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Automated inspection of highway structures 2008/09

S G McRobbie



Transport Research Laboratory



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2008/09

by S G McRobbie (TRL)

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Executive summary

This research has been carried out with the objective of developing a more objective and repeatable inspection procedure than the current system of manual inspections. The improved inspection procedure is based on the proposal that images of structures could be collected and processed (manually or automatically), to identify defects. The research has concentrated on two key areas - image collection and display, and image analysis.

The research discussed in this report is from the fourth stage of an ongoing process, with another phase of development to come in 2009-10.

The condition of highway structures is determined by visual inspection. There are five main types of inspection which are undertaken at different frequencies. These inspections cover a range of detail, from a cursory check for obvious defects, through to a close examination of particular areas or defects causing concern. The quality of data collected depends on the ability of inspectors to observe and accurately record details on visible defects. This could be affected by many factors, such as the environmental conditions, and the knowledge and experience of the inspectors. Possibly for these reasons, it has been found that the data provided by such inspections can vary significantly. Improvements to the quality of the inspections are therefore desirable.

The imaging approach has now been finalised, and tested on a limited selection of structure types, and the calculations needed to plan a site imaging visit have been automated. This should enable any suitable site to be properly imaged with a minimum of on-site planning, providing usable images of abutments, soffits and wingwalls.

The imaging equipment has been obtained, and is operational, requiring only a short period of training. Some issues with the equipment have been identified, such as the accuracy of the elevation and bearing setting devices, and the goal of automating the collection process, but these are in the desirable category, rather than being strictly necessary.

The type of inspection offered by the automated system appears to fit nicely in the regime of UK highway structure inspections between general inspections, which are undertaken every two years, and principal inspections which are undertaken every six years. The automated inspections could provide very useful information which would help the inspector in his assessment of the bridge condition.

The development of a rust identification module for the segmentation and classification phase has been a simple yet effective improvement to the system, enabling the detection of an important but previously overlooked defect.

There are still an unacceptably high number of false positive and negative reports from the system, and more research is needed to develop segmentation methods to overcome this.

1 Introduction

This research has been carried out with the objective of developing a more objective and repeatable inspection procedure than the current system of manual inspections. The improved inspection procedure is based on the proposal that images of structures could be collected and processed (manually or automatically), to identify defects in highway structures. The research has concentrated on two key areas in the development of this procedure - image collection and display, and image analysis.

The research has been funded by, and performed on behalf of the Transport Research Foundation (TRF).

The research discussed in this report is from the fourth stage of an ongoing process, with another phase of development to come in 2009-10. The results presented herein are therefore based on the current performance of the system, and may improve following further development.

2 Background

The condition of highway structures is determined by visual inspection. There are five main types of inspection which are undertaken at different frequencies. These inspections cover a range of detail, from a cursory check for obvious defects, through to a close examination of particular areas or defects causing concern. The quality of data collected depends on the ability of inspectors to observe and accurately record details on visible defects. This could be affected by many factors, such as the environmental conditions, and the knowledge and experience of the inspectors. Possibly for these reasons, it has been found that the data provided by such inspections can vary significantly. Improvements to the quality of the inspections are therefore desirable.

2.1 Need for inspection

O'Reilly (O'Reilly, 2002) quotes a figure of \in 49.581 billion as the replacement cost of the UK bridge stock. This works out at an average cost of \in 529k per bridge. This is a significant sum of money, and a convincing argument for maintaining the existing bridge stock in as good a condition as possible, for as long as possible.

An even more compelling reason to maintain the bridge stock is provided by Fish (Fish, 2007) in an article in Highways Magazine. Fish discusses the collapse of the I-35W in Minneapolis, which caused the deaths of 13 people, and injured 145 more. Fish suggests that this tragedy gives a clear indication of the possible consequences of bridge failure, which in turn shows the need for a practical and meaningful programme of inspection and maintenance. Fish correctly points out that in order for a network of bridges to continue to safely meet the demands of the public sustained funding will be necessary from those responsible for the bridges.

For a long time it was felt that bridges, once built and in service, did not really need very much maintenance or inspection. This situation persisted until the 1960's. Following the 1967 collapse of the Silver Bridge in West Virginia this perception changed. A study by the 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 which was adopted by many countries, and still forms the basis of many current bridge inspection philosophies, including that of the UK.

The situation has moved a long way from that of 40 years ago when inspection was seen as unnecessary, to one where it is now seen as a vital part of the management of the national infrastructure asset. The need for a bridge inspection programme seems clear now. As the Highways Agency states in BA 35/90:

"To enable structures to retain their serviceability it is important that defects and causes of deterioration are identified as soon as possible so that remedial works can be carried out." (Highways Agency, 1990).

2.2 UK bridge inspection regime

The requirements for inspecting highway bridges in England are defined in Volume 3, Section 1, Part 4 of the DMRB (BD 63/07) (Highways Agency, 2007). Slight variations to these requirements apply to the rest of the UK, mostly to do with reporting format. The document is to be read in conjunction with Volume 3, Section 1, Part 6 of the DMRB (BD 53/95) (Highways Agency, 1995) when dealing with tunnels. These documents and the guidance therein apply to all trunk roads in England, Scotland and Wales, and to all designated roads in Northern Ireland.

The guidance sets out the inspection requirements based on the following principles (Highways Agency, 2007):

- a. "To detect in good time any defect that may cause an unacceptable safety or serviceability risk or a serious maintenance requirement in order to safeguard the public, the structure and the environment and to enable appropriate action to be taken.
- b. To provide information that enables the management and maintenance of a stock of structures to be planned on a rational basis in a systematic manner
- c. To ensure that inspections are undertaken by suitably experienced and competent staff."

BD 63/07 gives details of five different levels of inspection to be used on highway structures, what each level involves, when it should be performed, and how the results should be reported.

The five inspection levels defined in the DMRB are as follows:

2.2.1 Safety Inspection

"The purpose of a Safety Inspection is to identify obvious deficiencies which represent, or might lead to, a danger to the public and, therefore, require immediate or urgent attention." (Highways Agency, 2007).

These are similar to the Superficial Inspections performed under previous DMRB guidance BD 63/94 (Highways Agency, 1994) which has now been superseded by the current guidance. The inspections are not performed specifically to assess the condition of structures but are part of an overall inspection of the whole highway environment carried out by trained staff from a moving vehicle. Safety inspections provide only a cursory check of those parts of any structure which are visible from the highway with the aim of identifying any obvious dangers and deficiencies.

2.2.2 General Inspection

"The purpose of a General Inspection is to provide information on the physical condition of all visible elements on a highway structure." (Highways Agency, 2007).

General inspections are performed without any special access equipment or traffic management arrangements and thus can only report on what can be seen from relatively accessible parts of the structure. Before performing a general inspection the inspectors should review the structure records, including previous inspections in order to familiarise themselves with the likely conditions when they arrive on site, and to highlight any areas which may require special attention.

General Inspections must be performed every 2 years on every structure covered by the guidance and must, as a minimum, report the location, severity, extent and type of any defects.

2.2.2.1 Condition rating details

Part 2 of the Highways Agency Network Management Manual (Highways Agency, 2006) explains the defect reporting system used in England. This is summarised below in Table 1:

Table 1: Meanings of Severity and Extent codes for reporting defects in GeneralInspections

	Δ	No significant defect			
		No significant delect			
Ę	В	Slight; not more than 5% of length or			
kter		area affected			
ш	С	Moderate; 5% - 20% affected			
	D	Extensive; more than 20% affected			
	1	No significant defect			
	2	Minor defects of a non-urgent nature			
ť	3	Defects which shall be included for			
veri		attention within the next annual			
Se	maintenance programme				
	4	Severe defects where urgent attention is			
		required			

These severity and extent combinations provide a very versatile and informative framework with which the condition of a structure, or part of a structure, can be assessed. The ability to report the severity and extent separately is very helpful for later interpretation of reports.

2.2.3 Principal Inspection

"The purpose of a Principal Inspection is to provide information on the physical condition of all inspectable parts of a highway structure. A Principal Inspection is more comprehensive and provides more detailed information than a General Inspection." (Highways Agency, 2007).

Principal Inspections enable the inspector to get close access to all parts of the structure, enabling the inspector to touch the structure and look at it from a variety of angles and directions when determining the condition of bridge elements. The execution of a Principal Inspection is usually performed with access equipment, traffic management and a selection of relatively simple tools such as binoculars, or hammers to test for delamination.

As with the General Inspections, the inspectors are required to familiarise themselves with the previous notes on the structure and its condition before visiting the site.

Principal inspections must be made for every structure every 6 years, unless special circumstances dictate that this interval can be altered. Principal Inspections are required to include as a minimum the details from a General Inspection as well as more detailed drawings and/or photographs to show the extent and severity of defects. They must also

include comments on any significant changes which have occurred to the condition of the bridge since the last inspection, and any information regarding required maintenance or additional testing.

2.2.4 Special Inspection

"The purpose of a Special Inspection is to provide detailed information on a particular part, area or defect that is causing concern, or inspection which is beyond the requirements of the General/Principal Inspection regime." (Highways Agency, 2007).

There is no such thing as a standard Special Inspection as 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.

Special Inspections should provide detailed information on the parts of the bridge inspected, including photos and/or sketches. As in the Principal Inspection reports any significant changes to the condition of the element must be reported, along with details of any testing undertaken as part of the Special Inspection, and what the test results mean. The report should also include any recommendations for further testing, monitoring or maintenance.

2.2.5 Inspection for assessment.

"The purpose of an Inspection for Assessment is to provide information required to undertake a structural assessment. BD21/01 (DMRB 3.4.3) (Highways Agency, 2001) provides guidance on undertaking an inspection for assessment and recommends that these are done in conjunction with a Principal Inspection." (Highways Agency, 2007).

2.2.6 Appropriate level for automated inspection system

An examination of the goals and procedures used in the five types of inspection made on UK highway structures would suggest that an image-based automated, or semiautomated system could aim to perform surveys which were between general and principal inspections in their scope and coverage.

The images would be collected in such a way as to provide full, detailed coverage of all visible elements of the structure, providing more detail than can currently easily be obtained when performing a general inspection with no artificial aids.

2.3 Reliability of Visual Inspections

"When recording and comparing the visual condition of a wide variety of bridges it is difficult to be precise and consistent" (Wallbank, 1989).

There has not been a great deal of research into the specific area of reliability of visual inspections on highway structures. Moore, et al., (Moore, Phares, Graybeal, Rolander, & Washer, 2001) represents the major study in this field. However, problems with consistency and objectivity when dealing with visual inspections are not confined to bridges, but are common in many fields. As a result much more research has been done in the area of visual inspection reliability in other areas.

2.3.1 Reliability of Visual Inspection of highway structures

Prior to the Moore, et al study (Moore, Phares, Graybeal, Rolander, & Washer, 2001) there were only a few attempts made to investigate the reliability of visual inspection on highway structures. Those studies that were found in the literature were often broader studies on the use of Non-Destructive Evaluation, (Rens, Wipf, & Klaiber, 1993), (Rens & Transue, 1998) with only very limited discussion of visual inspection.

Some of the inherent problems with visual inspection were discussed in the Purvis (Purvis, 1988) report on the inspection of fracture critical bridge members. Purvis understood that some defects are of huge importance if the structural integrity of the bridge is not to be compromised and as such it is imperative that they are identified correctly and identified as soon as possible. In order for this to happen the inspector must know enough about the structure to recognise the importance of these defects and their implications. The inspector must also have access to the correct parts of the structure. The inspector must also look closely and attentively when access has been afforded as some of the key defects can be very small and easy to miss.

Purvis identifies the need for inspector training as being one of the keys to a successful visual inspection programme.

Estes, (Estes, 1997), notes that achieving any level of consistency of visual inspection results between different inspectors will not come without training and experience. Estes suggests the use of formalised quality control systems to help ensure consistency between inspectors and cites a system used in Colorado. Among the approaches used in the Colorado system is a form of quality audit in which an inspector performs evaluations of each inspector's inspections. This is done with no prior warning to the inspector whose work is being audited. The auditing inspector revisits one of the bridges inspected previously and inspects it himself, with no reference to any prior condition information. The audit inspection and the auditee inspection are than compared to ensure consistency. Additionally the inspector may have inspected a certain bridge so often that he becomes familiar with it. In such situations it is easy for the inspector to 'know' before looking what he will find, and the actual inspection can become sloppy as a result.

Moore, et al., (Moore, Phares, Graybeal, Rolander, & Washer, 2001), claim their work to be the first complete study into the reliability of visual inspection specifically in terms of bridge inspection. Their study involved a large scale performance trial test programme involving 49 practicing bridge inspectors from 25 States, each inspecting a series of test bridges, and undergoing a battery of physical and psychological testing.

This study by Moore, et al., focussed on the two most common types of inspection undertaken in the USA, routine inspections (which are comparable to UK based General Inspections), and in-depth inspections (comparable to UK Principal inspections), and had four specific objectives:

- a. Overall measure of accuracy and reliability of routine inspection;
- b. Overall measure of accuracy and reliability of in-depth inspection;
- c. Study influence of several key factors to provide qualitative measure of influence on reliability of visual inspection;
- d. Study inspection protocol and reporting differences between states.

During the routine inspections the bridges were assessed using the Standard Condition Rating guidelines in Bridge Inspectors Training Manual (Federal Highway Administration, 1995). These inspections assign a condition rating to each element of the bridge using a numerical scale from 0 (zero) to 9, where zero signifies the failure of the element, and 9 signifies that the element is in excellent condition.

Table 2 shows the details of the US routine inspection rating system. Staff from the study team also inspected each structure to determine its 'true' or reference condition, against which the inspectors' ratings would be compared.

Table 2: Condition ratings for use in Routine Inspections in the USA

(AASHTO90).

Condition Rating	Description
Ν	Not applicable
9	Excellent condition
8	Very good condition – no problems noted
7	Good condition – some minor problems
6	Satisfactory condition – structural elements show minor deterioration
5	Fair condition – all primary structural elements are sound, but may have minor section loss, cracking, spalling, or scour.
4	Poor condition – advanced section loss, deterioration, spalling or scour.
3	Serious condition – loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	Critical condition – advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.
1	"Imminent" failure condition – major deterioration or section loss present in critical structural components, or obvious vertical or horizontal movement affecting structural stability. Bridge is closed to traffic but corrective action may bring bridge back in light service.
0	Failed condition – out of service; beyond corrective action.

The assessment of the reliability of in-depth inspections was made using field notes taken by the inspectors whilst performing the test.

The study acknowledged that there is no guarantee that the reference data is actually correct, but that the spread in the levels of categorisation being reported by the inspectors guaranteed a high number were reporting incorrect condition ratings.

The study found that the condition ratings reported following the routine inspections showed a normal distribution. On average each assessed element of the bridges had somewhere between 4 and 5 condition assessment ratings assigned to it, with a maximum spread of 6. Such cases were clustered in the middle of the ranking scale (between rankings of 3 and 8) and cases of classification discrepancy involving the extreme ends of the scale were not seen. It is however concerning that trained, qualified inspectors, who were operating under test conditions and so were unlikely to be sloppy, could report such widely differing conditions on the same elements.

The study also found that in-depth inspections were often no better than routine inspections, and provided little information which could not be obtained from the routine inspection reports.

The test data suggested that inspectors tend towards reporting mid-range assessments and avoid extreme values: good elements of the bridge tend to be underscored, while the condition of poor areas tends to be overrated. The need for inspector training appears to be one of the most important facets in getting reliable visual inspection data. Purvis, Estes and Moore, et al., all mention this need.

2.3.2 Reliability of Visual Inspection in other industries

Visual inspections are common in many fields including aviation, (Spencer, 1996), electronic engineering, (Schoonard, Gould, & Miller, 1973), and telecommunications, (Jamieson, 1966).

Spencer, reporting on behalf of the Aging Aircraft Non-destructive Inspection Validation Center (AANC), argued that although the name visual inspection is used for the process, and that the visual aspect dominates, the process is not purely visual. He writes:

"visual inspection is the process of examination and evaluation of systems and components by use of human sensory systems aided only by such mechanical enhancements to sensory input as magnifiers, dental picks, stethoscopes and the like. The inspection process may be done using such behaviours as looking, listening, feeling, smelling, shaking and twisting. It includes a cognitive component wherein observations are correlated with knowledge of structure and with descriptions and diagrams from service literature." (Spencer, 1996)

Clearly not all of these non-visual behaviours are necessarily applicable to highway structures but Spencer does make a very valid point that the inspector is not simply impassively viewing his subject. A good inspector will interact with it as much as possible, feeling it and looking at it from other angles. Although general inspections are essentially visual inspections with no requirement for testing, many inspectors will make use of hammers or other tools to 'ring' the concrete and listen for indications of delaminations.

A 1973 study by Schoonard, et al., (Schoonard, Gould, & Miller, 1973) into visual inspection from the perspective of circuit inspection found that inspectors often try to look at many things at one time, this is because they are expected to be quick. As a result Schoonard, et al., concluded that inspectors are not very accurate.

Schoonard recommended three areas where improvements were necessary. As with many of the studies into the reliability of visual inspection on concrete structures, one of the recommendations was for more training for inspectors. The other recommendations were for improved and clarified procedures, and better working conditions and/or equipment for the inspector.

Jamieson (Jamieson, 1966) found that the lack of clear guidance on what should, or should not, be reported as a defect was the most important factor in determining the reliability of the inspection. This situation could be improved with improved procedural guidance or training.

2.3.3 General literature on visual inspection reliability

Megaw (Megaw, 1979) in their study into factors affecting visual inspection accuracy developed four categories of factors which may affect the quality of a visual inspection. Megaw's categories are shown below in Table 3.

Table 3: Megaw's categories of factors affecting visual inspection (Megaw,

1979).

Subject factors	Task factors
-----------------	--------------

Visual acuity	Time	
Colour vision	Direction of movement	
Scanning strategies	Viewing area	
Age	Density of items	
Experience	Fault probability	
Intelligence	Fault mix	
Etc.	Fault conspicuity	
	Product complexity	
Physical and environmental factors	Organizational factors	
Lighting	Instructions	
Aids	Feedback	
Noise	Feedforward	
Music	Training	
Workplace design	Standards	
	Time on task	
	Isolation	
	Working in pairs	
	Motivations	
	Incentives	
	Job rotation	

Clearly not all the factors in Table 3 are relevant to bridge inspection, but some are; for example the inspector's vision, experience and intelligence are all likely to have a large part to play in the quality of any inspections performed. Once again, training is mentioned as a factor affecting visual inspection quality.

Visual inspection tasks are often performed for long periods without any real variation. Such tasks can easily become soporific and induce boredom in the inspector (Fox, 1971), even if motivation to complete the task is high. Poulton (Poulton, 1977) gives an excellent illustration of this with an example from World War 2. At this time sonar was a relatively new technology and the sonar operator on board a ship had the responsibility for detecting enemy submarines before they launched a torpedo at the ship. As such the sonar operator had huge responsibility on his shoulders and a massive motivation to do a good job. To help the sonar operator perform as well as possible he was often given comfortable work quarters, away from distractions or noise, and with subdued lighting to make it easier to view the sonar display. Under these conditions, and in spite of the huge incentive to do a good job, the sonar operator was found asleep at his post when the officer of the watch looked in on him.

Poulton argues that the mental fatigue from concentrating on his task, combined with the lack of distracting stimuli and comfortable environment meant that if the sonar operator was sticking to his job it was almost inevitable that he would fall asleep. Poulton recommends the need for external stimuli to keep the mind alert and stave off boredom.

Given that the majority of concrete structures are essentially sound then a lot of visual inspection on such structures will consist of looking at large areas of concrete with little or no sign of any defect. Under such conditions, if Poulton and Fox are correct then the concentration levels of the inspector will almost certainly fall unless external stimuli are

present. If the inspections are being performed with no traffic management in place then the passing traffic may well provide all the stimulation the inspector needs, but if there is no traffic, the inspector may need to find some other form of stimuli. It is likely that photographing, sketching and writing notes would provide the necessary activity.

The numbers and varieties of potential defects which the inspector has to look for can also influence the success of the inspection, as does the levels of distinction between sound elements and defects. If the inspector has only to look for a single type of defect which is clearly and obviously distinct from the samples then it is an easy task to perform. Megaw alludes to this in his study and it is shown in his table of inspection factors as the defect conspicuity and the fault mix / product complexity. Gallwey and Drury (Gallwey & Drury, 1986) performed a study investigating the effect of the number of distinct defect types which the inspector must consider during the inspection. They agreed with Megaw's conclusion that as the number of potential defects increases the reliability of the inspection decreases. Gallwey and Drury reported that the decrease in inspection reliability is non-linear – that is that increasing the number of potential defects from two to four had a more detrimental effect on the inspection reliability than increasing the defect types from four to six. It was unclear at which point the decrease in reliability would stop and that adding additional defects would no longer degrade the inspection results.

A wartime study into the training and selection of inspectors by Tiffin and Rogers perhaps best illustrates some of the difficulties in trying to determine which inspector characteristics best correspond with inspection quality (Tiffin & Rogers, 1941). Tiffin and Rogers report on a test in which 150 inspectors were given 150 samples of tin-plate which they were asked to assess. As with the Moore, et al., study (Moore, Phares, Graybeal, Rolander, & Washer, 2001) each inspection was subjected to a range of questions and tests to assess their physical and psychological characteristics. Analysis of the results found a number of factors which seemed to mark out what employers should look for when selecting inspectors. Among these were that the inspectors should be taller than 1.57m, and weigh at least 55kg. This appears to be utter nonsense, but does demonstrate the difficulties in determining which parameters do matter in predicting how well any inspector will perform, and the importance of proper planning of experimental data analysis to avoid reporting non-causal correlations.

In summary, the literature highlights the need for inspector training and clear task guidance or instruction on what is and is not a defect as key areas which affect the quality of visual inspection. The literature also highlights the difficulties of performing visual inspections, even when properly trained and motivated, and shows that the quality of any given inspector or inspection is affected by a variety of factors, not all of which are in the inspector's control.

2.4 Previous TRF work

Earlier work performed on behalf of TRF found that it was possible to perform a visual assessment of a structure using images alone, and that the results of this image-based condition assessment would be comparable with the results of a more traditional on-site assessment (McRobbie, Lodge, & Wright, 2007).

2.4.1 Image requirements

This previous TRF work, and the following study (McRobbie, 2008), developed a list of image quality requirements if the images are to be useful for detecting defects of interest to the engineers responsible for maintaining the structure. These images must be:

- Colour;
- Minimum resolution of 1 pixel per mm;
- Lighting should be used as necessary to ensure the images are as consistent as possible;
- The location of each image on structure must be recorded (camera position, bearing, elevation);
- The images should cover the whole surface of the structure, with some overlap between images to ensure full coverage.

Additionally, if the images are to be easily interpreted by an engineer, then it must be possible to join or tessellate the images. This is to enable a set of images to be viewed together, to provide some context, as individual images can be hard to interpret with no sense of the surrounding area.

2.4.2 Imaging problems

The preceding research performed on behalf of the TRF reported that the effects of parallax were apparent on the images. This resulted in the tessellated images looking very unnatural and making it harder for engineers to interpret them. The fact that some images were taken relatively perpendicular to the surface being imaged, while others were taken at relatively oblique angles also meant that the area of the structure captured in the images changed with imaging angles. A single pixel in an image taken perpendicularly to the surface would represent a smaller real world area than the same pixel in an image taken at an angle.

Figure 1 shows how images taken at various bearings and elevations can end up representing different sized and shaped areas of the real world, even though all will be displayed as identically sized rectangular images. The blue rectangle shows the size and shape of an imaged area if the image was taken perpendicularly to the surface being imaged. The other four shapes show the sizes and shapes of real world areas which have been imaged at various bearings and elevations.



Figure 1: Illustration of how viewing angle can affect size and shape of view represented in image.

It was found that these issues could be overcome by use of image reprojection techniques. However, the implementation of these reprojection techniques was found to be only partially successful, as the method used was not easily transferrable to structures other than the one it was initially developed for. This was a problem with the way in which the reprojection had been implemented, not the reprojection approach itself.

It was also discovered that the image collection process was time consuming, and the process of trying to line up and tessellate the images by hand, without any positioning information for which image goes where was more time consuming.

2.4.3 Image segmentation

Image processing and segmentation routines were developed in the previous research which were able to process all the images of a structure, one after the other, and determine which areas of these images contained any features which were likely to be of interest to the engineer. Visual comparison with reference data showed that this approach was achieving some success, but with too many false positives to be of any real use without further refinement.

3 Objectives of research carried out in 2008/09

The current phase of research has had several goals designed to build on the previous work and improve our understanding of the issues affecting the practicalities of automating (or semi-automating) the inspection of highway structures. These goals have included:

- Improving the automation of the calculation of the required imaging positions for any given structure;
- Improving and automating the image reprojection;
- Improving the automatic object segmentation and classification algorithms to provide more accurate output;
- Extending the system to operate on masonry arch structures.

3.1 Methodology

The methodologies used in this work were similar to those used in the earlier stages. As before, a grid-based approach was used, in which the surfaces considered were broken down into a series of 200x200mm cells, and each of these cells was assessed to see if it contained any defect or feature of interest.

3.1.1 Reference data

Given the findings in the earlier stages of the research into the automation of highway structure inspections ((McRobbie, Lodge, & Wright, 2007) and (McRobbie, 2008)) which found there was good agreement between inspections performed on-site and those performed offsite using images it was decided to use image-based inspections as the reference data for the study.

This meant that the reference data could be produced in the same grid format which would be directly and easily comparable with the automated segmentation and classification output.

To produce the reference data the inspector looked at the reprojected and tessellated images of the structure, and used software to mark the locations and types of any defects which were seen. The inspector had a list of defects to look for, and was able to zoom in or out of the images.

4 Data

Although other sites had been surveyed in previous stages of the research, most of the development work had been carried out using images from a single structure at Winnersh. This site was again surveyed in the current stage of research in order to provide continuity within the data, but in addition, another concrete structure, and a masonry arch were also surveyed.

4.1 Sites

The site selection had to bear in mind the restrictions placed by the imaging system. That is, the sites had to be accessible, and have safe footways from where the images could be taken. The sites had to be safe enough and accessible enough to not require a closure or any special traffic management arrangements. Details of the sites chosen are given in Table 4:

Site	Site reference	Description	Туре	Width (m)	Length (m)	Height (m)
Winnersh	M4/59.2	M4 over B3030	Concrete	33.8	12.9	5.05
Frilsham	M4/85.4	M4 over Brocks Lane	Concrete	36.0	12.5	6.55
Broad Lane	4/28 RDG1	Railway over Broad Lane (Bracknell)	Masonry arch	6.1	10.3	4.1

Table 4: Details of sites used in research

4.1.1 Winnersh site

The structure imaged is the one carrying the M4 over King Street Lane (B3030), in Winnersh. This structure is M4/59.2 King Street Lane, and its location is shown in the following map (Figure 2):



Figure 2: Winnersh site M4 over King Street Lane (B3030). Map reproduced by permission of Ordnance Survey on behalf of HMSO. © Crown Copyright 2009. All rights reserved. Ordnance Survey Licence number 100021177.

The Winnersh structure (M4/59.2) is a simply supported beam and slab highway underbridge, constructed in 1971. The structure consists of precast post-tensioned beams, an in-situ concrete slab, and has reinforced concrete cantilever abutments on spread footings. The structure has a skew of 38° to the road it passes over (King Street Lane (B3030)).

4.1.2 Frilsham site

The structure imaged is the one carrying the M4 over Brocks Lane, approximately 6km east of Junction 13. This structure is M4/85.4 Frilsham Manor, and its location is shown in the following map (Figure 3):



Figure 3: Frilsham site M4 over Brocks Lane. Map reproduced by permission of Ordnance Survey on behalf of HMSO. © Crown Copyright 2009. All rights reserved. Ordnance Survey Licence number 100021177.

The Frilsham structure (M4/85.4) is another simply supported beam and slab highway underbridge, also constructed in 1971. The structure consists of precast pre- and post-tensioned beams, an in-situ reinforced concrete slab, and has reinforced concrete cantilever abutments on bored cast-in-place piles. The structure has a negligible 1° skew over Brocks Lane.

4.1.3 Broad Lane site

The structure imaged is 4/28 RDG1, a masonry arch carrying the railway line over Broad Lane, in Bracknell. This structure and its location is shown in the following map (Figure 4):



Figure 4: Broad Lane site – railway over Broad Lane. Map reproduced by permission of Ordnance Survey on behalf of HMSO. © Crown Copyright 2009. All rights reserved. Ordnance Survey Licence number 100021177.

Information about the date of construction, or details of the construction design and materials, of the Broad Lane railway bridge were not available.

5 Image Collection

Algorithms were developed which would enable the user to input a number of parameters including the dimensions of the bridge, the number of pixels in the camera sensor, the required minimum resolution, the desired overlap between images, and the available camera lenses. The number, and location of camera stations, and the number of images to be taken at each location were then calculated automatically.

5.1 Image collection procedure

The earlier phases of this research ((McRobbie, Lodge, & Wright, 2007) and (McRobbie, 2008)) had resulted in the development of equipment, and a setup procedure for the image collection rig. The equipment was put together as shown in Figure 5.



Figure 5: Imaging rig (tripod, mounting head, camera, distance measurement lasers, laser mounting bracket)

Once correctly set up, the tripod was located such that the camera was 1.5m above the ground, in the correct location (determined using the theodolite). The camera was oriented so that it pointed perpendicularly towards the structure surface when the imaging rig was aligned at 0° horizontally and 0° vertically.

Images were collected in such a way that the entire surface of the abutments and soffit were imaged. This involved setting up the camera and tripod in one position, taking an image, recording the distance measurements from both laser units, and then reorienting the camera to the next required bearing and elevation. It was later discovered, during the image processing and analysis work, that this method did not provide usable soffit images and so the methodology has been altered to fix this problem for future data collection.

The tripod was located on the footway, in such a way as to provide minimum obstruction to pedestrian access along the footway for the public, but so that staff involved in taking the photographs and measurements were not required to leave the footway while working. The camera mounting head allows free movement vertically, but moves in discrete steps horizontally. The step size was set using the screw in the base of the head (shown in Figure 6).



Figure 6: Holes for setting horizontal rotation step on mounting head.

At each camera location all images were collected at all the desired bearings, then the unit was raised, and the next layer of images were taken.

Figure 7 shows operators in the process of collecting images and noting the camera bearing and elevation, and laser distance measurements.



Figure 7: Image collection in progress (Winnersh bridge)

6 Image Reprojection

Although image reprojection was attempted in a previous stage of the research (McRobbie, 2008) it was found that the reprojection methods used had to be modified for use on other structures. A method was developed which made use of the camera bearing and elevation data, as well as the distance from the camera to the surface, for each image and then produced a reprojected image.

The image reprojection was performed following the trigonometric principles discussed below. Figure 8 shows a set of diagrams which are helpful in understanding the concepts involved in reprojection of images.



Figure 8: illustration of some of the concepts and angles involved in image reprojection

Image plane pan relative to projection plane:	α;
Reprojection plane tilted at:	β_r (not shown);
Image (camera) tilted at:	β_{I} (not shown).

Note that the drawings shown as Figure 8 do not illustrate the effects of tilting the camera relative to the reprojection plane (i.e. looking above or below a horizontal viewing angle). This is purely due to the difficulties in trying to represent a third dimension in the diagrams while maintaining clarity.

If we set up a coordinate system (x, y, z) such that (0, 0, 0) is at the camera node point, P. The y = 0 plane contains the spherical equator with tilt = 0°, and the x = 0 plane passes through the centre of the reprojection plane.

With a camera Field of View angle (FOV), and an image sensor (CCD) width of w pixels we find using tan x = opp/adj that tan (FOV/2) = (w/2)/d.

This gives $d = w/(2\tan(FOV/2))$, where d is the distance in pixels from the node point to the image plane.

For an image tilted at β_i and panned α from the reprojection plane each pixel has a coordinate location relative to the centre of the image, and in the same plane as the image: i.e. all pixels have $z_i = d$.

It can be shown that the image pixel locations can be transformed onto the coordinate system of the reprojection plane using the following equations:

TRL

 $\begin{aligned} x_{\rm r} &= d\cos\beta_{\rm i} \sin\alpha + x_{\rm i} \cos\alpha - y_{\rm i} \sin\beta_{\rm i} \sin\alpha; \\ y_{\rm r} &= d\sin\beta_{\rm i} + y_{\rm i} \cos\beta_{\rm i}; \\ z_{\rm r} &= d\cos\beta_{\rm i} \cos\alpha - x_{\rm i} \sin\alpha - y_{\rm i} \sin\beta_{\rm i} \cos\alpha. \end{aligned}$

The projection plane is rotated β_r about the x-axis. Rotating the coordinates for the pixel by β_r about the x-axis allows the coordinates to be placed on a plane parallel to the z = d plane. This can be done using:

 $\begin{aligned} &x'_r = x_r; \\ &y'_r = y_r \cos\beta_r - z_r \sin\beta_r; \\ &z'_r = z_r \cos\beta_r + y_r \sin\beta_r. \end{aligned}$

Then simple scaling such that $z'_r = d$ brings the x'_r and y'_r onto the z = d plane and therefore these become the xy coordinates in the reprojected space.

$$x = x'_{r} (d/z'_{r});$$

$$y = y'_{r} (d/z'_{r}).$$

Figure 9 shows a tessellation of nine separate images with (on the right) and without (on the left) reprojecting the images.



Figure 9: Example of effect of reprojection - Mosaic of nine un-reprojected images (left) and the same nine images following reprojection (right).

By using the reprojected data from the corners, or centre of the images, it was also possible to automatically create an alignment data file giving coordinates of each image for the tessellation process to use.

7 Image segmentation and classification

The previous research had identified the use of the Haar transform, and the image entropy as giving the most promising results in the segmentation of objects from the bridge background.

Rust staining on the surface of concrete structures is more than just a cosmetic problem, and can be a key indicator of serious corrosion of the reinforcement. Along with some general improvements to the segmentation algorithms, making the effects of changes easier to identify and test, some effort was directed towards trying to develop a way of specifically segmenting and classifying rust in the images. This made use of the colour information present in the images.

Rust is easily identifiable by eye in the images by its reddish-brown colouring. By looking at the difference between the red channel and the blue channel, areas which are noticeably redder than the rest of the structure can be highlighted. These areas can then be further processed using some basic image processing techniques to remove noise. The results can then be assessed and categorised as rust staining if appropriate.

The sequence of operations in the processing of each image is as follows:

- 1. Read in image
- 2. Calculate new image based on image entropy (red channel only)
 - a. Threshold, remove small objects, dilate, erode image
- 3. Calculate new image based on Haar transform of image (red channel only)
 - a. Threshold, remove small objects, dilate, erode image
- 4. Calculate new image based on the differences in pixel intensity between the red and blue channels of the original image
 - a. Threshold, remove small objects, dilate, erode image
- 5. Split image into MxN grid cells
- 6. Start at first cell
- 7. Count number of segmented objects in cell using entropy and Haar images.
- 8. Characterise each object in terms of following parameters:
 - a. Area
 - b. Eccentricity
 - c. Extent
 - d. Orientation
 - e. Major Axis length
 - f. Minor Axis length.
- 9. Use rust image, and above parameters to classify each cell as containing a 'defect', a 'feature', something 'other' or no object.
- 10. Move on to next cell
- 11. Move on to next image
- 12. Create output file of classified, aligned cells.

It is then possible to align the classified cells with the reference data, and directly compare them to get a quantifiable assessment of the automated systems performance.

8 Masonry arch structures

Attempting to extend the approach to include masonry arch structures runs into a number of key, and hard to overcome, difficulties:

- 1. The bricks and mortar, which, when segmented, tend to swamp any objects;
- 2. The arch of the bridge, which makes reprojection of the images much more complex;
- 3. The different types and nature of defects on a masonry bridge, compared to those encountered on a concrete structure.

Figure 10 shows an example of a reprojected image of a masonry structure, the processed image entropy-based output of the same image, and the processed output based on the application of the Haar transform to the image.



Figure 10: Reprojected (left), entropy (centre), and Haar (right) images of a part of a masonry structure.

9 Current System Performance

The performance of the current system was assessed, on the two concrete structures, by quantifying and comparing the results of the automated system against the reference data in a number of ways. The image segmentation on the masonry arch structure was not good enough to separate the brick/mortar pattern from the rest of the image, and resulted in virtually all the bridge being flagged as containing defects. At this stage the performance on masonry structures has therefore been excluded from the analysis.

The system performance was assessed in a number of ways. Firstly the 'defect maps' were compared for the reference and automated outputs. This allowed a qualitative performance assessment to be made, and identified areas which required further investigation. Next the total area of the structures which were assessed as containing any defect or feature were compared to see if the automated system seemed to be grossly over or under sensitive. The proportion of the cells flagged in the reference data as containing a defect, which were also flagged by the automated system as containing something was found, as was the proportion of reference defect cells correctly identified as defects following the classification stage. Finally the false positives (cells marked as containing nothing in the reference data, but containing something in the automated data) and the false negatives (cells which were classed as defective in the reference survey, but were not flagged by the automated system) were counted.

9.1 Qualitative assessment

9.1.1 Reference data

Figure 11 shows a display of tessellated, reprojected images for one of the surfaces being considered (Winnersh bridge, south end of west abutment). Figure 12 shows the reference data created for the surface shown in Figure 11. In this display red represents defects, blue and amber show features, and grey shows the edge of the surface. White areas are those where no defect was reported.



Figure 11: Tessellated, reprojected images for one of the surfaces studied



Figure 12: Reference data produced for the surface shown in Figure 11.

9.1.2 Automatic output

Figure 13 shows the automatically generated segmented and classified output. Here red again represents defects, brown shows rust staining, the two blue colours represent vertical and horizontal construction features, and amber shows 'other' segmented features which the system was unable to classify. White represents areas where no feature or defect was reported.



Figure 13: Automatically segmented and classified data produced for the surface shown in Figure 11.

9.1.3 Rust detection algorithm

Figure 14 shows the same image as in Figure 11, represented to aid comparison with Figure 15, which shows the classifications of cells as shown in Figure 13, but this time with the colours adjusted to make the rust areas show up more clearly.



Figure 14: Tessellated, reprojected images for one of the surfaces studied



Figure 15: Automatically segmented and classified data produced for the surface shown in Figure 11, with rust areas highlighted.

It can be seen in a comparison of Figure 14 and Figure 15 that the automatic reporting of areas of rust is quite promising, having picked up most of the cells where rust is visible in the image. It has not picked up the large spalled area in the middle of the image where the reinforcing steel is visible, but although the metal does appear to be rusty it has not stained the surface and the fact that the surface has spalled is of more significance.

9.1.4 *Performance assessment*

Figure 16 shows an assessment of the performance of the automated data segmentation. Green shows cells which contained something in the reference data (Figure 12) and something in the segmented automatically generated output (Figure 13). Blue shows cells which were flagged as containing something in the automatic analysis, but not in the reference data. These are false positives, and may result in the inspector being led to believe that the structure is in worse condition than is actually the case. Red represents false negatives, or cells where the automated system suggests there is no problem, but which contained something in the reference data. White

represents cells which were blank in both the reference and automatically generated data, and are successful 'hits'.



Figure 16: An assessment of the hits and misses of the automated data.

Comparison of Figure 16, and Figure 11 shows that most of the false negatives are to do with the positioning of the horizontal cable towards the top of the structure, and the horizontal lighting wire at the very top of the abutment.

Most of the rest of the false negatives are adjacent to areas which have been correctly identified as containing defects and so would not be missed by an inspector taking guidance from the automated output regarding which parts of the structure required most attention.

There are still too many false positive reports (blue). These are distributed across the face of the abutments and are often caused by variations in the concrete appearance, or marks on the surface which confuse the segmentation algorithms. Efforts must still be made to reduce the incidence of these false positives, perhaps by improved classification to remove objects which are not defects.

9.2 Quantitative assessment

In the dataset used for the quantitative analysis there were almost 7000 individual cells. Of these, the reference data showed 450 contained defects, 816 contained features, and 806 contained something other. This made a total of 2072 cells which contained something, and 4790 blanks.

In the automatically assessed data 725 contained defects, 1315 contained features and 1443 contained 'other', giving a total of 3483 cells containing something and 3379 containing nothing. This implies that the automated system was reporting approximately 60% more cells as containing something than it should have. This suggests that the segmentation could be more aggressive to remove features which are not definitely defects.

The automated system reported a total of 1965 false positives, and 531 false negatives. False negatives are more important than false positives as missing a defect could prove catastrophic, whereas falsely reporting a defect may only prove expensive, however these numbers are too high and more must be done to reduce these numbers. Table 5 gives a breakdown of the number of cells containing defects, features, other, or anything in both the reference and automated datasets, as well as a count of the numbers of false positives and false negatives reported by the automated data.

There were 1372 cells which were classed as containing something in both the reference and the automated data. This is 66% of the total reference cells which contained something.

	Reference Data	Automatically generated data
Total number of cells	6862	6862
Cells containing anything	2072	3483
Cells containing defects	450	725
Cells containing features	816	1315
Cells containing 'other'	806	1443
False Positives	-	1965
False Negatives	-	531

Table 5: Cells containing defects, features or other in both the reference andthe automated data sets.

Of the 450 cells which were classed in the reference data as containing defects of one sort or another, 348 (77%) were segmented as containing something by the automatic system. This suggests that the system is better at detecting defects (77%) than it is at detecting features or 'other' (66% hit rate when these are included). In terms of correct classification, 33% of defect cells (147 of 450) were segmented and classified as containing defects by the automated system. Table 6 shows the figures for automated system assessment of the 450 cells marked as defects in the reference data.

 Table 6: Cells which were classified as containing defects in reference data.

	Count	%
Cells classed as defects in reference data	450	100
Automated output classed cell as containing anything	348	77
Automated output classed cell as containing defect	147	33

10 Discussion

During the research it was discovered, as mentioned in Section 5.1, that the method of collecting soffit images was inappropriate. The method used was to begin by imaging the opposite abutment, and tilting the camera up. The soffit was imaged by continuing this upward sweep. However, it became apparent when looking at the images that the soffit should have been imaged by looking directly above the camera, and not by imaging the soffit on the opposite side of the road. The soffit images were too low in resolution, and too distorted to be usable in this work. The methodology for collecting the soffit images has been altered for future work.

It was also discovered, during the reprojection work, that the accuracy and resolution of the devices used to measure and set the camera bearing and elevation were insufficient for perfect reprojection to take place. This was a mechanical issue, not a procedural one, but meant that instead of removing the effect of parallax, it was merely reduced. This was not a major problem in itself but any future improvements to the imaging rig should consider the need for accurate camera orientation data.

The general approach to the imaging of the structures, and the required information needed in order to properly reproject the images has now been established. The image processing techniques have been further enhanced with the development of the rust detection algorithms, but, as was seen in Section 9 there are still too many false positive and negative reports of features and defects.

11 Conclusions

As stated before, this research is not complete, and a further stage is due in 2009-10. Therefore the conclusions drawn are not final, but merely an indication of the current state of the system and scope for further investigations.

The imaging approach has now been finalised, and the calculations needed to plan a site imaging visit have been automated. This should enable any site to be properly imaged with a minimum of on-site planning required, providing usable images of abutments, soffits and wingwalls.

The imaging equipment has been obtained, and is operational, requiring only a short period of training. Some issues with the equipment have been identified, such as the accuracy of the elevation and bearing setting devices, and the goal of automating the collection process, but these are in the desirable category, rather than being strictly necessary.

The type of inspection offered by the automated system appears to fit nicely in the regime of UK highway structure inspections between general inspections, which are undertaken every two years, and principal inspections which are undertaken every six years. The automated inspections could provide very useful information which would help the inspector in his assessment of the bridge condition.

The development of a rust identification module for the segmentation and classification phase has been a simple yet effective improvement to the system, enabling the detection of an important but previously overlooked defect.

There are still an unacceptably high number of false positive and negative reports from the system, and more research is needed to develop segmentation methods to overcome this.

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The condition of highway structures in the UK is determined by visual inspection. There are five main types of inspection which are undertaken at different frequencies. These inspections cover a range of detail, from a cursory check for obvious defects, through to a close examination of particular areas or defects causing concern. The quality of data collected depends on the ability of inspectors to observe and accurately record details on visible defects. This could be affected by many factors, such as the environmental conditions, and the knowledge and experience of the inspectors. Possibly for these reasons, it has been found that the data provided by such inspections can vary significantly. Improvements to the quality of the inspections are therefore desirable.

This research has been carried out with the objective of developing a more objective and repeatable inspection procedure than the current system of manual inspections. The improved inspection procedure is based on the proposal that images of structures could be collected and processed (manually or automatically), to identify defects. The research has concentrated on two key areas - image collection and display, and image analysis.

The research discussed in this report is from the fourth stage of an ongoing process, with another phase of development to come in 2009-10. The results presented herein are therefore based on the current performance of the system, and may improve following further development.

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