybotII: Climbing Hard Walls with Compliant Microspines*. IEEE, Seattle, WA, USA, pp. 601–606.
- Lea F (2005) *Uncertainty in Condition and Strength Assessment of Reinforced Concrete Bridges*. PhD thesis, University of Cambridge, Cambridge, UK.
- Li G, He S and Ju Y (2013) Image-based method for concrete bridge crack detection. *Journal of Information and Computational Science* **10**(8): 2229–2236.
- Lim R, La H, Shan Z and Sheng W (2011) *Developing a Crack Inspection Robot for Bridge Maintenance*. IEEE, Shanghai, China, pp. 6288–6293.
- McCormick N, Jonas D and Lane B (2013) Digital imaging for condition asset management (DIFCAM). *Proceedings of Rail Research UK Association (RRUKA) Annual Conference, London, UK*.
- McRobbie S, Lodge R and Wright A (2007) *PPR 255 Automated Inspection of Highway Structures – Stage 2*. TRL, Crowthorne, UK.
- Megaw E (1979) Factors affecting visual inspection accuracy. *Applied Ergonomics* **10**(1): 27–32.
- Metni N and Hamel T (2007) A UAV for bridge inspection: Visual servoing control law with orientation limits. *Automation in Construction* **17**(1): 3–10.

Offprint provided courtesy of www.icevirtuallibrary.com
Author copy for personal use, not for distribution

- Middleton C (2004) Bridge management and assessment in the UK. *5th Austroads Bridge Conference, Hobart, Tasmania, Australia*.
- Moon HG and Kim JH (2011) Intelligent crack detecting algorithm on the concrete crack image using neural network. *IAARC, Proceedings of 28th ISARC, Seoul, South Korea*, pp. 1461–1467.
- Moore M, Phares B, Graybeal B, Rolander D and Washer G (2001a) *FHWA-RD-01-020 Reliability of Visual Inspection for Highway Bridges*, Federal Highway Administration, West Virginia, USA, Final Report, vol. 1.
- Moore M, Rolander D, Graybeal B, Phares B and Washer G (2001b) *FHWA-RD_01_033 Highway Bridge Inspection: State-of-the-Practice Study*. Federal Highway Administration, West Virginia, USA.
- Murphy MP and Sitti M (2007) Waalbot: An agile small-scale wall-climbing robot utilizing dry elastomer adhesives. *IEEE/ASME Transactions on Mechatronics* **12(3)**: 330–338.
- OECD (Organisation for Economic Co-operation and Development) (1976) *Bridge Inspection*. OECD, Paris, France.
- Oh JK, Jang G, Oh S *et al.* (2009) Bridge inspection robot system with machine vision. *Automation in Construction* **18(7)**: 929–941.
- PIARC (World Road Association) (2011) *Inspector Accreditation, Non-destructive Testing and Condition Assessment for Bridges*. World Road Association, Washington, DC, USA, Technical Committee D3 Road Bridges.
- Purvis R (1988) *Inspection of Fracture-Critical Bridge Members*. Transportation Research Board, Washington, DC, USA.
- Rens K and Transue D (1998) Recent trends in nondestructive inspections in state highway agencies. *Journal of Performance of Constructed Facilities* **12(2)**: 94–96.
- Schoonard J, Gould J and Miller L (1973) Studies of visual inspection. *Ergonomics* **16(4)**: 365–379.
- Sites (2014) *SITES – Ingénierie, Surveillance Préventive des Structures et des Equipements Génie Civil et Nucléaires, et de l'Environnement, Instrumentation, Inspection, CND, SHM, SHMS, Lasergrammétrie, Topographie – Resources and Technical Tools*. See <http://www.sites.fr/index.php/en/moyens-et-outils-techniques-en> (accessed 05/11/2014).
- Spencer F (1996) *Visual Inspection Research Project Report on Benchmark Inspections*. Federal Aviation Administration, Albuquerque, New Mexico, USA.
- Uhl T, Kohut P, Holak K and Krupinski K (2011) Vision based condition assessment of structures. In *Proceedings of 9th International Conference on Damage Assessment of Structures (DAMAS 2011)*, *Journal of Physics: Conference Series* **305** (2011) 012043. IOP Publishing, Oxford, UK.
- Woo DC (1995) Robotics in highway construction and maintenance. *Public Roads* **59(2)**: 26–30.
- Woodward R (2006) *Bridge Inspection: The Case for Automation*. Brunel University Press, London, UK, pp. 71–80.
- Yella S, Dougherty M and Gupta NK (2009) Condition monitoring of wooden railway sleepers. *Transportation Research, Part C* **17**: 38–55.

WHAT DO YOU THINK?

To discuss this paper, please email up to 500 words to the editor at journals@ice.org.uk. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial panel, will be published as discussion in a future issue of the journal.

Proceedings journals rely entirely on contributions sent in by civil engineering professionals, academics and students. Papers should be 2000–5000 words long (briefing papers should be 1000–2000 words long), with adequate illustrations and references. You can submit your paper online via www.icevirtuallibrary.com/content/journals, where you will also find detailed author guidelines.