DEVELOPMENT OF AN IMAGE BASED SYSTEM FOR ROUTINE VISUAL INSPECTION OF UK HIGHWAYS BRIDGES

by

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Abstract

Accurate inspection data is important for efficient bridge management. Visual inspections play a key role in providing this information, but the reliability of such data has limitations. A range of techniques addressing these limitations are used in other sectors, but not to assist routine visual bridge inspection.

Work has been undertaken investigating the feasibility of performing routine visual bridge inspections based on systematically collected images alone. The requirements of such a system are considered and defined.

The research demonstrates that more detail can be seen in images at 1-pixel-per-mm than can be seen from 3m, and that images at this resolution can be systematically collected, processed, displayed, and inspected to complete General Inspections with results comparable to traditional routine visual inspections.

No existing systems were found to be suitable for routinely providing visual inspection data; consequently a prototype was developed demonstrating the feasibility of the image-based inspection approach. The development considered hardware, image collection methodology, processing, alignment, display and interpretation. Inspectors tested and used the system to perform image-based General Inspections on several bridges. It is concluded that an image-based approach can be used to perform routine visual bridge inspections, with no loss of detail compared to traditional inspections.

For Susie,

For Heather,

For Gail,

Forever.

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1 INTRODUCTION

Routine visual inspection of bridges is the primary source of information for engineers involved in ensuring the bridges remain functional and safe (Lea, 2005). It is known that visual inspections produce results which are highly variable and subjective (Megaw, 1979), even under test conditions following training (Moore, et al., 2001), and consequently the information provided by such inspections may not be as reliable as it would be in an ideal world. These issues affect visual inspections in all fields, not only bridge inspection. The area of Structural Health Monitoring and collection of bridge condition data has benefitted from a lot of research into improved methods for monitoring and processing data collected on bridges (Chang, et al., 2003). However, very little of this research has looked at the need for, or methods of, improving routine visual bridge inspections. The work described in this thesis was carried out to investigate improvements to the data provided by such routine visual bridge inspections by making better use of technological tools, specifically high-resolution digital images. The novelty of this work lies in its experimental demonstration, in a context specifically designed to simulate bridge inspection tasks and conditions, of the fact that detail detectable within high-resolution images is comparable or better to that detectable when on-site; the development of a set of draft specification requirements for an Image-Based Inspection System; and the development and assessment of a prototype system which meets the draft requirements, including techniques for collecting, reprojecting and aligning images to provide images free from the effects of perspective in which all pixels represent constantly sized areas of the bridge.

The work has concentrated specifically on routine visual inspections of UK Highways bridges, at the General Inspection (GI) level (routine visual inspection, discussed further in Section 2.2.2), although many of the findings and conclusions are applicable to inspections on non-highway structures and at other levels of detail.

The aim of the work is to establish whether the use of images can produce improvements in the process of undertaking routine inspections on bridges and the data produced in such inspections, and if so, how could this be achieved. Such improvements would lead to standardised methods of systematically collecting processing and presenting image data for inspection. This would reduce the variability in the defects and features seen in different inspections of the same bridge, and also improve the consistency of detail available to the inspectors for features regardless of where they are located on the bridge. It would also provide a full image record of all visible parts of the bridge. This record could be used for, among other things, tracking the progress of defects, conferring with colleagues about the importance of detected features or defects, or training purposes.

To accomplish this the following objectives have been set:

- Establish the role of routine visual inspection data in the UK highway bridge inspection regime;
- Establish the potential for adoption of an Image-Based Inspection approach;
- Establish the levels of detail which such a system would have to provide;
- Establish how such data could be collected;
- Understand how such data could be processed;
- Understand how such data could be presented and used.

1.1 Methodology

The theoretical framework for this research is influenced in part by experiences gained in the development and implementation of traffic speed pavement condition survey systems (Ferne, et al., 2003).

The research is based on the hypotheses that the current method of collecting visual condition data on bridges is not perfect; that visual inspection data could be improved by technological tools; and that use of such tools in a systematic manner could provide more consistent, quantitative and objective results than are currently achieved, without sacrificing any detail. The key assumptions of the theoretical framework and how they are validated are shown in Table 1.

Table 1: Key assumptions of theoretical framework for research

Assumption	Method of validation
Visual inspections are important sources of data in bridge maintenance	Consultation with inspectors and engineers. Review of current inspection requirements and guidance.
Visual inspection data is subjective, inconsistent and qualitative	Review of literature on visual inspections in general. Review of literature on specific issues affecting visual inspection on bridges.
Visual inspection data can be made more reliable, consistent and objective by using technology; specifically by the systematic collection and use of images.	Review of literature on mitigation techniques. Experimental demonstration of required image resolution. Development of draft specification for suitable system.
A practical system can be developed which would enable the collection and use of such images, and which would produce useable and useful results with no loss of detail	Consideration of suitability of existing systems. Iterative development and use of system on a range of bridges. Comparison of results obtained with IBIS against results obtained in traditional inspection. Consideration of IBIS performance judged against draft requirements.

The methodology of the research has been developed to operate within this framework and provide robust ways of validating the key assumptions, and addressing the objectives of the research.

The need for, and importance of, routine visual inspection of bridges is established by a mixture of review of relevant specifications and guidance, and a consultation and interview process. Problems affecting the reliability and objectivity of visual inspections, and potential solutions to these are explored by an in-depth review of the literature, with particular attention paid to work by Megaw (1979) on factors affecting visual inspections in general, and Moore, et al. (2001) on the role and reliability of visual inspections within the specific application of undertaking routine visual bridge inspections. Consideration of previous work on the implementation of machine based pavement condition surveys (Ferne, et al., 2003) leads to the position that an increased use of technological tools and approaches can provide a standardised, systematic, consistent method of collecting images which can be presented to inspectors in such a way to remove some of the subjectivity inherent within visual inspections. These images would be suitable for use within image-based defect detection systems. This leads to the formulation of the research question posited in Chapter 5:

> Can systematically collected, high-resolution image data be used to enable General Inspections to be performed which provide at least as much information to engineers as traditional on-site General Inspections? If so, how can the data be collected, presented and interpreted, and what are the benefits of such an approach?

In order to answer the research question a draft specification is developed detailing the requirements for an Image-Based Inspection System (IBIS) to be used for routine visual inspections. These requirements are established by a mixture of review of the current capabilities of a GI and the use of GI data, and an experiment to determine the levels of detail discernible from a range of typical inspection distances, and within images presented at different resolutions.

These requirements for a successful system are used to assess the potential usefulness and readiness of various existing systems and system components for use in such a system. Where possible this assessment is performed by practical use and investigation of how the system could be operated and the data produced. In cases where a practical assessment is not possible then desk based reviews of available specifications, literature and data are used.

The development of a prototype system used to explore and demonstrate the potential of an Image Based Inspection (IBI) methodology is described. The development of this prototype has been undertaken to specifically address as many of the requirements defined in Chapter 6 as possible. The iterative development of the prototype makes use of readily available hardware and software where appropriate, with upgrades and modifications being implemented to address problems and shortcomings as necessary.

Images collected, processed and aligned using the prototype IBIS are used to perform GI level inspections. The results from these Image Based Inspections are compared against inspection data gathered onsite using traditional inspection methods. The potential usefulness of the Image Based approach, as well as the benefits of the standardised, systematic, controlled methods of collecting and presenting the data for inspection are assessed by comparing Image-Based Inspection results with the results of traditional inspections carried out on the same structures.

The thesis is structured in two main parts, with appropriate reviews of literature and more detailed discussion of methodologies included where appropriate. Part 1 discusses the role of visual inspections, how they are performed, what their shortcomings are, and what could be done to overcome these. Part 1 concludes with a recommendation that the use of technological tools should be investigated (specifically the use of high-resolution digital images). Having established that technological approaches and tools could be beneficial, Part 2 establishes the requirements for an image-based system for collecting routine visual inspection data at the required level of detail, including establishing by experiment what the appropriate level of detail is. Part 2 also presents a review of existing systems and methods and considers their suitability as methods for collecting and presenting routine inspection data. Part 2 then discusses the development and assessment of a prototype Image-Based Inspection System (hardware and software). The thesis concludes by presenting the findings and conclusions of the work, and highlighting some areas for potential future development.

PART 1 – VISUAL INSPECTIONS: PURPOSE, PROBLEMS AND POTENTIAL MITIGATIONS

Part 1 of this thesis establishes the position of visual inspections within the current bridge inspection regime, and shows that although they provide important information within the process of maintaining the structures, there are a number of problems which affect their reliability and objectivity. Some approaches to improving the reliability of visual inspections are discussed, with particular emphasis on the use of technology.

The work presented in Part 1 demonstrates that the research gap exists and there is a need for the development and assessment of the prototype system presented in Part 2.

- Chapter 2 discusses the role and purpose of visual inspection data within existing bridge inspection regimes, and concludes that there is a clear need for visual inspections of structures.
- Chapter 3 discusses some limitations of visual inspections, considering the general case of visual inspections, as well as more specific cases of visual inspections in civil engineering and bridge inspection. This finds that bridge inspections are difficult to perform consistently and that visual inspection has known weaknesses.
- Chapter 4 discusses a number of mitigation techniques which can be used to address the weaknesses of visual inspections. This finds that there are possible benefits from using technology, specifically images, in a more systematic way to collect inspection data, and that the use of such data could be acceptable to engineers.

- Chapter 5 provides a summary of the work and findings of Part 1. This sets the scene and provides justification for the work described in Part 2.

<u>Note on terminology used:</u> in this thesis the words 'engineer' or 'engineers' refer to those end users of the data responsible for making maintenance decisions on particular bridges or structures. 'Inspector' or 'inspectors' refers to the people who have performed the visual inspections to collect condition data on the bridge. Using these terms, it is entirely possible for an inspector to also be an engineer, or vice versa.

2 ROLE AND PURPOSE OF VISUAL BRIDGE INSPECTIONS

> "The primary source of information for assessing the condition of the Highways Agency's reinforced concrete bridges is visual observations…" (Lea, 2005).

For a long time it was considered that bridges, once built and in service, did not require much inspection or maintenance. However, following the deaths of 46 people in the 1967 collapse of the Silver Bridge between West Virginia and Ohio in the USA, a report (National Transportation Safety Board, 1970) was produced which made a number of recommendations, including the development of improved inspection equipment and procedures.

A study in the 1970's by 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 which was adopted by many countries, and still forms the basis of many bridge inspection philosophies, including that of the UK.

Incidents such as the 2006 collapse of the De la Concorde overpass in Quebec (Johnson, et al., 2007), which killed five and seriously injured another six people, and the 2007 collapse of the I-35W in Minneapolis (Hao, 2009), USA, which caused the deaths of 13 people, and injured 145 more, provide terrible reminders of the potential consequences of bridge failure. These in turn show the need for a practical and meaningful programme of inspection and maintenance. More recently, a series of high profile problems in the UK on bridges on the A4 (Wynne, 2011) and M4 (Wynne, 2012) in the months leading up to the Olympics, have reinforced the importance of detecting faults in structures.

Each of these bridges differed in construction, traffic and identified defects, and not all the defects which led to the collapse or closure of the structure could have been detected using the same monitoring or inspection approach. It is important therefore to have a range of techniques and methods for collecting bridge condition data, and for these to be used appropriately. Visual inspections are merely one tool available to inspectors and engineers when monitoring a structure.

The situation has moved a long way from that of 50 years ago when inspection was seen as unnecessary, to one where it is now accepted as a vital part of the management of infrastructure assets. As the Highways Agency states in BA 35/90 (Highways Agency, 1990):

> "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).

The information collected during visual bridge inspections is needed to help engineers efficiently plan and manage their maintenance programmes. This data can be used to inform asset management systems, or calculate bridge condition indicators, and is essential to the recommendation and planning of follow-up work, whether this is scheduling additional inspections or monitoring, or actual maintenance work.

2.1 Current research into other bridge condition data collection techniques

Visual inspections are only one tool available to engineers and inspectors in assessing the condition of a structure. There are a range of testing and monitoring techniques which can be used such as half-cell potential measurements, acoustic monitoring, materials sampling methods, or more intrusive methods such as drilling test holes to observe post-tensioning tendons. A useful survey of some of the more common approaches used in the non-destructive evaluation of bridges is given in a PIARC (Permanent International Association of Road Congresses, now known as the World Road Association) report into inspector accreditation, non-destructive testing and condition assessment for bridges (PIARC Technical Committee D3 Road Bridges, 2011).

2.2 How are bridge inspections carried out? – Regulations

This thesis is specifically concentrating on the collection of routine visual inspection data on UK highways bridges (General Inspections – see 2.2.2.2). However, in order to establish that the UK approach was not anomalous or unique in its use of visual inspection data, a review of bridge inspection practice in other countries was undertaken.

2.2.1 Highways Inspection regimes outside the UK

A summary of the inspection regimes and the role of visual inspections within them is given in Table 2, and is based on work done by the US National Cooperative Highway Research Program, as reported in NCHRP 375 (Hearn, 2007). Additional studies considered were the EU HeROAD investigation (Žnidarič & Kreslin, 2012) and the PIARC investigation (PIARC Technical Committee D3 Road Bridges, 2011). Table 2 shows that visual inspections play a central role in the condition monitoring regimes in all the countries for which data was considered.

Table 2: Summary of inspection regimes and the role of visual inspections within them

Country	Primary inspection	Frequency	Nature of inspection	Next more detailed level	Frequency
UK	General	2 years	Visual, no special access equipment	Principal	6 years
USA	Routine	2 - 4 years	Visual, no special access equipment	In-depth	10-15 years
Denmark	Routine	12 months	Visual, no special access equipment	Principal	6 years
Finland	Annual	12 months	Visual, no special access equipment	General	5-8 years
France	IQOA	3 years	Visual, no special access equipment	Detailed	1-9 years depending on condition
Germany	Minor test	3 years	Visual, no special access equipment	Major test	6 years
Norway	General	1-2 years	Primarily visual with some measurement	Major	5-10 years
South Africa	Monitoring	12 months maximum	Visual, no special access equipment	Principal	5 years
Sweden	General	3 years	Visual, no special access equipment	Major	6 years

No evidence was found to suggest that visual inspection is not a core requirement of any of the inspection regimes considered.

2.2.2 UK Highways Agency bridge inspection regime

The requirements for inspecting highway bridges on trunk roads in England are defined in Volume 3, Section 1, Part 4 of the DMRB (Design Manual for Roads and Bridges) (BD 63/07) (Highways Agency, 2007). Slight variations to these requirements apply to the rest of the UK, mostly to do with the reporting format. Although the requirements are not mandatory on non-Highways Agency roads, they are widely adopted by Local Authorities following the advice in the Code of Practice (Department for Transport, 2005).

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 of inspection involves, when it should be performed, and how the results should be reported. The five inspection levels defined in the DMRB are as follows:

2.2.2.1 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. The inspections are not performed specifically to assess the condition of structures but are part of a wide-ranging 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.

2.2.2.2 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. In some circumstances (where the bridge is believed to be undergoing rapid changes in condition or use) the frequency of inspection may be increased, or the General Inspections may be supplemented with additional monitoring.

General Inspection 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 in Table 2.

Table 3: Meanings of Severity and Extent codes for reporting defects in General Inspections

Extent	A	No significant defect
	B	Slight; not more than 5% of length or area affected
	C	Moderate; 5% – 20% affected
	D	Extensive; more than 20% affected
Severity	1	No significant defect
	2	Minor defects of a non-urgent nature
	3	Defects which shall be included for attention within the next annual 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 reported. The ability to report the severity and extent separately is very helpful for later interpretation of reports.

The lack of any special access arrangements or equipment means that the inspector is usually restricted to reporting what can be seen from ground level. As will be seen later (Section 2.3) some inspectors use equipment to get a better view of elements which are difficult to see, but this is not a requirement.

General Inspections are purely visual in nature – the inspector is only required to report what can be seen – with no requirement for touching the surface of the structure, or for taking samples or measurements. The need to report what can be seen, combined with the lack of special access or equipment, means that the inspector will be able to see far smaller defects in some parts of the structure than in others. For example a fine crack at eye-level on an abutment next to a footway will be easier to observe, and more likely to be reported, than the same crack, or even a much larger one, at the top of an abutment, or on a parapet. The way in which the results of a General Inspection are recorded means that any part of the structure which is not mentioned as exhibiting signs of deterioration has to be assumed to be sound. There is no requirement to collect any photographic images of the structure, although it is recommended. The code of practice related to bridge inspection data (Department for Transport, 2005), and wider bridge asset management, mentions that digital cameras can be useful, and notes that it is essential to have some method of accurately locating which part of the bridge is shown within each image.

However, in spite of the limitations in what is included in a General Inspection (visual defects only), and the difficulties in seeing small defects in potentially difficult conditions at distances of several metres, General Inspections are an accepted and fundamental source of information on bridge condition.

2.2.2.3 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 hammers to test for delamination. As with the General Inspections, the inspector is required to familiarise themselves with the previous notes on the structure and its condition before visiting the site.

Principal Inspections must take place 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.

Principal Inspections, although they have a requirement for a much closer inspection than a General Inspection, and include limited testing, are still in essence visual inspections. This is because the areas of bridge which are chosen for testing are largely driven by the inspectors' interpretation of what they see. It is left to the inspector's discretion precisely which parts of the structure are closely inspected, and which defects are recorded, which defects are photographed, and from what positions, and what defects to include on the detailed drawings. Unlike General Inspections, where the inspector may be too far away from surfaces to detect small defects, a Principal Inspection requires the inspector to be within touching distance of all surfaces. However, only those areas which have been deemed to be defective by the inspector on-site get recorded. There is no way of knowing if the inspector has missed or overlooked something during the inspection, and no way of revisiting the actual condition of the bridge at the time the inspection was performed, only the record of the inspection.

2.2.2.4 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: each one is tailored to the needs of the particular structure being inspected. These inspections are carried out when a need is identified. A Special Inspection can be a series of inspections looking for and monitoring changes over time.

Special Inspections should provide detailed information on the parts of the bridge inspected, including photos and/or sketches. As in Principal Inspections, 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.

Special Inspections differ in form and approach depending on the nature of the defect or deterioration being monitored but they retain some visual aspects, as reflected by the requirement to record photographs and detailed drawings of the findings of the inspection. Indeed a Special Inspection could comprise one or more very close visual inspections of a small part of a bridge which is causing concern, with no other testing. These can be used to identify and monitor changes in the condition of any defects, although care must be taken to record the visual condition in such a way that enables any changes to be accurately assessed, and isolated from apparent changes which have occurred as a result in changes to the way in which the data has been recorded.

2.2.2.5 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).

These inspections, whose purpose is to provide information for the calculations of the load carrying capacity of the bridge, involve a detailed geometric survey of the bridge, and inspections to detect any deterioration or defects present. The presence of defects may change the parameters used in the calculations of the bridge strength, therefore it is important that as accurate a picture of the bridge condition as possible is obtained at this stage. It is recommended in the DMRB guidance (Highways Agency, 2007) that these are performed in conjunction with Principal Inspections. Other advice (Highways Agency, 2001) points out that it is doubtful that the data recorded during a General Inspection would be sufficient for assessment purposes. It appears therefore that these inspections would essentially be carried out as Principal Inspections and would record the same types and levels of data, and would suffer from the same weaknesses.

2.2.3 Highways bridge inspection regimes on non-trunk UK roads

The standards outlined in the DMRB are only mandatory for Highways Agency structures. Many more road bridges fall under the responsibilities of Local Authorities or other bridge owners, all of whom have a legal responsibility to maintain their bridges to an acceptable standard (HMSO, 1980). A Code of Practice has been produced (Department for Transport, 2005) to advise on best practice for maintaining highways structures across the UK. The code is not mandatory, but any departures from its advice must be justified and recorded.

The guidance recommends that an 'adequate' inspection regime be implemented, and that this should include Safety, General, Principal and Special Inspections, as well as Inspections for Acceptance and routine surveillance. The details of these inspections are the same as those specified in the DMRB for bridges on the Highways Agency network.

As a result of the Code of Practice, many of these non-Highways Agency owners adopt the use of Highways Agency bridge management standards as a method of demonstrating best practice and sufficient care. Consequently, visual inspections form a key and central component of the collection of condition data on these bridges as well.

Also of note in the guidance offered within the Code of Practice is the advice given in Section 6.5.17 – 6.5.19, pp161-162. This states that "digital cameras can provide an effective means of recording defects and other features of a structure", and that "it is essential to provide a means of referencing for all forms of pictorial records" to help identify which part of which structure is shown in each image.

2.3 How are bridge inspections carried out? – UK Practice

Before attempting to improve the way routine visual inspections are performed on UK highways bridges it was important to understand how they are currently performed, and how the resulting data is used. In order to better understand how inspections are performed in practice on UK highways bridges a series of informal meetings were held with a number of engineers and inspectors responsible for collecting and interpreting bridge inspection data in various parts of England. Those interviewed had varying levels of experience in planning, performing and reporting bridge inspections, as well as interpreting and acting on the results of inspections performed by others. In all, fourteen engineers/inspectors were involved in these face to face discussions, which took place between November 2009 and August 2011.

The initial discussions were not formally structured and the engineers/inspectors were largely allowed to lead the discussions, with prompting and steering to ensure that appropriate areas were covered. As well as questions about their areas of responsibility and experience they were asked about the usefulness of General Inspection data, what levels of detail they would expect to include, or find in a General Inspection report, and the practical processes involved in producing an inspection report. Areas covered included: training and QC procedures; preparation for the site visit; what actually takes place on site; equipment used; time taken; what is done with this information.

A wider consultation then took place with the aim of confirming the initial findings, and obtaining additional information, not covered in the initial discussions. This second consultation did not involve face to face interviews, but involved the completion of a questionnaire. Appendix A contains the questionnaire as sent to the consultees. Care was taken to word the questions and possible responses to avoid leading questions, or misleading answers (Belson; 1981; 1986). A total of 28 responses were received from this consultation, meaning that in total, the views of 42 engineers and inspectors were considered. It is recognised that this is not a statistically significant sample of the bridge inspection community; however the purpose of the consultation was to provide background information over current practice in inspection, rather than to undertake an exhaustive review.

2.3.1 Responsibilities and experience of consultees

The responsibilities of the inspectors and engineers interviewed include maintaining and inspecting all types of structures (culverts, walls, etc.). All of them agreed that bridge inspections were the most time consuming of their responsibilities, and that these took a significant part of their resources.

The respondents to the email-based consultation had a mixture of backgrounds. 21% of them described themselves as engineers, 46% as inspectors, and 33% as both engineers and inspectors.

Of those who responded to the questionnaire, two of them mainly had overseas experience, (one in Portugal, and one in various parts of Africa), however their responses were largely in line with those from UK based inspectors and engineers. Significant discrepancies between the responses of the overseas respondents and the UK ones will be discussed as and when appropriate.

The respondents had a mixture of experience, with the most inexperienced inspector having been in the job for only a few months, while the most experienced had been involved in the use and collection of inspection data for over 30 years. Figure 1 shows the distribution of experience among those who either took place in the face to face interviews, or responded to the questionnaire.

Figure 2 shows how many bridges the respondents to the questionnaire estimated that they had inspected in the last two years, and Figure 3 shows how many they estimated they had inspected over their careers. These questions were not asked during the face to face interviews.

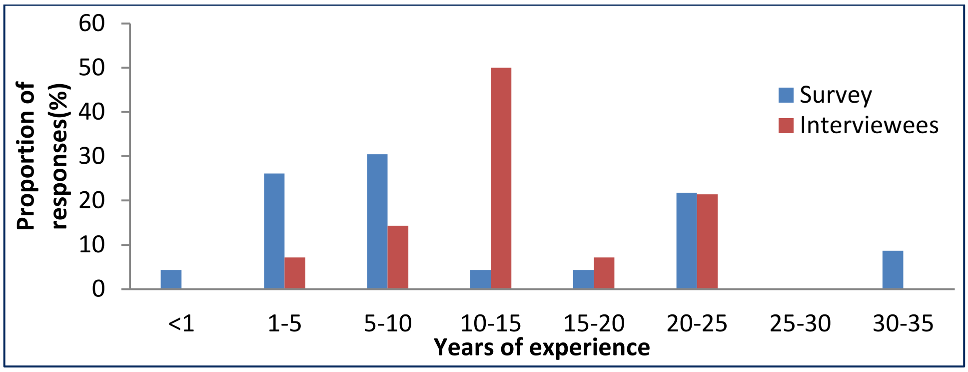


Figure 1: Distribution of experience in use and collection of bridge inspection data among those engineers and inspectors who either responded to the questionnaire, or were involved in the face to face discussions.

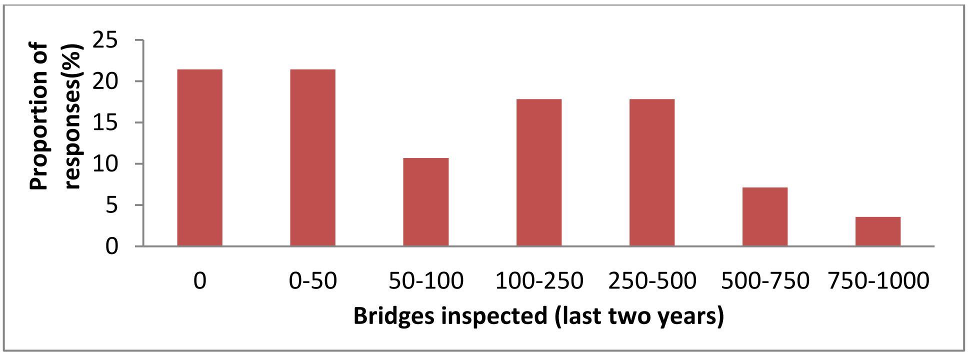


Figure 2: Estimated number of bridge inspections carried out by respondents to questionnaire within the two year period leading up to the consultation taking place.

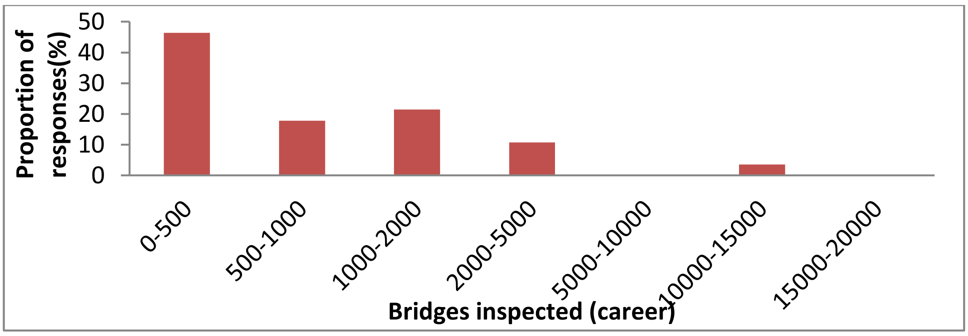


Figure 3: Estimated number of bridge inspections carried out by respondents to questionnaire within their careers.

The data presented in Figure 1, Figure 2, and Figure 3 shows that the people who have provided information and opinions on the role, performance, and usefulness of General Inspection data have been involved in the area for a while, have produced or used a large number of bridge inspection reports, and should know what they are talking about. Although only a small sample of all the engineers and inspectors involved in the collection and interpretation of bridge inspection data, and not necessarily statistically significant, they are experienced and knowledgeable, and their opinions, therefore, are worth listening to.

2.3.2 Training of bridge inspectors

The consultees were asked about the levels of training, education or experience required in order to perform inspections. None had any formal requirement for any training or qualifications, although some did try to use graduate engineers in their inspection teams. These were felt to provide more reliable inspection reports than unqualified (those with A-level or lower qualifications) inspectors. Some of the consultees had attended a two-day bridge inspection course run by the Institute of Civil Engineers (Bridge Maintenance and Inspection). To help new inspectors develop the necessary skills it was stated by most of the consultees that experienced inspectors accompany new ones for at least six months.

2.3.3 Quality Assurance of inspection results

During the interviews none of the engineers reported any formal quality assurance or checking of bridge inspection reports within their organisations. They did however all state that each inspection report is read by a responsible (usually Chartered) engineer who questions any dubious results and may ask for further information, or a follow-on report to resolve any uncertainties.

2.3.4 Purpose and usefulness of General Inspections

The questions in the first section of the questionnaire were intended to establish the views of the respondents on the purpose and usefulness of General Inspections, and the data they generate.

Figure 4 shows a summary of the responses given to question 1.1 – "General Inspections are the primary source of information about the visual condition of a bridge". Almost 90% (89.9%) of the responses to this statement agreed, slightly agreed, or strongly agreed with the statement.

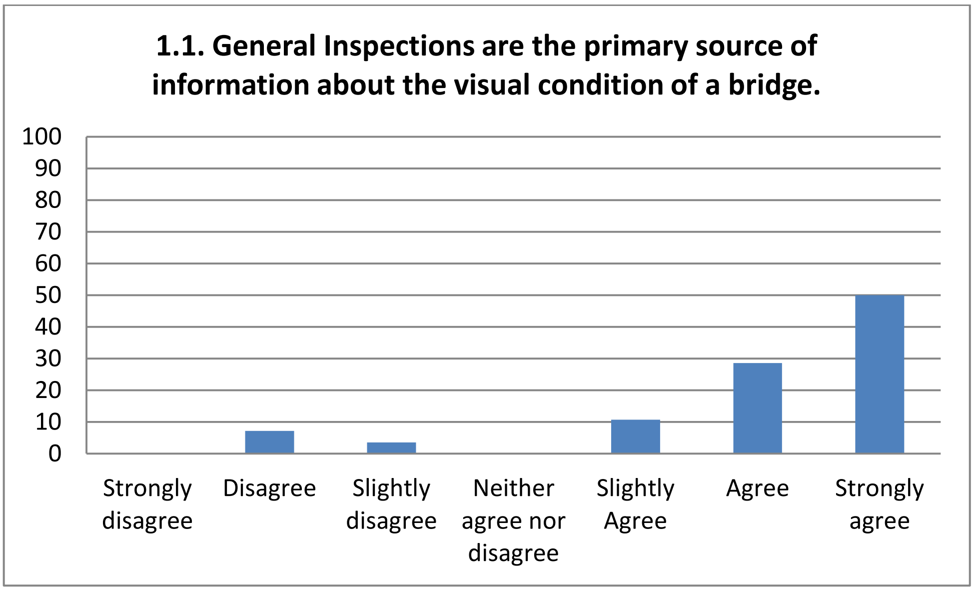


Figure 4: Summary of responses to question 1.1 in questionnaire.

85.7% of respondents to question 1.2 gave a positive response (slightly agree, agree, or strongly agree) with the statement that a GI produces "an accurate picture of the visual state" of a bridge (Figure 5). However, only 75% of respondents agreed that a GI records everything that an engineer may be interested in (question 1.3 - Figure 6).

This is backed up by the fact that only 7.14% of respondents disagreed with the statement in question 1.4 – "General Inspections sometimes fail to spot small defects which are not close to the inspector". This is shown in Figure 7.

Thus the consultation responses show 89% of respondents agreeing that GIs are the primary source of information on the visual condition of a bridge, 85% saying that GIs are accurate, 75% of people saying that GIs record everything of interest, but over 92% saying that they sometimes fail to spot small defects.

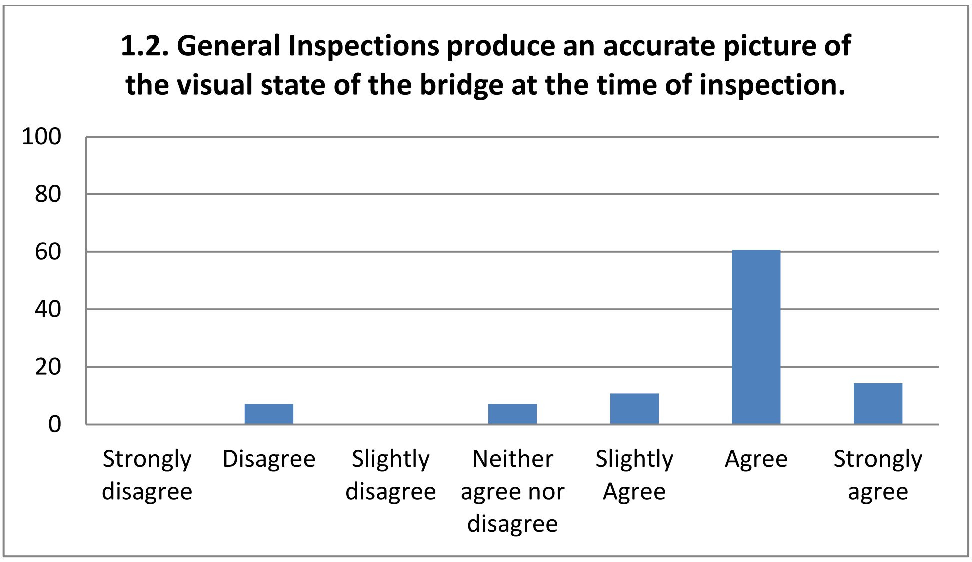


Figure 5: Summary of responses to question 1.2 in questionnaire.

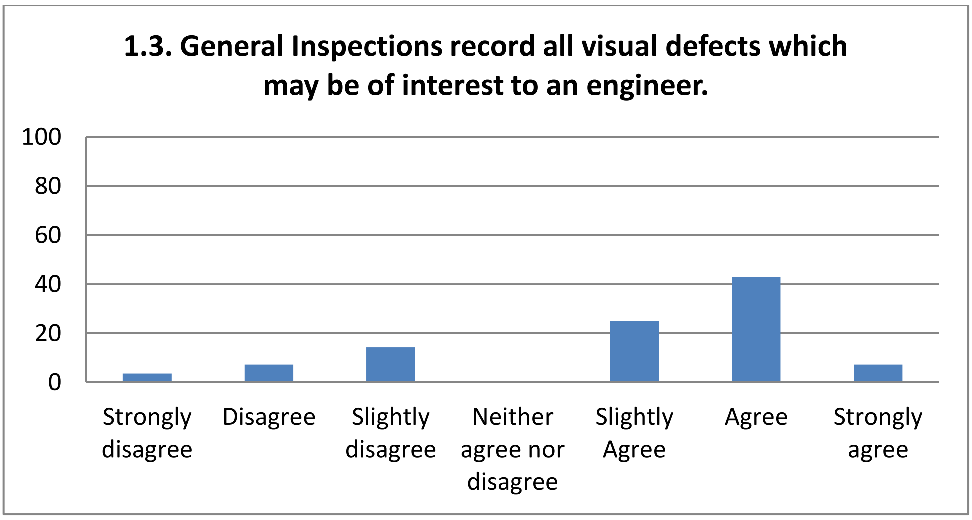


Figure 6: Summary of responses to question 1.3 in questionnaire.

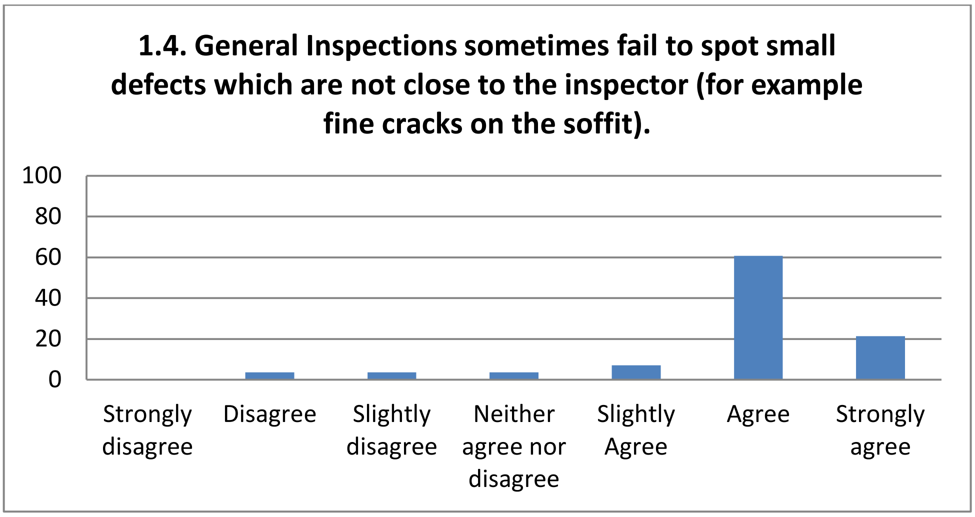


Figure 7: Summary of responses to question 1.4 in questionnaire.

Question 1.5 attempted to establish the sizes of defects which should be detected during a GI. This asked what would be an acceptable size of defect to fail to detect during an inspection. Figure 8 shows the responses to question 1.5. The most common response (33%) was that all cracks wider than 0.2mm must be detected. However, with 33% demanding the detection of the finest cracks, and 11% wanting 0.4mm cracks to be detected, this leaves 55.6% of responses who would be happy as long as all cracks wider than 0.6mm could be detected. Chapter 6 presents further discussion relating to the detection of features of different widths.

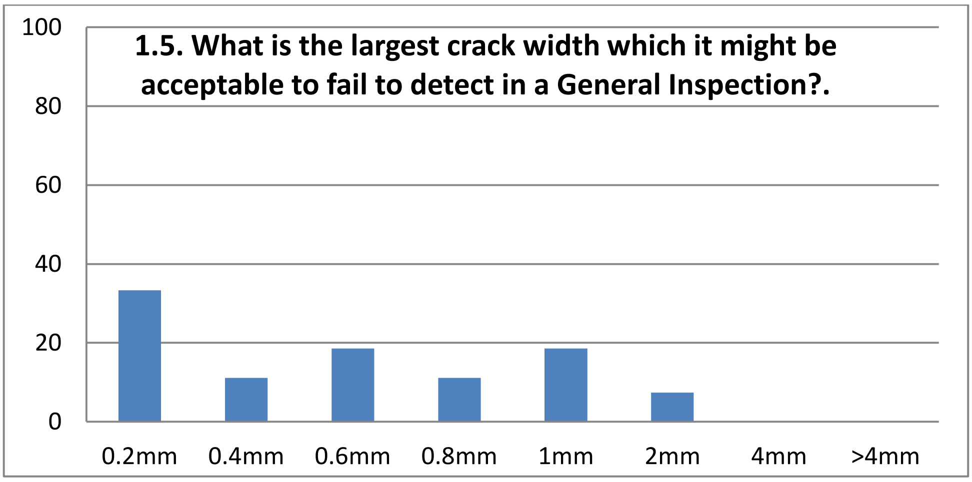


Figure 8: Summary of responses to question 1.5 in questionnaire.

Questions 1.6 and 1.7 asked the respondents to state how much they agreed with the statements that the results of GIs are used to plan maintenance, and further inspections respectively. The responses to these questions are shown in Figure 9 and Figure 10.

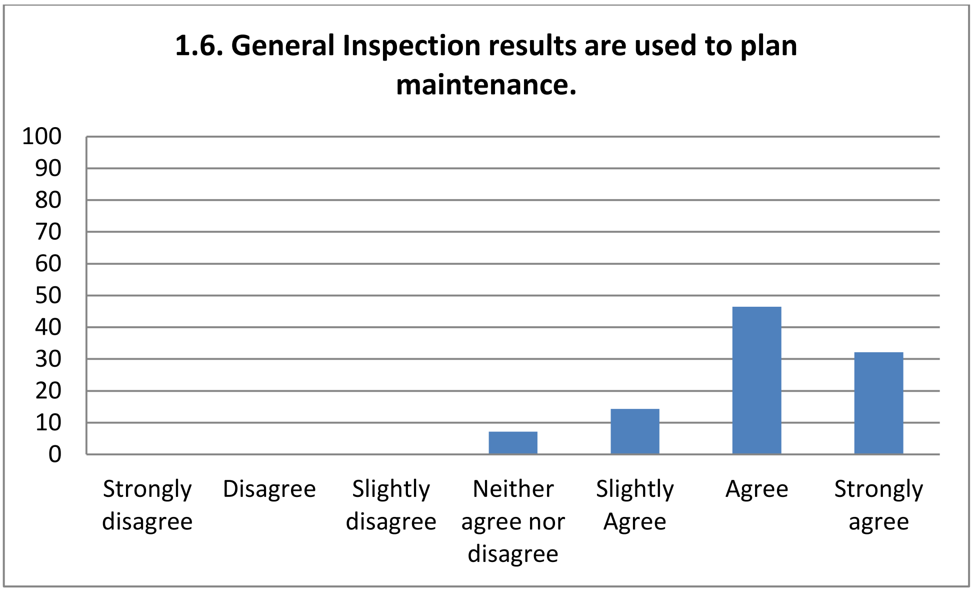


Figure 9: Summary of responses to question 1.6 in questionnaire.

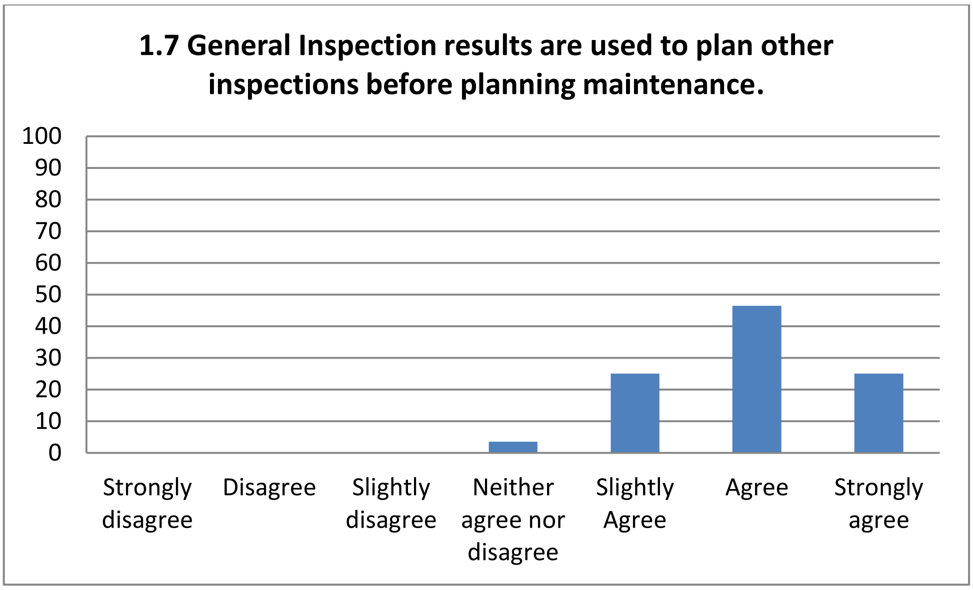


Figure 10: Summary of responses to question 1.7 in questionnaire.

Only slightly more than 7% of responses to question 1.6 did not agree that GI results were used to plan maintenance, and only 3.6% of responses to 1.7 said that the results were not used to plan further inspections, before deciding on a maintenance approach. 78.6% of responses agreed, or strongly agreed that GI results were used to plan maintenance, with 71.4% agreeing, or strongly agreeing, that they are used to plan further inspections.

Figure 11 displays a summary of the responses to question 1.8. This asked how much the respondents agreed with the statement that GIs provide useful information: 92.9% either agreed, or strongly agreed with this statement. No responses indicated that they disagreed with this statement.

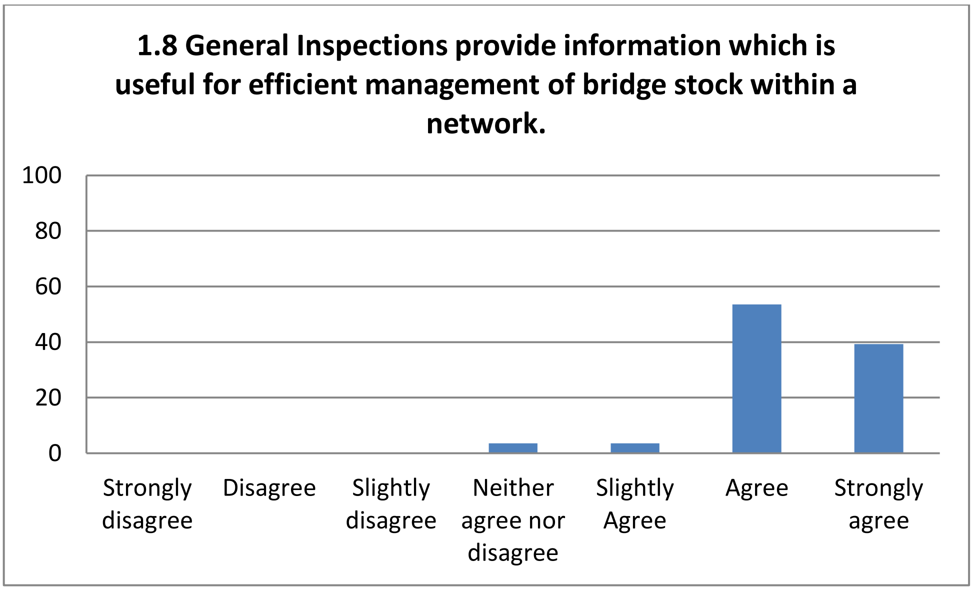


Figure 11: Summary of responses to question 1.8 in questionnaire.

Figure 12, Figure 13, and Figure 14 show the responses given to questions 1.9, 1.10, and 1.11 respectively. These asked whether the data provided by a GI was consistent, objective and quantitative.

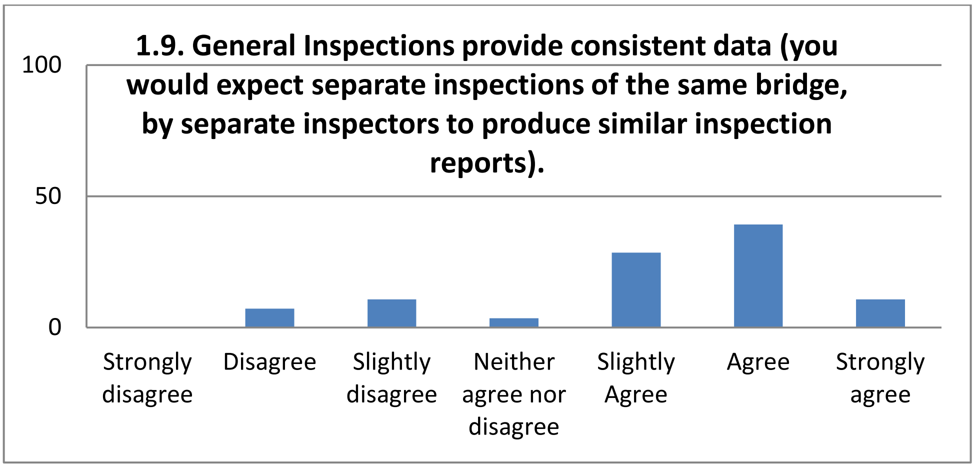


Figure 12: Summary of responses to question 1.9 in questionnaire.

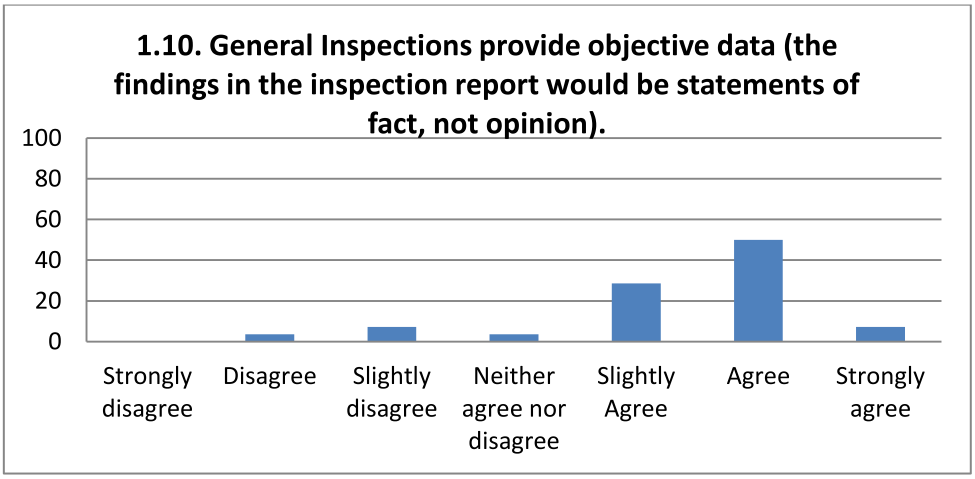


Figure 13: Summary of responses to question 1.10 in questionnaire.

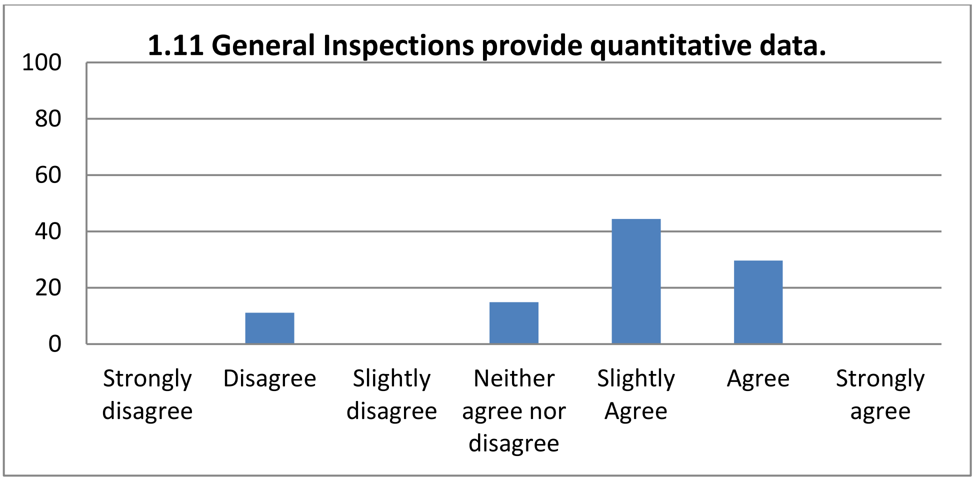


Figure 14: Summary of responses to question 1.11 in questionnaire.

These responses show that 50% of consultation respondees are happy that the results of GIs are consistent (agree, or strongly agree), and 57.1% either agree or strongly agree that the results are objective. There is 74% agreement that GIs produce quantitative data, but the agreement here is less strong than in previous questions, with 44.4% of the respondents only slightly agreeing with the statement.

2.3.4.1 Purpose and usefulness of General Inspections – summary

General Inspections are seen as the primary source of information about the visual condition of a bridge, and are believed to provide an accurate picture of the condition, having detected all defects of interest to an engineer (not necessarily all defects: it is acknowledged that some details may be missed). Presumably this means that they are believed to provide information which enables engineers to make informed decisions, even if some details are unreported. Engineers are happy with the outputs of existing GI's, and stated they would accept a system which did not fail to detect defects smaller than 0.6mm. It can therefore be assumed that GI's are able to detect defects of this size or larger.

The respondents to the questionnaire believe that GI's provide information which is objective, consistent and quantitative. The belief that the data is objective and consistent is very interesting as this is at odds with most of the research into visual inspections in other fields (Chapter 3). It could be that the data provided is objective *enough*, and consistent *enough* for use, or it could be that the respondents are not aware of some of the problems to do with consistency and subjectivity in visual inspection data. It must be remembered that the inspectors who were asked to judge how useful and informative the GI data is were experienced, and have spent, on average, over 12 years collecting and using such data. It therefore might be expected that they would not be overly critical of the data. Having said that, it must also be borne in mind that there is no obvious crisis of condition in the UK highway bridge stock, as bridges are not collapsing or being condemned on a frequent basis. Any problems with the quality and reliability of the routine visual inspection data clearly have not yet had widespread catastrophic consequences.

2.3.5 Inspection process

According to the interviewees, the inspection process itself can be thought of in three phases: revisiting available information and planning; on-site inspection itself, where defects are detected and recorded; and the reporting process which takes place in the office following the inspection.

Figure 15 shows the breakdown of responses regarding how the total time spent on an inspection was split between the three phases. Figure 16 shows the distribution of answers given to the question. The colour scheme used in Figure 15 is maintained throughout the questionnaire responses, with purple being used for questions relating to preparatory activities, amber for on-site activities and red for post-inspection activities.

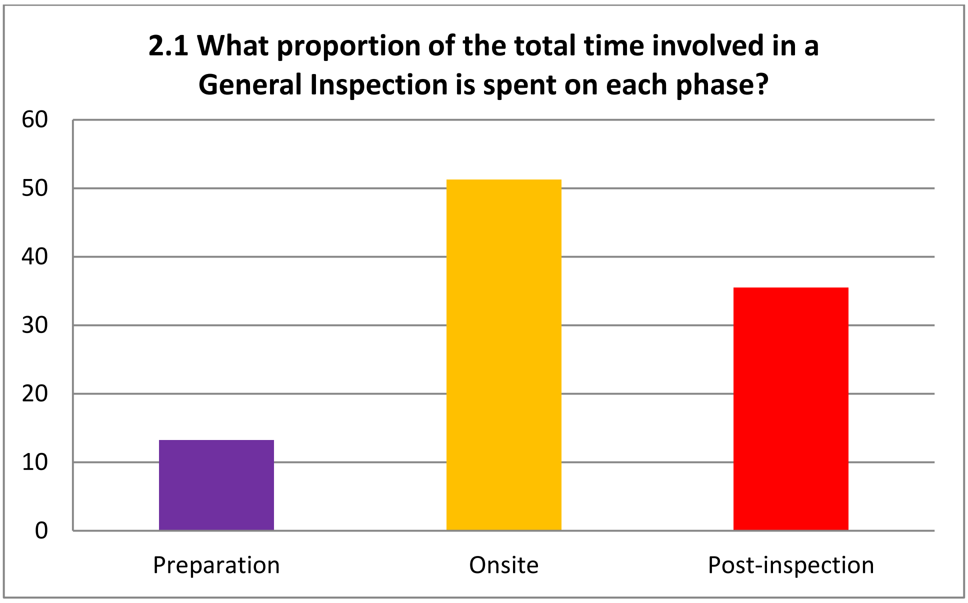


Figure 15: Summary of responses to question 2.1 in questionnaire.

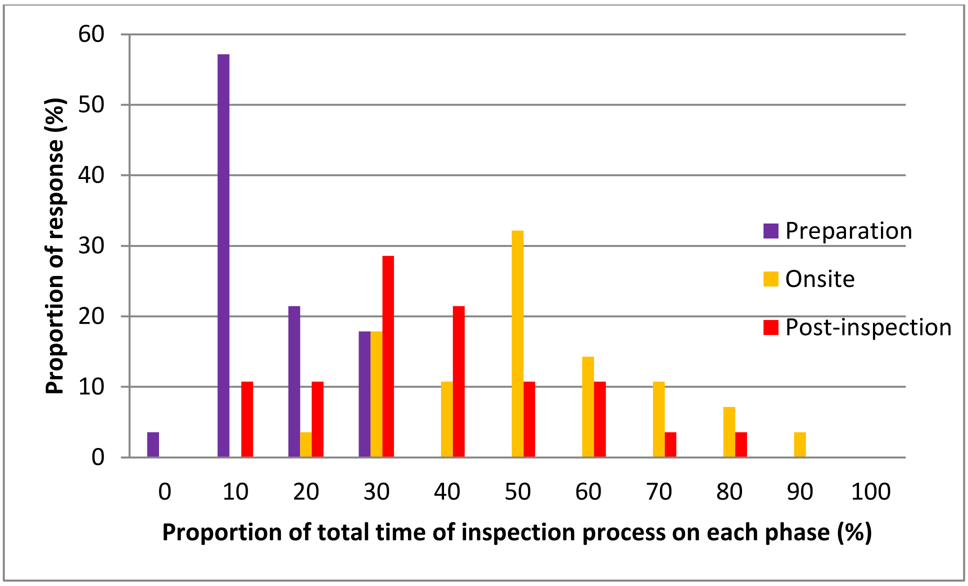


Figure 16: Distribution of responses to question 2.1 in questionnaire.

It can be seen in Figure 15 that the bulk of the effort takes place on-site (51.3%) and in the post-inspection interpretation of data and production of the report (35.5%). However, there is a large spread in the data shown in Figure 16, suggesting that the way in which the inspectors approach the process is not consistent: some spend as much as 90% of the total inspection time on-site, while others spend as little as 20% on-site; some spend as much as 80% of their inspection effort in the post-inspection phase, others spend only 10% of their time in this phase.

This large spread in the distribution of effort in each of the three phases of inspection is further reflected in the answers to the rest of the questions about what is done before, during and after the inspections (questions 2.2 to 2.15). There is significantly less consensus in the answers given to these questions than was seen in the answers given to the questions in Section 1 of the questionnaire.

Regardless of the spread in the efforts given in each of the inspection phases, the bulk of the effort is spent on-site, and in the office following the inspection. Therefore a system which could help reduce the time spent by skilled engineers and inspectors on-site, and away from the office, or assist the interpretation of data and production of reports could be beneficial.

2.3.6 Preparation prior to site visit (General Inspection)

According to the interviews, standard practice when preparing for a GI is to examine any available inspection reports for the structure, and for the inspector to familiarise themselves with the type, layout, and history of the bridge. This provides some idea on what sort of things to look for during the inspection, what previous defects have been noted, and what repairs may have been undertaken, and helps the inspector know what to expect when they arrive on site.

As shown in Figure 17, the use of previous inspection data is not universal. Most of the respondents to the questionnaire indicated that they always (42.9%) looked at any previous inspection reports when planning an inspection, or did so in the vast majority of inspections (21.4% of respondents looked at inspection reports for between 80% to 100% of inspections). However, there was a sizeable minority who only rarely look at such information (25% of respondents look at previous inspections less than 40% of the time). Whether this non-use of previous inspection data was intentional (to avoid potentially prejudicing the inspection and trying to ensure the inspector reports what is seen rather than what they expect to see) or unintentional (a consequence of not having sufficient time to sift through previous records and prepare thoroughly) was not addressed directly in the questionnaire, but comments were received from respondents supporting both viewpoints.

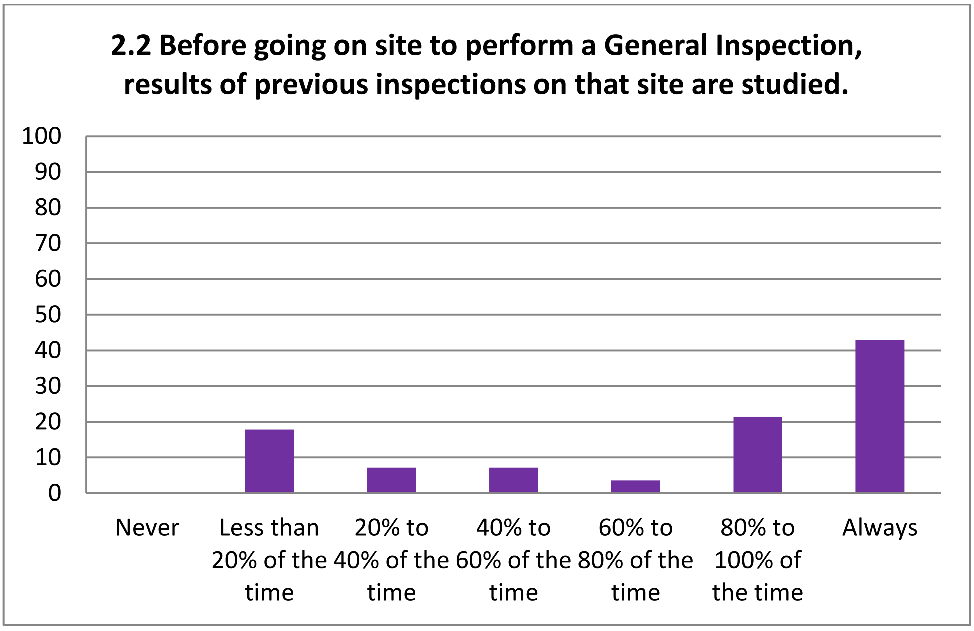


Figure 17: Summary of responses to question 2.2 in questionnaire.

Question 2.3 asked about the use of tools such as Google StreetView© (Google, 2007) as a means of site familiarisation before visiting the site. These do not show the condition of the structure, and are not updated regularly, but enable the inspector to get a feel for what to expect when performing the inspection. In conjunction with site maps and other drawings this can give a good picture of how the bridge is set up, what access will be possible and what traffic conditions could be expected. However, as with the use of previous inspection reports, the use of such methods are not universal. Figure 18 shows the responses to the question about using such tools. Most of the survey responses (64.3%) indicated that this approach is used on fewer than 40% of all inspections, while only 21.4% of the respondents say they always try to make use of such information.

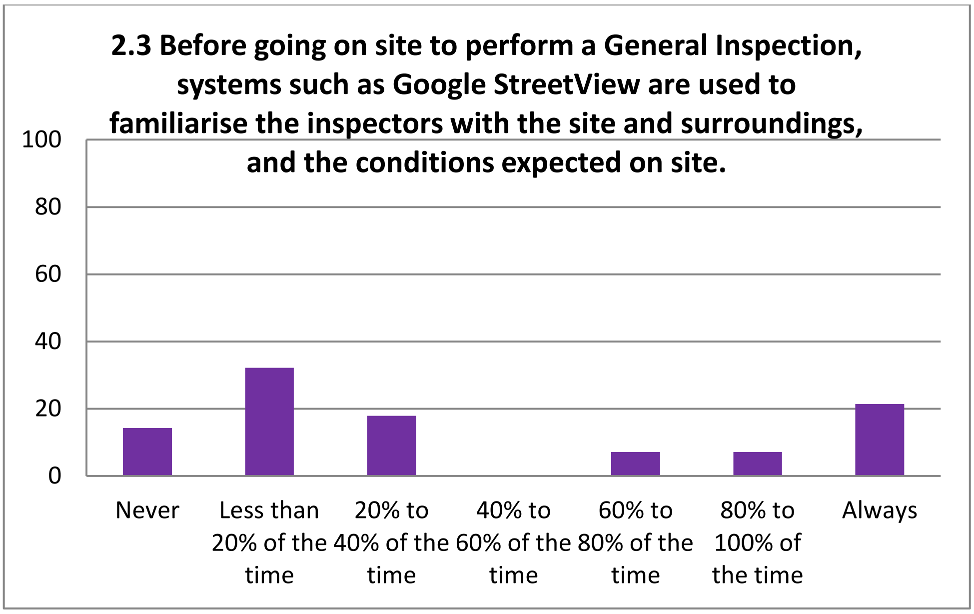


Figure 18: Summary of responses to question 2.3 in questionnaire.

A number of the interviewees indicated that they sometimes undertake pre-inspection reconnaissance visits to determine the conditions on-site before the actual inspection. These pre-inspection visits are generally reserved for very large structures. Figure 19 confirms that the use of pre-inspection reconnaissance visits is rare, with 53.4% of the responses saying the never undertake such visits, and a total of 85.7% indicating that they undertake such visits on less than 20% of bridges.

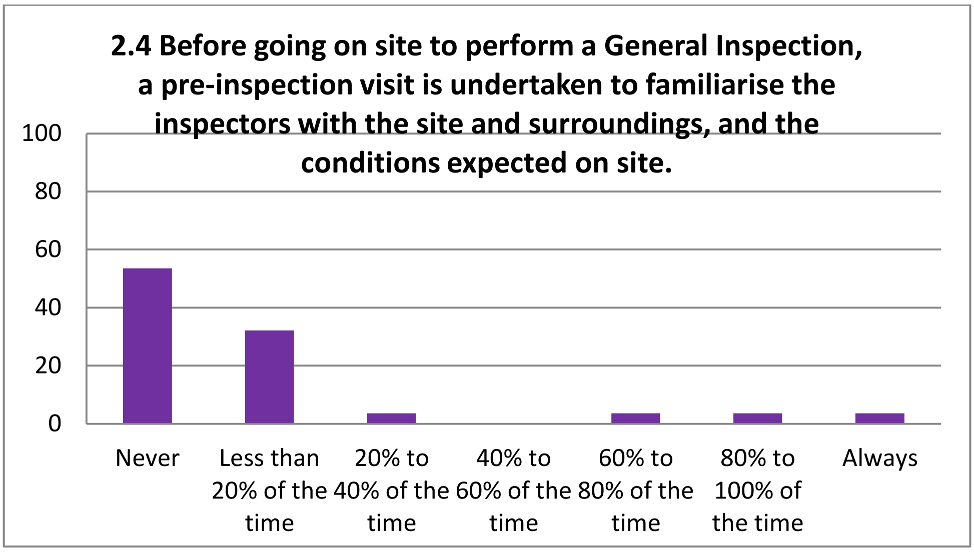


Figure 19: Summary of responses to question 2.4 in questionnaire.

2.3.6.1 Preparation prior to site visit – summary

The responses to questions 2.1 to 2.4 indicate that there is quite a lot of variability in the planning and preparation of General Inspections. However, it is possible to extract some findings:

- The preparation for inspections takes up only 13% (mean of responses given to question 2.1) of the total inspection effort.
- Most inspectors look at previous inspection data for all (42.9%), or almost all inspections (21.4% do this for 80 to 100% of inspections).
- The majority of inspectors do not, or rarely, make use of tools such as Google StreetView to familiarise themselves with a site prior to visiting it. Only 35.7% of the respondents do this for more bridges than they do not.
- Pre-inspection reconnaissance visits are rare, with over 53% of respondents never carrying them out, and a further 32% carrying them out on less than 20% of their inspections.

From Section 1 of the questionnaire it is concluded that engineers have similar ideas of what a GI should provide, and how useful the data is. The responses given to the questions regarding how the GI is planned indicate that there is much less agreement about how the information should be collected.

2.3.7 On-site inspection process (General Inspection)

Those consulted during the face to face interviews seemed to follow a similar procedure when on-site, and said that the inspection sequence is based on the way in which the Bridge Condition Indicator (BCI – a numerical indicator of the condition of a bridge based on the condition assigned to individual bridge elements) is calculated. After arriving on-site, the first step is the confirmation of bridge dimensions and clearances. This is followed by taking a few general photographs showing the bridge and its surroundings. Any defects which were reported following previous inspections are looked at, and the current condition compared against the records. The inspector also inspects any locations which were reported as requiring maintenance to see if, and how well, the maintenance has been performed.

The amount of time spent on-site depends on a variety of factors such as the size, condition, complexity of construction of the bridge, access, traffic and personal preference. The consultees were asked to estimate how long they would spend actually on-site inspecting a typical bridge. The responses to this question are shown in Figure 20.

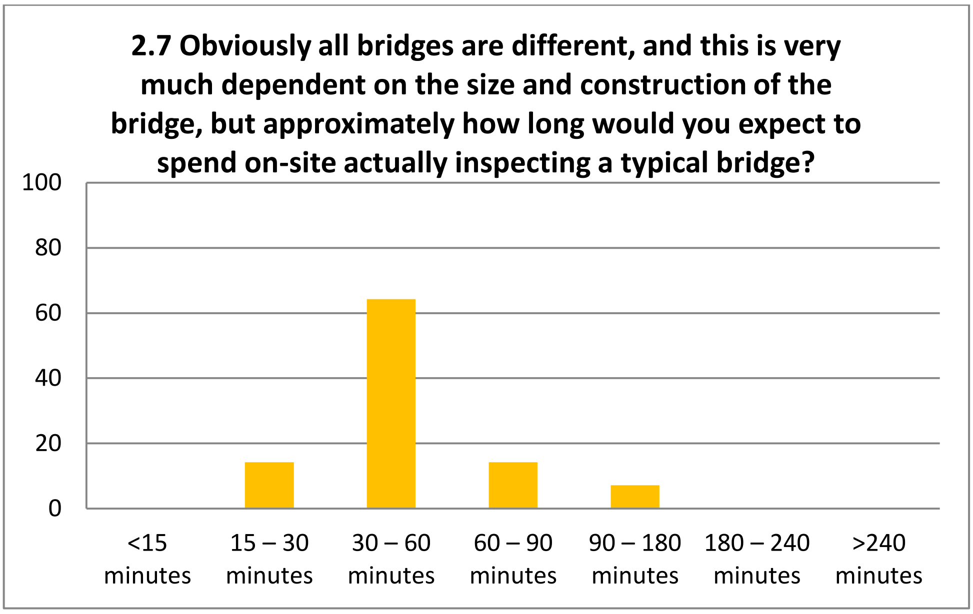


Figure 20: Summary of responses to question 2.7 in questionnaire.

This shows that most (64.3%) of the inspectors estimated that they would spend between 30 and 60 minutes actually carrying out the inspection. This includes the initial check of dimensions, the collection of general view photographs, the inspection of any elements of interest, as well as the rest of the structure, and the recording of the inspection data and additional photographs of any defects or features of interest. In total 78.6% of the respondents estimated that they would spend no more than 1 hour on-site performing an inspection. The inspectors with predominantly non-UK based experience of bridge inspections both reported that they tended to spend longer than this on-site doing the inspection (one reported a time of 60-90 minutes, one reported that they would usually spend 90-180 minutes on-site). There are a number of possible explanations for this including personal preference of the inspectors, bridge condition, frequency of inspection, and inspection requirements.

Questions 2.5 and 2.6 asked whether or not the respondents would be likely to use any equipment during a GI to help them view elements which were difficult to see, and if so what sort of equipment they would be likely to use. The responses to these questions are shown in Figure 21 and Figure 22.

It can be seen in Figure 21 that there is no consensus on the use of tools such as binoculars or ladders to obtain improved views of anything while on-site: the responses were almost evenly spread between all the possible responses, with the same number of respondents (11.5%) reporting that they never use such tools as those that report they always do.

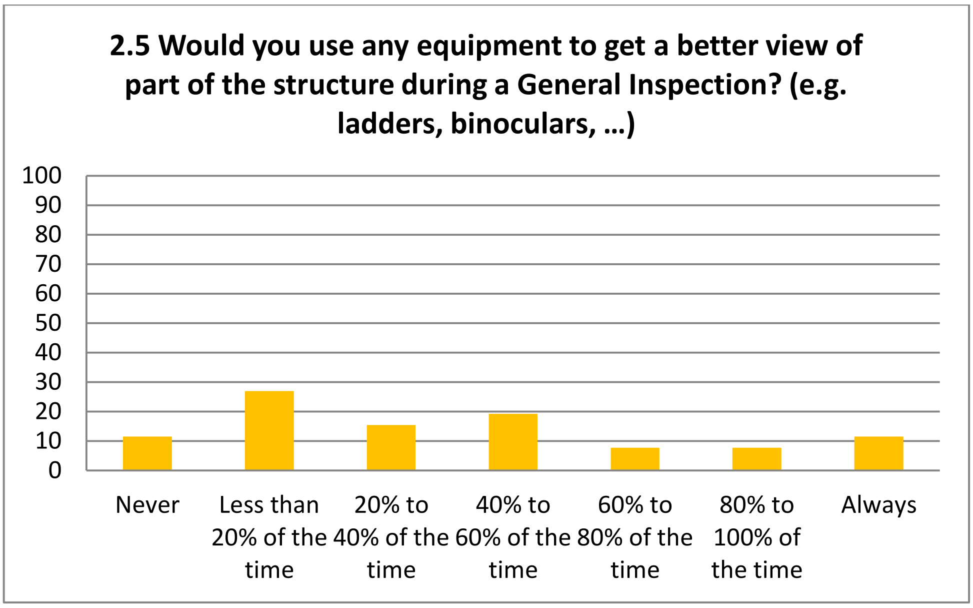


Figure 21: Summary of responses to question 2.5 in questionnaire.

It appears, given the responses to question 2.6 (Figure 22), that most of the respondents seem to have not considered cameras in their answers to 2.5 (Figure 21), as otherwise it is impossible for 84% of respondents to report the use of cameras and zoom lenses during all their inspections, when only 11.5% reported they always use any tools to provide improved views.

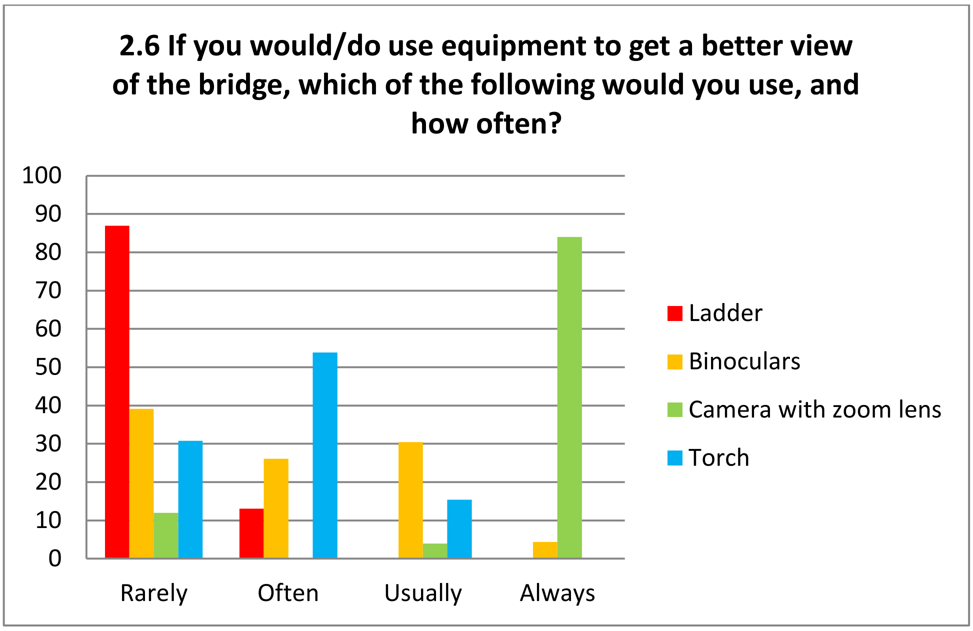


Figure 22: Summary of responses to question 2.6 in questionnaire.

It is suggested by the author that the responses here refer to the fact that the consultees use cameras to record defects, but not to search for them. 85.71% of responses stated that they would take photographs in all, or in between 80 and 100% of their inspections (Q2.8, shown in Figure 23), which seems to back up this interpretation of cameras being used to record, but not find defects. Figure 22 shows that ladders are rarely (or never) used by the vast majority of respondents (87.0%), but most (84.0%) inspectors use cameras in all their inspections. The use of binoculars and torches is much less uniform, which probably reflects the fact that such tools may not be appropriate on all bridges. The respondents also indicated the use of additional tools such as hammers, waders, or mirrors to try to improve their inspections.

The low reported use of ladders probably reflects the fact that they are bulky objects which can be hard to transport. Also, it may be that the health and safety policies of some organisations or bridge owners may preclude or inhibit the use of ladders. The widespread use of cameras reflects the fact that cameras are small and easy to transport, and also is testament to the usefulness of photographs in terms of recording and demonstrating bridge condition and defects. It appears that, despite there being no official requirement to collect images during a GI, they are nearly always recorded. It can be inferred from this that engineers are happy to accept images as evidence of bridge condition, and image data is already influencing their maintenance and management decisions.

During the inspection notes are made of any defects observed, recording their location, type, extent and also the inspectors' interpretation of their importance. The inspectors photograph most structural defects and mark their locations on diagrams. Figure 23 shows a summary of the responses given to question 2.8 in the questionnaire. This found that 75% of the respondents would always take photographs, and an additional 10.7% would expect to take photographs in most (over 80%) of their inspections. Interestingly, 7.1% of the respondents stated that they would only rarely take photographs (on fewer than 20% of their inspections).

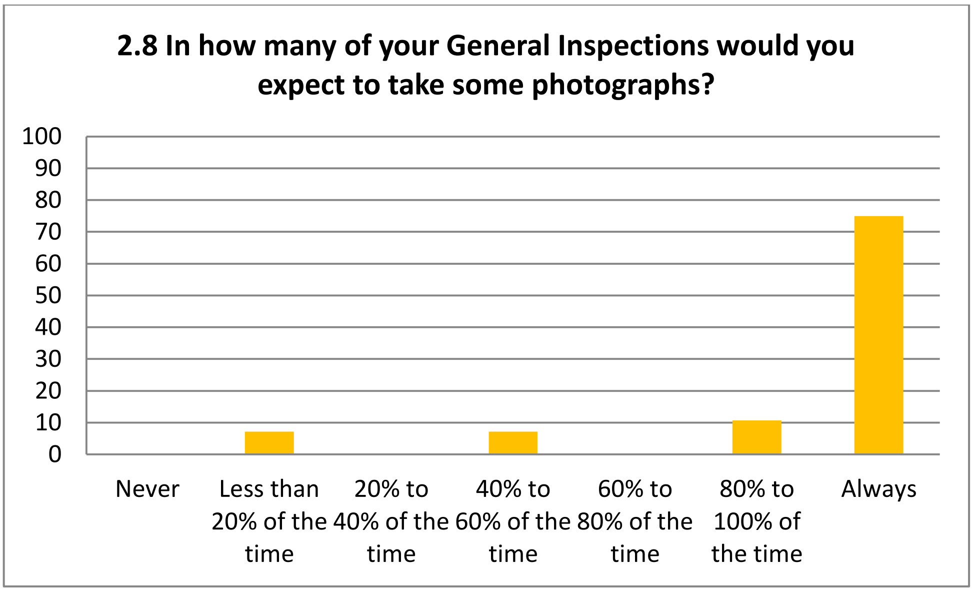


Figure 23: Summary of responses to question 2.8 in questionnaire.

There is only very loose guidance on the number of photographs to take during an inspection, or how these should be taken, but generally the engineers just require the inspectors to take 'enough' photographs. How many photographs are 'enough' is left up to the inspector, and is influenced by the size and type of the bridge, and the engineer who would be looking at them.

Question 2.9 in the questionnaire asked the engineers and inspectors to state if they thought their image collection approach was systematic during a GI. Figure 24 shows that 75% of the responses either agreed or strongly agreed with the statement. From comments received in the questionnaire it seems likely that the respondents interpreted the question in a way slightly differently to the way it was intended. They have responded that they have a systematic approach to the collection of images when they tend to take a few general view images, and then work around the structure taking images of defects as and when they are encountered, as well as previous repairs. They do not tend to have a systematic approach in the sense that they do not cover the whole structure, and they do not have any protocols for ensuring that images are taken in a consistent fashion, from consistent distances or using consistent camera settings.

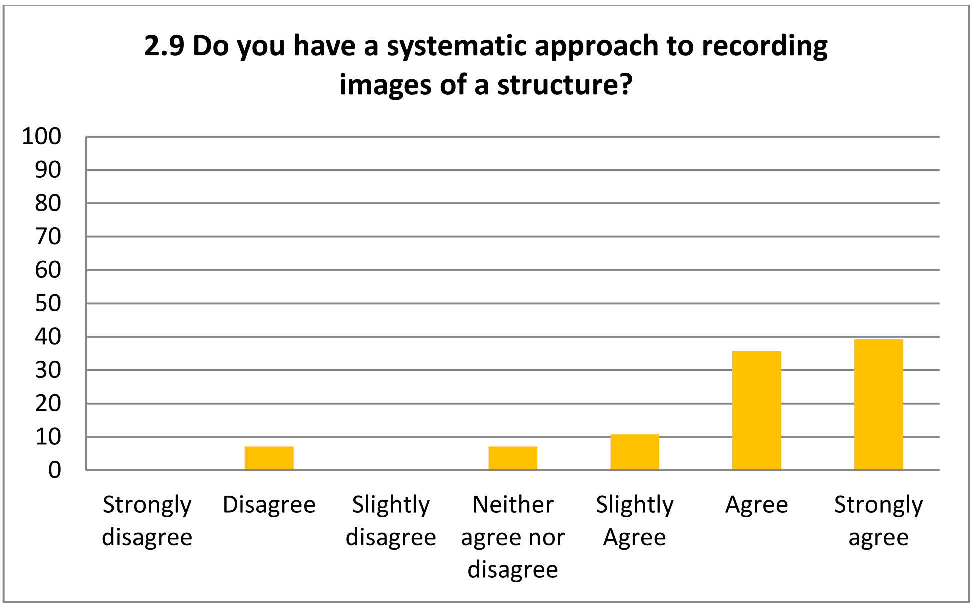


Figure 24: Summary of responses to question 2.9 in questionnaire.

Figure 25 shows how many images the respondents reported taking during a typical GI. The majority (67.9%) only take between 1 and 20 photographs. A further

17.9% take between 21 and 40 images during a GI. Given that almost all respondents tend to take a few general views of the whole structure, and of individual elements, this does not leave many images for showing specific defects. The response stating that over 100 images would be taken was from one of the two inspectors with mainly non-UK based inspection experience.

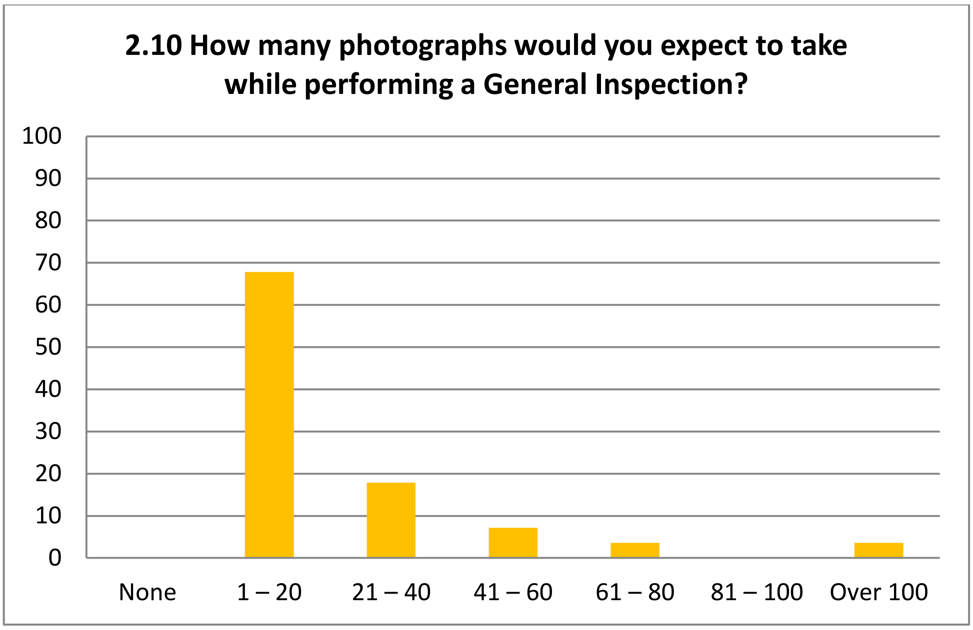


Figure 25: Summary of responses to question 2.10 in questionnaire.

2.3.7.1 On-site inspection process – summary

- Most inspectors spend between 30 minutes and 1 hour on-site performing the inspection.
    - This accounts for 51.3% of the total effort involved in inspecting structure (mean of responses to question 2.1).
- There is little consistency in how often tools would be used to help obtain a better view of the structure.
    - Ladders are rarely used during inspections; binoculars and torches are more frequently used.

    - Most inspectors use a camera during inspections. Typically they collect 1 to 20 images of a structure. These show general views of the bridge as well as specific shots of defects and previous repairs.
- The inspectors feel that they generally have a systematic approach to collecting photographs of the structure.

2.3.8 Reporting process (General Inspection)

While on-site an inspector completes an inspection pro-forma and includes their own interpretation of any detected defects and the bridge condition. It was established during the face to face interviews that the engineer responsible for interpreting the report will read and consider this information, and ultimately has the final say on the bridge condition and can overrule the on-site inspectors' interpretations and recommendations. When interpreting the inspection reports the engineers' main source of information is often the photographs taken by the inspector: these sometimes contradict, and are used to overrule, the thoughts and conclusions of the inspector.

A number of questions in the questionnaire asked about the use and interpretation of images taken during the on-site part of the inspections. Figure 26 shows a summary of the responses given to question 2.11, about the likelihood of defects of interest within the current inspection being there also being visible in images recorded in previous inspections. Question 2.12 asked whether these previous images would be looked at and compared with the current images (Figure 27), and question 2.13 asked about the confidence of the inspector that any changes apparent in the condition of the bridge would be down to genuine changes in the defect, as opposed to changes in the image collection protocol (Figure 28).

These questions were asked in order to understand how easily and reliably changes in defects could be tracked from one inspection to another. The ability to determine whether a defect is getting worse, and if so, how quickly it is deteriorating, would be beneficial in forecasting the future condition of a bridge, and when maintenance may be required. If the engineer cannot determine the rate of deterioration of a defect there is a risk of carrying out interventions too soon, resulting in inefficient management of resources, or not carrying out work when it was needed, allowing further deterioration, which could be more expensive and disruptive to correct.

There is little consistency in the responses to these questions, perhaps reflecting that the current image collection approaches are not producing images which are as useful as they could be.

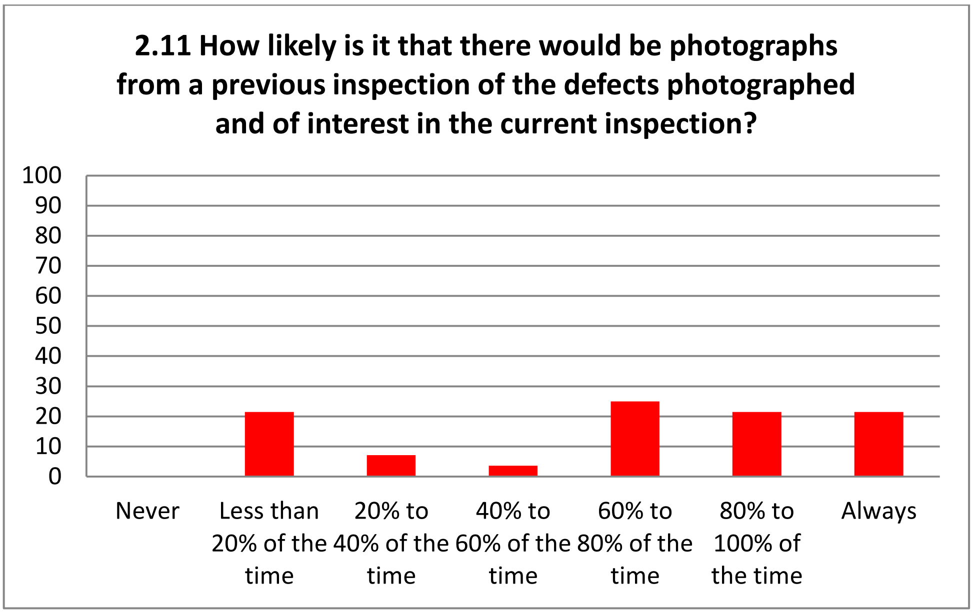


Figure 26: Summary of responses to question 2.11 in questionnaire.

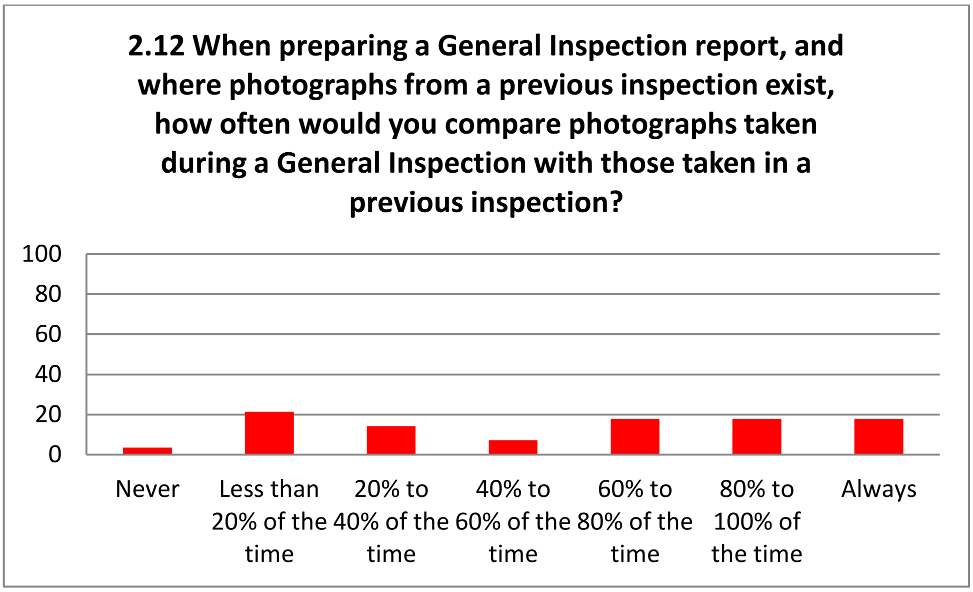


Figure 27: Summary of responses to question 2.12 in questionnaire.

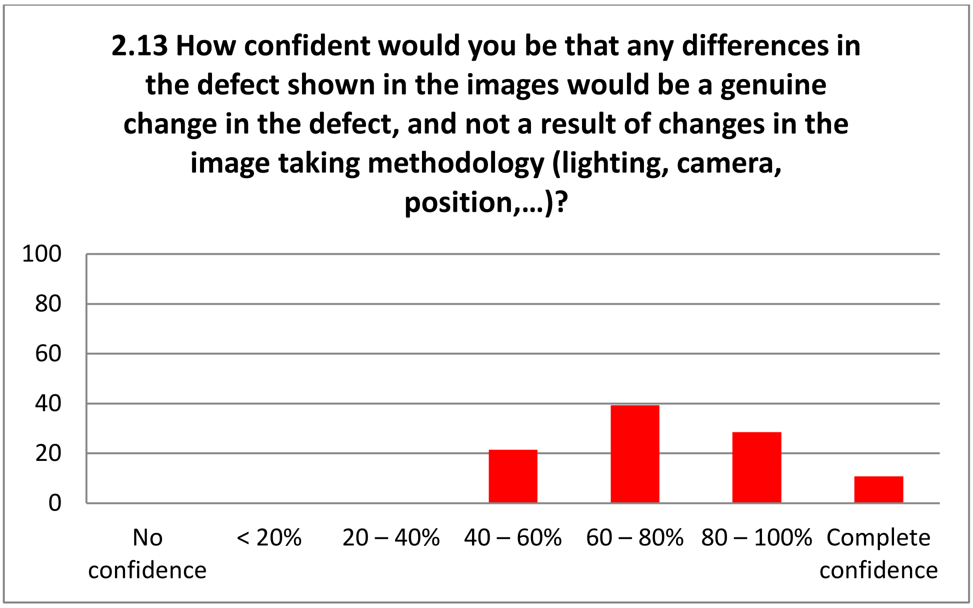


Figure 28: Summary of responses to question 2.13 in questionnaire.

32.1% of responses felt it would be unlikely that defects would have been photographed previously (in fewer than 60% of inspections) (Figure 26). Even where images from previous inspections exist, 46.4% would only compare them with current photographs on fewer than 60% of inspections (Figure 27), although there is generally high confidence that any change apparent in the defects would be genuine, and that differences in the way the images were taken would not be confusing (Figure 28).

One of the things which came up during the face to face interviews was the fact that sometimes, following an inspection, the engineer responsible for making the final decision on the condition of the bridge would disagree with the interpretations of the inspector, or would want additional information or photographs, particularly if the report is not clear or the supplied photographs are inconclusive. This was mentioned by four of the engineers involved in the discussions. In such cases they send out the inspectors to revisit specific defects or elements.

Question 2.14 addressed this issue by asking how frequently engineers felt they might want additional information when interpreting an inspection report. The responses to this are shown in Figure 29.

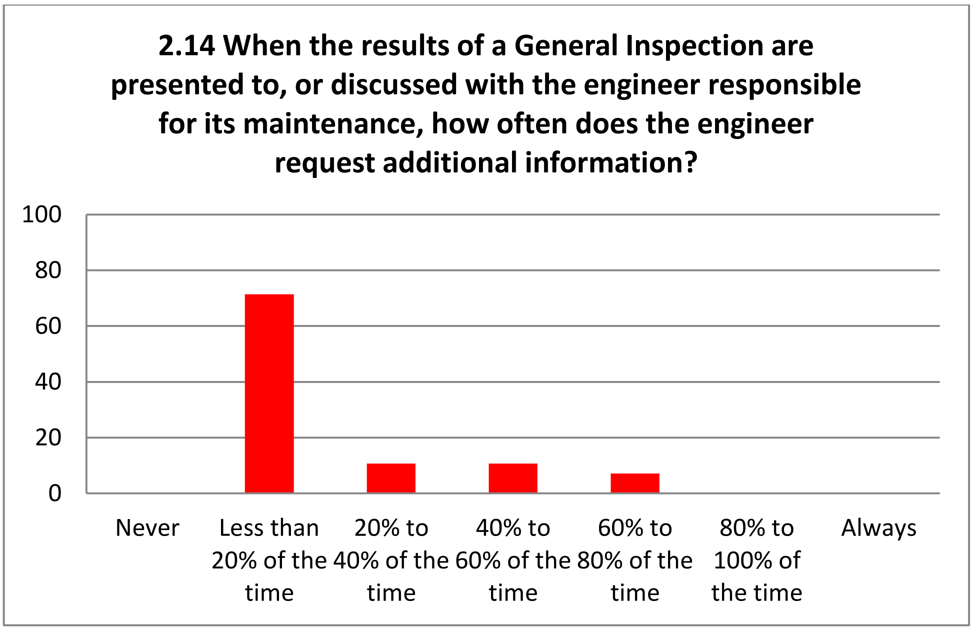


Figure 29: Summary of responses to question 2.14 in questionnaire.

Most of the respondents (71.4%) agree that there are occasions when additional information is requested, but that this happens in fewer than 20% of inspections.

Interestingly, and surprisingly, two respondents reported that additional information was requested in 60% to 80% of inspections. One of these responses was from an inexperienced inspector with less than 1 year of experience, but the other was from an engineer with 25 years' experience.

2.3.8.1 Reporting process – summary

- The post-inspection process accounts for 35.5% of the total effort involved in undertaking a General Inspection.
    - Most respondents report spending 30 minutes to 1 hour on-site. This accounts for 51.3% of the inspection effort.
    - Assuming a 1 hour on-site inspection time, the 13.2% of inspection effort devoted to preparation corresponds to approximately 15 minutes of preparation time.
    - The 35.5% of inspection effort devoted to interpretation and reporting corresponds to a total of approximately 42 minutes per GI.
    - This suggests that each GI takes a total of just under 2 hours for preparation, inspection, interpretation and reporting.
- Engineers use data collected on-site to assess the bridge condition and determine the appropriate course of action.
- This data is recorded in pro-forma reports, and is supplemented with photographs, and sometimes drawings.
- There is no guarantee that photographs from previous inspections would be available to compare with current photographs of particular defects or features.
- Even when such photographs exist, they are often not consulted: 39.3% consulted such images in fewer than 40% of inspections.

- Engineers are, however, confident that when images are compared, any apparent changes would be genuine, and not just due to changes in the image collection protocols (78.6% were at least 60% confident that changes would be genuine).
- All responses indicate that additional information is sometimes requested, which can lead to follow-up visits. This is necessary in relatively few (less than 20%) inspections.

2.3.9 Discussion of UK Highways General Inspections

Table 4 provides a short summary of the data recorded and delivered in a General Inspection.

Table 4: Summary of General Inspection

	General Inspection
Inspected elements	All visible elements, which can be seen with no special access equipment.
Level of detail reported	Type, location, severity and extent. Severity and extent reported using five-level scales.
Defects detected	Visible defects only (cracking, spalling, rust, staining, joint defects etc.).
Recommendations	Remedial work or additional investigations for any defects noted, and estimated costings for these works.

According to the regulations GIs are to be carried out with no special access arrangements or equipment, and the initial consultation found that this is usually the case, although inspectors sometimes use tools to try to get a better view of parts of the bridge. Among such tools the use of cameras has been overwhelmingly reported to be the most common, although torches and binoculars were reported as being often, or usually, used. Ladders are seldom used, possibly because they are bulky and hard to transport, and possibly because of policies making it difficult for inspectors to use them. Based on the estimates of how long inspectors spend on-site performing an inspection, and the breakdown of the total effort involved in a GI into the preparation, inspection and reporting phases it is estimated that inspectors spend approximately 15 minutes preparing for an inspection, 60 minutes on-site, and 42 minutes producing and interpreting the inspection report.

There is no defined protocol determining what parts of the structure are recorded in images, or what level of detail the images should show. Instead, most inspectors appear to follow a similar approach of taking a few general photographs of the bridge, and then taking additional photographs of defects, features or repairs as and when appropriate. Most inspectors take between 1 and 20 images during a typical GI. This results in good image records of most of the defects noted, but gaps in the image record where no defects were seen or photographs taken. Additionally there is no advice or control over the position from which images are to be recorded, meaning that a defect could be imaged from one position in a particular GI, and from a different position, at a different distance in a subsequent inspection. This could make it difficult to accurately track the development of the defect as there will be uncertainty about whether any apparent change in the defect is genuine, or merely an artefact of the different imaging conditions. This uncertainty and variability in image collection procedures between inspections may explain the relatively low rates of inspectors looking at images from previous inspections and comparing them with images from the current inspection.

The inspector on site has no way of observing any obscured or hidden parts of the structure, and no way of seeing detail in hard-to-reach or distant parts of the bridge. This is OK if the bridge is relatively small as the inspector will be close to all parts of the structure, but on bridges with more than a few metres of clearance, or with long spans it can be very difficult to get clear detailed views of the whole structure from the footway.

GIs rely heavily on the experience, and expertise of the particular individual inspector on-site as what is deemed worthwhile recording is entirely down to them. If an inspector either fails to see a defect, or sees it but deems it not worth reporting then there will be no record of it.

In spite of the limitations placed on the inspector and the difficulties in getting clear views of distant parts of the structure GIs are a valued and trusted part of the inspection regime and the asset management process for UK highways bridges. Inspectors feel that they get a good idea of the general condition of a bridge, and while on site they can easily place what they see in the context of the overall health of the bridge. Engineers believe that the information collected during a GI provides them with an accurate, consistent, objective appraisal of the visual condition of a bridge and can use this information to plan maintenance or monitoring as appropriate.

Inspectors and engineers seem to be in good agreement about the purpose and usefulness of GIs and associated data. There appears to be much less agreement about how to go about undertaking the GIs in practice.

2.4 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 this data which is used to determine whether or not additional more specialised testing or inspections are necessary. Discussions with engineers and inspectors have established that engineers will accept photographic evidence to assist in establishing the condition of a structure, indeed the guidance in the Code of Practice for maintaining bridges recommends the use of images. However, the photographic evidence is currently being recorded and presented to the engineers an unstructured manner (i.e. there is no specific protocol for the collection of images, which are displayed and viewed as individual images). Among other things, this makes it difficult to compare photographs from successive inspections as changes in the images could be due to condition changes or differences in the way the image was taken.

It was found that visual inspections are common to all inspection regimes considered. The inspections are important and are well trusted, and the information which is used in the asset management process is largely derived from these inspections. Engineers are happy to accept inspections which contain images, and to use these images to determine the condition of bridges. Engineers are also happy to accept the limitations of General Inspections – notably the need for inspectors to have to try to determine the condition of elements which are situated several metres away in hard to observe locations. It follows that engineers would be happy to accept images which show these locations in more detail than is currently achievable on-site, especially if these were recorded in a systematic way covering all of the structure.

The value of the inspection data is largely derived from the on-site inspector recording the correct data in the correct way, and engineers applying their knowledge and experience to the data presented to them. It is therefore vital to ensure that this data is collected as accurately, objectively and reliably as possible.

Currently the inspector visits the site and prepares an inspection report which the engineer then must interpret. If a systematic image collection approach was used the inspector (or an automated system) could inspect the images and use these to prepare the inspection report for the engineer's interpretation. There are no fundamental barriers or objections to the use of detailed images as an inspection aid.

Research is underway elsewhere in the area of NDE or SHM in developing new and improved techniques for collecting data on different aspects of bridge condition, but the basic area of visual inspection of a structure, at a level similar to that obtained in a General or Principal Inspection however, seems to have been overlooked in favour of the 'sexier' research areas on NDE. As a result there are many new techniques and tools available to inspectors and engineers to enable them to obtain information about features or defects which were previously hard or impossible to inspect. However, the way in which the visual condition data – the most widely used and collected data for monitoring the condition of most structures – is collected and reported has not changed since the 1960s or 1970s when the inspection regimes were originally devised.

3 VISUAL INSPECTIONS

As discussed in Chapter 2, visual inspection data forms an important source of information about bridge condition. The results of visual inspections are used to plan further inspections, maintenance interventions, and also in calculations of parameters such as BCIs ((Sterritt, 2002), (Sterritt & Harris, 2002), (Shetty & Sterritt, 2002)) or in condition models within Bridge Management Systems such as SMIS, (Highways Agency, 2003). Although the parameters derived from the visual inspection data are quantitative and may give the impression of being objective assessments of the condition of a bridge which can be directly compared with parameters from other bridges, the reality is that the inspection technique used to produce the data from which the parameters are calculated is subjective.

The inspectors and engineers involved in the consultation as part of this research expressed confidence that GIs produce accurate, consistent, objective results. However, the inspection data is collected by human inspectors and is subject to possible judgement errors. There are a number of known issues and shortcomings related to the collection and use of such subjective data. This Chapter describes some of the issues affecting the reliability and limitations of visual inspection data in general, in industry, in civil engineering, and in bridge inspection.

3.1 General shortcomings of visual inspections and inspection data

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

Problems with consistency and objectivity when dealing with visual inspections are not confined to bridges, and are common in many fields. As a result much research has been done in the area of visual inspection reliability.

3.1.1 Literature on visual inspection reliability

In a study into factors affecting visual inspection accuracy across a range of industries, and in laboratory test conditions, Megaw (1979) developed four categories of factors which may affect the quality of a visual inspection (Table 5).

Table 5: Megaw's 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
	Fault conspicuity
	Product complexity
Physical and environmental factors	**Organizational factors**
Lighting	Number of inspectors
Aids	Instructions
Noise	Feedback
Music	Feedforward
Workplace design	Training
	Standards
	Time on task
	Social factors
	Motivations
	Incentives
	Job rotation

Not all the above factors 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.

Visual inspection tasks are often performed for long periods without any real variation or stimulation. 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 in which a sonar operator on board a ship, with the responsibility of monitoring for incoming torpedoes was found asleep at his post when the officer of the watch looked in on him. Poulton's point is that if someone with such a high motivation to do a good job can fall asleep then it is highly indicative of how hard it can be to focus on a task requiring long periods of intense visual concentration. Poulton recommends the need for external stimuli to keep the mind alert and stave off boredom.

The majority of concrete structures are essentially sound. Many visual inspections of such structures will consist of looking closely at large areas of concrete for defects which are not there. 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 to keep the inspector alert and focussed on the task. Passing traffic may well provide all the stimulation the inspector needs (although, as discussed by Moore, et al. (2001), this stimulation may not be entirely beneficial), 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 may provide the necessary activity.

The number and variety of potential defects for which the inspector must look also influences the success of the inspection, as does the 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 background 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 fault conspicuity and the fault mix / product complexity. Gallwey and 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. They also suggested that allowing the inspector more time to complete each task could mitigate this issue. Time is also seen in Megaw's table of factors affecting inspection success. Gallwey and Drury reported that the decrease in inspection reliability is non-linear – increasing the number of potential defects from two to four has 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, such that adding additional defects would no longer degrade the inspection results.

Sheehan and Drury (1971) discuss the difficulties encountered when features are introduced to inspection samples which are not actually defects, but which do differ from the general sample appearance. These features require the inspector to make a decision as to whether or not it should be reported. This is often more taxing than encountering a defect, where there is no doubt that it should be reported, or the sample rejected. This is particularly relevant for a complex inspection task such as bridge inspection. In this situation the inspector can expect to find many objects which require a decision to be made about whether or not the object is a defect, or a non-defect feature.

3.1.2 Reliability of visual inspection in other industries

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

Spencer (1996), 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 included a number of non-visual inspection behaviours which may be involved in an inspection process. Not all of the non-visual behaviours are necessarily applicable to bridge inspections but the point that the inspector is not simply impassively viewing his subject is valid. A good inspector will interact with the subject as much as possible, feeling it and looking at it from other angles.

Although GIs on the UK Highways Agency network are defined as visual inspections with no formal requirement for the inspector to be in physical contact with the structure, inspectors sometimes make use of hammers or other tools to 'ring' the concrete and listen for indications of delamination. Question 2.6 in the questionnaire discussed in Chapter 2 asked about the use of tools in a General Inspection. Although it was not listed as one of the examples, 14.3% of respondents said they sometimes used a hammer to test for delamination during their inspections.

A study by Schoonard, et al., (1973) into visual inspection from the perspective of circuit inspection found that inspectors often try to look at many things at one time. Schoonard, et al., conclude that the likely cause of this is because they are under pressure to be quick. As a result Schoonard, et al., recommended three areas where improvements were necessary to improve the accuracy of the inspections. 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 better working conditions and/or equipment for the inspector, and improved and clarified inspection procedures. Jamieson (1966) also called for improved procedural guidance or training, having found, in a study of inspections in the telecommunications industry, 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.

3.1.3 Reliability of visual inspection of highway structures

The work undertaken by Moore, et al, (2001) represents the major study in this field. They performed and reported on a large-scale study into the state of practice in the USA. This involved sending a survey to all the US States, plus all 99 Counties in Iowa, asking them about various aspects of visual bridge inspection. It also included a large scale performance-trial test programme involving 49 practicing bridge inspectors, each inspecting a series of test bridges, and undergoing physical and psychological testing.

The study concluded that Professional Engineers (analogous to UK Chartered Engineers) were rarely on site during bridge inspections, and when they were, it was usually to follow up a previous inspection. Almost all responses reported no requirement for their inspectors to pass any form of eyesight test. Where inspectors did have to demonstrate that their eyesight met any defined standards, it was only as part of a driving licence requirement. Moore, et al, also found that there was increasing use of NDE techniques during inspections.

The practical testing performed by Moore, et al. (2001), focussed on the two most common types of inspection undertaken in the USA: routine inspections, and in-depth inspections.

The testing had four specific objectives:

1) Assess accuracy and reliability of routine inspection;

2) Assess accuracy and reliability of in-depth inspection;

3) Study influence of several key factors to provide qualitative measure of influence on reliability of visual inspection;

4) 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). This describes the condition rating system for use with routine inspections in which each bridge element is assigned a single rating from zero (failed) to nine (excellent).

Staff from the study team also inspected each structure to determine its 'true' or reference condition, against which the inspectors' ratings would be compared. 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.

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 ratings assigned to it, with a maximum spread of 6 for the primary elements of the bridge (deck, superstructure, substructure), and 7 for some of the secondary elements. Such spreads mean that it is conceivable that some inspectors were reporting a condition value of 7 (Good condition) while others reported 2 (Critical condition) for the same primary element of a bridge. In fact during the study this is precisely what happened with the deck on one of the test bridges.

For the secondary elements there was an instance where the parapet on a bridge was judged by one inspector as being in condition 2 (Critical condition) while another inspector judged it to be condition 8 (Very good condition); two sets of expansion joints both received ratings of condition 1 (Imminent failure), and also condition 7 (Good condition). It seems likely that in such cases the truth was actually somewhere in between, but it is concerning that trained, qualified inspectors who were operating under test conditions and were aware that their inspection reports were going to be closely scrutinised and compared against others, could report such widely differing conditions on the same elements.

In addition, even if the correct rating for an element is not known, the results of the work performed by Moore, et al, show that at least 48% of individual condition ratings for primary elements provided in their study were incorrect (i.e. for the primary elements of the bridges studied no more than 52% of the inspectors ever agreed on the same condition rating). If the reference data provided by the study staff are correct, then 58% of ratings assigned by the inspectors are incorrect (no more than 42% of the trial participants agreed with the reference data). It appears that inspectors may have difficulty consistently defining the level of deterioration according to condition rating systems.

Although there were no direct changes to the regulations controlling how bridge inspections were performed, this work increased awareness throughout the bridge inspection community of the variability in assigned ratings, and that these are not as absolute as was previously thought. Two of the lead authors of the report suggested via private communication that they felt that this increased awareness was a key positive outcome of the work ((Moore, 2009), (Washer, 2009)). Additionally, Washer (2009) felt that the work, and the improved understanding of the variability of the reported condition ratings, led to the introduction of requirements for systematic quality control and quality assurance programmes within the States. The development of an Image-Based Inspection approach as presented in this thesis is an attempt to address the variability of the condition reporting in an alternative way, providing a standardised, systematic way.

The work performed by Lea (2005) also looked at some of the issues surrounding condition assessment and the uncertainties inherent in the inspection process. Lea's work was performed with a view to understanding the impacts of variability and uncertainties within the inspection process on the assessment of the bridge strength and condition. Lea discusses interviews with inspectors in which they strongly backed their abilities to detect defects during inspections. No quantitative information is given to support or expand the statement, but it aligns with the findings of the consultation carried out in this research that engineers and inspectors feel that GIs detect all defects of interest and provide useful, consistent, objective information.

The results of the Moore study are in stark contrast to this, finding that the inspectors showed poor ability to detect localised defects. For example, on one of the bridges in the test only 66% of inspectors successfully identified a paint system failure (which is a general defect); only 2% of the participating inspectors identified some of the smaller cracks. The test data suggested that inspectors tend towards reporting mid-range assessments and avoid extreme values: good elements of the bridge tend to be under-scored, while poor areas tend to be over-scored.

The inspectors were asked during one of the bridge inspections to record photographic documentation for the inspection. Moore determined that there were essentially 18 different classes of photograph which could be taken of the bridge (general views of the bridge, views of the deck, views of the abutments, etc.), and that a minimum of 13 of these would be needed to fully document the condition of the bridge. The remaining 5 types of image would show features outside the scope of the inspection, or that were already visible in other images. On average the inspectors took 7 photographs, with a maximum of 19 (including multiple examples of some of the 18 different photograph 'classes'), and a minimum of 1. This large discrepancy in the number of photographs the inspectors felt necessary to document the bridge perhaps is indicative of the variability in the expectations of the inspectors in terms of what counts as providing an image record of bridge condition. As noted in Section 2.1 there is no detailed guidance on the collection of photographs during UK GIs. It is likely that there is similar variation in the photograph records available of these, a conclusion backed up by the variation in the answers given to question 2.10 relating to the number of images taken during a GI (Figure 25).

Analysis of the test results and the physical and psychological data obtained as part of the Moore study indicated that there were a number of factors and personality traits which correlated with the test results. These included vision, training, lighting and wind-speed at time of inspection, and fear of traffic. When asked about their attitudes towards passing traffic during hypothetical inspection scenarios many of the inspectors reported that they would be either fearful (24 out of 49 inspectors) or very fearful (2 out of 49). Analysis of the inspection data showed that those inspectors who did not report that they would be afraid tended to perform better in the tests, identifying more of the defects present.

Moore also found that the proximity to the structure affected the results of the inspection. The study team noted the position of the inspectors as they inspected various parts of the bridge, and noted, for example, that those inspectors who correctly identified a particular minor defect tended to inspect the relevant part of the structure from a distance of 0.2m, while those that did not identify it performed their inspections from a mean distance of 2.8m from the structure (Section 6.3 will present details of an investigation into the relationship between inspection distance and detection of detail). As stated previously, GIs are performed without access equipment, and it can be difficult to get close to some parts of the bridge. There is, therefore the potential that important defects, or early signs of them, are going unseen and unreported on bridges.

The data collected during the study showed that inspectors with better eyesight (measured during the test process) tended to produce better inspection results. This is a fairly obvious conclusion. However, at the time of the study, as reported above, most of the inspectors reported that they had never had to demonstrate any level of eyesight competence in order to become or remain a bridge inspector. Four years later Lea commented on these findings and suggested there was an "unarguable case for introducing eye tests and minimum vision standards for bridge inspectors" (Lea, 2005, p. 51). A recent piece of work on behalf of the UK DfT into the development of a set of Bridge Inspector Competences, aiming to setting up a certification scheme to get consistency of inspector qualification and improve the usefulness of inspection results (Atkins, TRL, 2012) chose not to include any eyesight requirement. At the time of writing, there is still no need for a bridge inspector on UK highways to demonstrate that they can see to a defined standard.

Prior to the Moore study there had only been a limited number of investigations into the reliability of visual inspection on highway structures. The studies found were often broader studies on the use of NDE, (Rens, et al., 1993), (Rens & Transue, 1998) with only limited visual inspection discussion.

3.1.4 Limitations of visual inspections on concrete bridges

Even if visual inspections are performed with consistency and to a high standard, the nature of concrete bridges, and the defects which can possibly be detected during a visual inspection, places limits on their usefulness in assessing the structural integrity. For example, a study for the DfT (Wallbank, 1989) looked at 200 bridges to determine if the categorisation of the bridge condition based on visual inspection data correlated with the categorisation of the condition data based on chloride levels and half-cell potential data. This study found that some of the most worrying defects could cause serious damage to the structure before any visible signs became apparent.

In Wallbank's study the bridges were grouped into three categories: Good, Fair, and Poor. This grouping was done using visual inspection data, and also based on the results of testing. The visual categorisation used the type of defect present, and the severity and extent ratings. The test data was used to categorise the bridges as follows:

> **Good**: if 95% of chloride values at the depth of the reinforcement were less than 0.2% by weight of cement; and 95% of half-cell potentials > -350mV.
>
> **Fair**: if more than 5% of chloride values at the depth of the reinforcement were > 0.2% by weight of cement; but 95% of half-cell potentials > -350mV.
>
> **Poor**: if more than 5% of half-cell potentials < -350mV, regardless of chlorides.

Table 6 gives the results of the assessment.

Table 6: Results of visual and tested condition comparison (Source (Wallbank, 1989))

		Visual condition			
		Good	Fair	Poor	
Chloride and half-cell	Good	16	34	9	59
	Fair	8	60	32	100
	Poor	1	20	20	41
		25	114	61	200

There was one bridge in the Wallbank study (lower left entry in Table 5) where the visual inspection classed the bridge as being in good condition while the test data indicated that it was probably in poor condition. False negative reports such as this are highly dangerous and every effort should be made to avoid them. False positive reports, of which there were nine in the Wallbank sample, pose much less of a risk to the integrity of the bridge, and are consequently of less concern, although they could lead to inefficient use of resources.

Whilst Wallbank suggested that the data shows some relationship between the visual condition of the bridge and the results of the testing, he found that the majority of visually poor bridges were found to be generally good or fair according to the study criteria for chloride and half-cell potential. Further, half of those reported as poor following the test procedures were visually assessed as good or fair. This suggests that just because a structure has no visible deterioration present it does not necessarily mean that there is no deterioration – just that it cannot yet be seen.

The Wallbank study took quite a simplistic approach to the categorisation of the tested structures using the test data, which is perhaps understandable when one considers the size and scope of the study. The half-cell potential data could have been interpreted in terms of the gradients in the measured potential values at different locations on the structure. It is the relative differences in these potential values which are indicative of currents flowing along the steel reinforcement causing the steel to corrode. By only considering the absolute values of the measured half-cell potentials and not the potential gradients it is possible that some of the structures were incorrectly categorised in the Wallbank study. However, the key observation is the fact that there are deterioration mechanisms which can cause serious damage to a structure long before any signs of defect are visible.

3.2 Discussion of visual inspection reliability and limitations

Visual inspections are not the only type of bridge monitoring approach needed for the management of structures. However, they are a relatively simple and non-invasive way of gaining an impression of the condition of the bridge. As discussed in Chapter 2, visual inspections are viewed as reliable and useful by the engineers responsible for the maintenance of structures. Visual inspections may not be perfect sources of information, but they play a central role in the monitoring of bridge condition and the asset management and consequently it makes sense to ensure that they are performed as consistently and objectively as possible to maximise the usefulness of the data and maximise the chances of spotting defects.

Section 3.1 discussed the issues affecting the reliability and limitations of visual inspections on bridges, showing how even trained inspectors under test conditions found it difficult to arrive at consistent condition assessments, and how visual assessments of bridge condition can differ from the assessments reached by physical testing of the bridges. The difficulties involved in performing accurate and objective visual assessments in other industries and environments was also discussed to show that performing such assessments and inspections is actually a far from trivial task, and that there is no guarantee that a condition assessment produced in such a way would actually be a true reflection of the condition.

Visual inspections, relying on subjective judgements made by a human inspector, have been shown to suffer from a high level of variability, and repeated studies have demonstrated the difficulties of performing an important yet un-stimulating task.

Despite the issues and shortcomings with visual inspections, it has been shown that there is a need for bridge condition data, and that current practice relies upon visual inspections to provide a large part of this data. Therefore it is valid to investigate ways of maintaining the content and detail of the visual inspection data, but reducing the subjectivity and inconsistencies inherent in such data.

When considering the topic of inspections it is important to remember that inspection is not an end in itself, but a way of getting information about the condition of a structure in order to understand its current and future maintenance needs and better plan the future maintenance programme.

Wallbank emphasises the importance of inspection by stating that, for a maintaining authority:

> "The most valuable asset … is staff with sharp eyes who can spot a defect and appreciate its significance' (Wallbank, 1989, p. 70).

This remains true, but perhaps it is time to consider adopting the use of methods and techniques which may assist these sharp eyed staff, and make it easier for them to produce objective, repeatable, reliable inspection data for use in the maintenance planning process.

4 CURRENT APPROACHES TO IMPROVE VISUAL INSPECTIONS

This chapter discusses some of the approaches which have been, or could be taken to improve the objectivity, reproducibility and usefulness of routine visual bridge inspection data. It concentrates on three possible approaches to the problem: training and qualifications; quality assurance; and the use of technological aids.

4.1 Training and qualifications

Performing a high-quality General or Principal Inspection, following the guidance defined in BD63/07 of the DMRB (Highways Agency, 2007) is not a trivial task. Indeed, performing complex visual inspections on any subject is recognised as being challenging. It is relatively easy to perform a visual inspection where there are only a few defects, which are clearly defined, and where they are obviously visually distinct from the background. However, as the number of defects goes up, and the distinction between defect and object becomes less clear, the difficulty of the inspection, the time taken to perform it, and the expertise required of the inspector also increase (Drury & Watson, 2002). In some bridge inspections there are clear examples of obvious defects which are not particularly hard to spot, but more often, those performing routine visual inspections are looking for very small features which are not clearly visually distinct from the background, such as those shown in Figure 30.

Figure 30: Example of defects expected to be detected during a General Inspection (top four images from CBDG Guide to testing and monitoring the durability of concrete structures (Concrete Bridge Development Group, 2002)).

In addition to this, the importance of apparently identical visual signs of defectiveness can change dramatically depending on where the defect is occurring on a structure. This would suggest that there is a need to train inspectors and for some form of quality assurance.

None of the engineers involved in the consultation, either face to face, or via the email questionnaire, reported any requirement for particular qualifications for bridge inspectors (see Section 2.3). This is because, on UK highways, there are no mandatory requirements for any such qualifications. Although individual employers or bridge owners may require inspectors to have A-levels, HNDs or degrees, there is no unified approach to defining the training, experience or education need in order to undertake bridge inspections. Research undertaken on behalf of the DfT (Atkins, TRL, 2012) has defined a number of levels of bridge inspector for UK highways structures, the responsibilities of inspectors at each level, and a set of competences which should be met in order for an inspector to undertake inspections at each level. The work is an attempt to make sure that everyone performing inspections on UK highways bridges is competent, and does it to a consistent standard. The findings also include a recommendation for training to be undertaken, but did not provide any training materials, rather, this is left at the discretion of the training organisations concerned. The definition of the competences and responsibilities of bridge inspectors is a good step forwards, and could lead to the creation of a scheme for certifying anyone wishing to perform bridge inspections on UK highways bridges. Such a scheme need not be mandatory, but could be acknowledged as being 'Best Practice'. As such anyone wishing to use uncertified inspectors would have to be able to justify their decision to do so. Unfortunately the recommendations of the research have not been taken forwards and there is no certification scheme in place, meaning that there is still no requirement for bridge inspectors to become certified. The situation is different for inspectors on the UK rail network, where there are standard qualifications which must be obtained before being authorised to perform bridge inspections (UK Bridges Board, 2009)).

There is little in the literature about the effect of training on the results of visual bridge inspection specifically. However, there is work from other industries and sectors which has identified training as a key way of improving inspector performance ((Jamieson, 1966), (Schoonard, et al., 1973), (Megaw, 1979), (Gramopadhye, et al., 1998)).

In the current inspection regime, the inspector must be able to: first of all see the signs of the defect; secondly determine that it is actually a defect, and not merely something which looks like a defect; and thirdly make an informed assessment of how much it matters to the integrity of the structure, and how much attention an engineer should give to it. The bridge inspector clearly has an important and challenging job, and it is clear that a high level of expertise is needed to perform the job properly. Training can be given to help provide the inspector with the required skills and competences, and improve the visual search techniques used during the inspection, making it more likely that a particular feature will be seen. Training can also improve the decision making process associated with deciding whether a feature is a defect, and how important it is (Nickles III, et al., 2003). Megaw reported that increased clarity of task (i.e. making the inspector more aware of what they are looking for, and what constitutes a defect) was also beneficial in improving the quality of the inspection data.

Training can take place either formally, with specific training courses, classes, exercises and tutors, or in a more informal on-the-job manner, in which expertise is gained through performing the task, often accompanied by a mentor. There are a number of training courses available for bridge inspectors in the UK. These tend to address the provision of specific knowledge to the inspectors, but the inspectors must gain experience and practical understanding elsewhere (Atkins, TRL, 2012).

Training inspectors is a recurring task which must be performed for each new inspector, with retraining also required to ensure skills stay current and up to standard ((Gramopadhye, et al., 1998), (Drury & Watson, 2002)). Additionally, merely having received training is no guarantee that the trained behaviours and knowledge will be consistently and correctly applied.

4.2 Quality Control and auditing

Another approach to improving the reliability of visual inspection results is the use of formalised Quality Control (QC) or auditing procedures (Estes, 1997). QC procedures can take a variety of forms, but typically involve making sure that some evidence is provided of the inspectors competence, and checking their performance on a sample of inspections. QC regimes can help to introduce consistency between inspectors, especially if they involve repeated inspections by multiple inspectors on the same structures. This may help to identify any inspectors who consistently produce outputs which differ from other inspectors, or from the 'average' inspection. The knowledge that their results may be audited and scrutinised may also help encourage inspectors to focus on each inspection more fully than they might otherwise do.

Megaw (1979) discussed the use of a feedback process in the inspection. The system as described by Megaw is not strictly a QC process, as its primary purpose was to inform the inspector of how they had performed, rather than to ensure that any particular inspection was up to scratch. The inspector performance feedback was believed to help in three ways: (1) maintain motivation; (2) provide information; (3) aid training and maintain standards. Megaw suggested that by providing feedback to the inspectors they would be more motivated to do well, and have a greater appreciation of the importance of their work, which in turn may improve their levels of commitment. Providing information to the inspectors included letting them know as much as possible about the samples they were inspecting, and what the typical defects to look for were. This is linked to the importance of task clarity discussed earlier, and is covered in bridge inspections by the recommendation to study previous inspections and records of the structures being inspected. The feedback also helps the inspector adjust their detection sensitivities as they discover they are over- or under-reporting the presence of defects. However, the use of Quality Control or auditing schemes will not solve all the problems associated with routine visual inspections of bridges. As was mentioned previously in Section 3.1.3, the participants in the large US study

(Moore, et al., 2001) knew they were under test conditions and knew that their inspection results would be closely examined. These inspectors were highly trained, experienced, knowledgeable professionals, yet there was still a large spread in the condition ratings they reported. If these trained and experienced engineers, who knew they were under test conditions, can vary so dramatically in their interpretation of the bridge condition then it appears clear that training and QC alone will not solve all the problems associated with visual inspections.

4.3 Use of Technology to improve visual inspections

The third recommendation from Section 3.1.2 to improve visual inspection data is the use of equipment or tools. Moore, et al., (2001) showed that factors such as the fear of passing traffic had an adverse effect on inspection performance. There appear to be two obvious ways around such issues: 1) remove traffic from site during inspection; 2) remove inspector from site during inspection.

Option 1 would involve introducing the need for traffic management, including closures, within routine General Inspections. This would be costly, disruptive and involve a major change in GI practice. Option 2 could be achieved if sufficient data could be recorded on-site by some method which was not affected by fear of traffic. The inspector could then interpret this data off-site in a comfortable and safe environment.

Technological tools or techniques are often adopted where the repeatability, reproducibility and objectivity of an inspection needs to be improved. Technological solutions have been successfully applied to improve or automate visual inspections in a number of industries and applications. For example agriculture (Brosnan & Sun, 2004), aerospace (Vora, et al., 2002), manufacturing (Demant, et al., 1999), and medicine (Thekkek & Richards-Kortum, 2008) have all described the use of computer vision techniques to assist the inspector. Many of these applications are relatively simple in that they are looking at objects under controlled conditions, and/or looking for a number of well-defined and distinct features.

There have been calls ((Chang & Abdelrazig, 1999), (Chang, et al., 2003), (Middleton, 2004), (Woodward, 2006)) for the use of such technology in bridge inspection. Such approaches could be applied to the bridge inspection process at various levels and stages, from data collection to data presentation and interpretation. If suitable tools were available they could help the inspector record observations on-site (Bowden, et al., 2003), improve the accuracy of measurement (Amann, et al., 2001), improve the working environment for the inspectors, and/or reduce the time spent on-site performing the inspection (Jauregui & White, 2003).

The environments encountered in and around many bridges are not optimised for easy computer vision inspections. The lighting, viewing angle, or viewing position are difficult to control, and the object being inspected is often affected by visual clutter which cannot easily be removed.

However, computer vision techniques and data collection methods have been successfully applied to archaeological site investigations, accident investigations, construction monitoring, pavement condition monitoring and other areas where data could previously only be collected by visual inspection methods. These applications involve large and complex scenes with more time pressure, less controlled lighting, and features of interest which are not clearly defined with respect to the background scene.

4.3.1 Archaeology / cultural heritage

The use of techniques such as digital images, photogrammetry, aerial photographs and laser scanners is increasing in the area of archaeology as a means of documenting sites and artefacts. Unlike in bridge inspection, there is no archaeological data collection regime specifying what types of data should be recorded at what levels of detail – instead the data collected depends on the artefact or site being surveyed. For relatively small artefacts such as statuary or pottery the requirement may be for photorealistic data at sub-millimetre levels of detail (Earl, et al., 2010); for larger outdoor scenes or buildings lower resolution may be acceptable (Tsingas, et al., 2008). The level of data to be collected, and the most appropriate way in which to collect it, depends very much on the subject and the ultimate use of the data. Often different methods will be used in combination of an attempt. In this way the benefits of the different methods can combine and overcome the weaknesses of other methods (Haddad, 2011).

The data collected can be used not just as a simple record of the site or excavation at a specific point, but also for providing illustrations of the progression of an excavation over a period of years, showing the site as different layers were excavated; helping with reconstructions of sites; or enabling collaborative data interpretation.

Archaeological excavations, or site surveys, are not routine events, and are often a means of collecting sufficient data that will enable the analysis and understanding of the site to carry on in future years, even when the site itself is no longer accessible, either because it has been destroyed, covered, or for other reasons (Escarcena, et al., 2011). Although there are time pressures involved in the collection of the survey data these tend to be to do with the window of opportunity for the collection of data, and not the time taken to do so, whereas for bridge inspections the window for undertaking the inspection may be less rigid, but the time taken on-site to collect the data is of more concern.

Haddad (2011) gave details of how long the data collection and processing took on a number of archaeological laser scanning applications, as well as the amount of data collected and the number of collection views or positions required. The data is summarised in Table 7. It can be seen that small or simple subjects can be fully surveyed in a relatively short time (e.g. two rooms in Buonconsiglio Castle took 30 minutes each, one required 4 viewpoints, the other required 3), but that more complex subjects require more data collection locations, and more time (e.g. Roman Boat (8 nights, 30 viewpoints), Fort at Saalburg Hessen (7 days, unspecified number of viewpoints)).

Table 7: Examples of scanned objects and selected scan/datapoint information (Source (Haddad, 2011))

Object scanned	View points	Recording Points (million)	Scanning time (field)	Processing time (lab)
Bronze statue, 80cm	11	0.780	1 day	10 days
Wooden Roman Boat, 15m x 3m	30	9	8 nights	45 days
El-Khazneh at Petra, Jordan, 40m height	3	4.7	1.5 h approx.	1 week
Tobacco Warehouse Xanthi, Greece	6	6.59835	5 man hours	2 man hours
Grave Mound at Kirchheim Osterholz, 10ha	–	20	5 h	5 days
Fort at Saalburg Hessen, 30ha	–	125	7 days	25 days
Koerich Castle, Luxembourg, 0.3ha	–	35	1 day	15 days
Theatre "Linz", Austria	26	–	20 h	2 days
Inner city excavation, Ulm 7m x 8m	–	–	6 h	7 days
Acropolis wall, Athens	–	–	20 h	1 day
Stone statue (Marc Anton) 3m height	10	7.4 (reduced to 4.0)	2.5 h	–

Object scanned	View points	Recording Points (million)	Scanning time (field)	Processing time (lab)
Sandstone sculptures, 4x10m	3	3	2 h	–
Room Camin Nero, Buonconsiglio Castle	4	–	30 min	–
Augustus Triumphal arch, Aosta, 17.5m height	19	30	2 days	–
Room Torrione da Basso, Buonconsiglio Castle	3	–	30 min	–

4.3.2 Accident investigation and reconstruction

Similar techniques are used in accident investigation and reconstruction. The aim in this application is to recreate collision scenes in order to analyse the events and circumstances leading up to the collision, and establish what happened. The investigation may be carried out to collect evidence for use in court proceedings, or to learn from the incident and develop improvements to the road layout or vehicle (Parry & Marsh, 2003).

The photographic data collected during the investigation is often used to make the reconstructions and visualizations more realistic, but this information is not crucial in the analysis which does not require complete photorealism. The key things of interest are factors such as vehicle position, road geometry and sightlines. These can be modelled and represented adequately without the need for particularly high data resolution.

What is important is that the data must be collected as quickly and comprehensively as possible, and that the data collection system requires minimal setup or site-specific tuning. The need to collect information and evidence following a collision is accepted, but there is pressure to collect the information and get the road reopened to traffic quickly. This need for fast collection must be balanced against the fact that the data collected may be used in court, and so must be reliable. It is often the case that the ultimate use of the data, or the level of detail required is not known at the time of collection. Accident investigators often use laser scanners (Pagounis, et al., 2006) and/or close range photogrammetry (Fraser, et al., 2005). These techniques collect a large amount of data in a comparatively short time.

Pagounis, et al., (2006) presents an example scan of a road junction. The data collection of this scene required 25 different data collection points and took 8 hours. A number of spherical targets were placed within the scene to assist and improve the data alignment and registration. The mean error in the resulting dataset was found to be 4mm for each datapoint. This produces an impressive 3-D model of the scene, but such uncertainty in the position of measured data could mask genuine, or produce apparent, distortions in the shape of a surveyed bridge. Pagounis, et al., also present other examples of scans which produced point spacings from 5mm to 70mm. Whilst these may be fine for working out road geometry and sightlines, or other parameters useful in the reconstruction and investigation of accidents, they would not produce data at sufficient resolution to enable the data to reflect fine details or defects of interest to engineers during a GI.

4.3.3 Construction

Photographs have been used to monitor construction progress for many years. These images are often used in applications such as dispute resolution (Bohn & Teizer, 2010), accident investigation (Wu, et al., 2010), training (Messner & Horman, 2003), or facility management (Klein, et al., 2012). Many of the systems and applications make use of time-lapse images (Golparvar-Fard, et al., 2009), enabling progress to be visualised, and/or virtual reality techniques (Whyte, et al., 2000), providing an immersive experience for people viewing the data off-site.

Traditionally images have been analysed manually, however recently image processing and computer vision techniques have been employed to assist the interpretation of the images ((Lukins & Trucco, 2007), (Ibrahim & Kaka, 2008)). Additionally, the demand for photorealistic 3-D models of buildings has increased (Wang, 2013). Data collected using laser scanners is beginning to play an increasingly important part in the domains of architecture and construction (Huber, et al., 2010).

4.3.4 Pavement condition monitoring

Until the last 15 years or so the condition assessment of road pavements was performed manually, using visual inspections performed at walking speed. The UK Highways Agency is responsible for approximately 20000 lane kilometres of pavement. It is clear that performing walking speed inspections of all these roads would take a very long time, and require a great many inspectors. The inspections would cause disruption to traffic, and visual inspections have been shown to produce results of variable quality.

The Highways Agency commissioned research to address these issues, which resulted in the development of automated survey systems which can assess the pavement for a number of key defects at traffic speed (Ferne, et al., 2003). Such surveys have now been adopted nationwide as TRACS (TRAffic-speed Condition assessment Surveys) on Highways Agency trunk roads and motorways (Highways Agency, 2011), and as SCANNER (Surface Condition Assessment of the National NEtwork of Roads) on local roads (Department for Transport, 2011).

Figure 31: HARRIS1 and HARRIS2 vehicles, developed and operated by TRL on behalf of the Highways Agency.

It is important to note that even though these surveys are widely performed and accepted they are not the final determining factor in undertaking maintenance, but merely provide condition data for those in charge of the maintenance programme to consider. No roads are ever repaired purely on the basis of TRACS or SCANNER data without subsequent investigation to confirm the condition of the road.

The automation of pavement condition monitoring has been very successful in terms of measurements of road profile, road geometry and surface texture (Fu, et al., 2013), but has had less success at reliably and reproducibly reporting more visual or subjective defects such as pavement surface cracking ((McRobbie & Wright, 2005), (Furness, et al., 2007), (Sharpe, et al., 2008), or fretting (McRobbie, et al., 2013)).

Woodward (2006) acknowledges that pavements are essentially flat, linear two-dimensional surfaces, and that bridges are more complex three-dimensional structures, with a wide variety of size and form. However, he asks whether a similar approach to that used in pavement inspection could work on structures. Woodward suggests there is scope to develop methods and/or equipment to assist the inspectors. He proposes that such aids could help provide more objective, consistent quantifiable condition assessments, and could help with tracking changes in structure condition.

4.3.5 Use of sensors to monitor non-visual aspects of bridge condition data

A range of Non-Destructive Techniques (NDT) and technologies are already used and established in various aspects of bridge inspection and condition assessment. These include half-cell potential (Elsener, et al., 2003), acoustic monitoring (Chang, et al., 2003), and GPR (Bungey, 2004), (McCann & Forde, 2001), (Scott, et al., 2003). The defects and condition parameters monitored by these techniques are not the types of defect recorded or observed in a visual inspection, although some of the NDT methods have been seen to correlate well with visual inspection for some defects (Adnan, et al., 2006).

Although the use of technology is widely accepted in many aspects of Structural Health Monitoring (SHM), the research seems to have overlooked the problems of collecting basic routine visual inspection data, and has instead focussed on more complicated and specialised applications (Jauregui, et al., 2005), (Jahanshahi, et al., 2009), (Uhl, et al., 2011). Given that routine visual inspections are the foundation upon which bridge condition knowledge is based, and are likely to remain so for the foreseeable future, the use of technologies which could improve the inspections should be further explored. Additionally, a number of researchers are looking at ways of automatically detecting forms of distress by processing and analysing photographs of bridges (Abdel-Qader, et al., 2006), (Abdel-Qader, et al., 2003), (Moon & Kim, 2011), (Li, et al., 2013). These techniques rely on the collection of high-quality images, and cannot work without them. The collection of high-quality, high-resolution images of all parts of a bridge is a non-trivial task.

4.3.6 Potential for using technologies in routine visual bridge inspections

There are similarities between some archaeological sites, and some bridges, indeed some of the heritage sites are bridges (Lubowiecka, et al., 2009). However, there are also some significant differences in the purposes of the data collection, and the limitations placed on the collection of the data. The collection of data on archaeological or cultural sites is not a safety critical task, and is not usually used to plan/programme further work. The purpose of the data is primarily to record the condition of the site or artefact of interest as accurately as possible to enable work to continue offsite or once site is destroyed/inaccessible (Allen, et al., 2004).

The consultation responses (discussed in Section 2.3) indicated that engineers would want to be able to detect minimum defect widths of 0.2mm to 1mm if the inspection was to be successful. A datapoint spacing of 1 point per mm would result in 100 datapoints in a square cm, or 1 million datapoints in a square m. The typical datasets produced for archaeological applications do not produce data at sufficiently high resolutions. For example, Haddad (2011) states that 3 million data points were collected on a series of sandstone sculptures, with a surface area of $40m^2$ (Haddad, 2011). This is approximately 1 datapoint every 13mm – good enough to give a visual representation of the appearance and shape of the sculpture, but not good enough to detect or display fine details or cracks. The data can be used for a variety of purposes, and can provide a lasting record of the site. There are many similarities between the needs of the archaeological surveys and those of bridge inspectors, but the data available from the systems used in archaeology does not meet the needs of the engineers.

There are a number of issues related to the collection of accident scene data which make it somewhat of a special case and have affected the development of the data collection systems. The scenes of interest can be many tens of metres long, but are often only a few metres wide, and most of the information of interest is confined to a narrow vertical band of only a couple of metres height. The techniques used are fast and accurate, but are also expensive and difficult to use for non-specialist staff (Fraser, et al., 2005). The data does not need to be photorealistic as it is parameters such as the relative positions of vehicles and obstructions, road geometry and sightlines which are of primary interest, not the presence or appearance of fine details. Consequently, although image data is often collected along with the laser data this is not collected or presented at resolutions adequate for detecting fine details which would be looked for in a routine visual bridge inspection.

Images collected on construction sites are used to enable visualisations of progress, or to provide condition records. The data is not routinely used to identify fine details and cracks such as those that would be of interest to engineers involved in bridge maintenance, and consequently high resolution is not required.

The methods used for pavement condition monitoring are not directly applicable to those which would be needed to perform routine bridge inspections, although there are some similarities and lessons which could be learned. The main difference is that the pavement is always (unless something has gone catastrophically wrong with the survey) in the same place relative to the vehicle: the survey vehicle drives along the pavement, and collects data on the part of the pavement it is on at any time. The pavement is also, essentially a two dimensional ribbon (for the purposes of these condition monitoring surveys it is only the surface of the pavement which is considered). Bridges, on the other hand, are three-dimensional structures, and can be of many varied sizes and shapes. This makes it much harder to collect data at the desired resolution covering all parts of interest on the structure without developing a tailored approach for each structure.

The pavement condition monitoring techniques have had good success in monitoring certain surface condition parameters, but less success on visual defects such as cracking and fretting. It is precisely these types of defects which would have to be detected in routine visual bridge inspections.

Bridge engineers have indicated that image data is already used when considering inspection reports, and that the images are very useful. The collection of inspection images is currently done non-systematically, and is only as methodical as the inspector taking the images. No inspectors interviewed as part of this research routinely collect a full image set over all visible parts of a bridge. This leaves some areas of the bridge unimaged. For bridge elements where no image exists, and with no notes in the inspection report, it must be assumed that the inspector inspected the element and found nothing to report, but there is no way of knowing that the inspector did not overlook that area of the bridge, or miss a defect which was present.

The use of images in GIs suggests that there is no objection in principle to using images to determine the condition of a bridge. Additionally, the adoption of advanced technological approaches such as GPR or acoustic monitoring shows that bridge inspectors and engineers are open to the idea of using new techniques and tools. Problems with visual inspection data have been addressed elsewhere successfully by using technology, but there are sufficient differences between bridge inspection and these other applications to make their solutions not directly suitable for Image-Based Inspection (IBI) of bridges. Therefore the questions are, could inspections be performed to an acceptable standard using images; and if so, how could these images be recorded, processed and analysed; and how would such inspections fit into the existing inspection regime?

An examination of the goals and procedures of the five types of inspection on UK highway structures would suggest that an image-based system could perform surveys which were between General and Principal Inspections in their scope and coverage. The development and adoption of Image-Based Inspections (IBI) could address many of the problems with visual inspections, produce a tool for defect progress tracking, and be a necessary first step towards the use of automated image processing and analysis techniques.

Images must be collected in such a way as to provide full, detailed coverage of all visible elements of the structure, providing no less detail than can currently be obtained when performing a GI with no artificial aids. The images would have to be accurately locatable on the structure so that the presence, severity, type and extent of any defect could be accurately recorded.

In order to produce such a system there are a number of areas which need to be investigated, such as appropriate ways of collecting, processing, analysing, interpreting and reporting the data. Successfully overcoming these problems could result in inspection data which was not as reliant as the current regime on the opinion and performance of a single on-site inspector, was easier to share and discuss, provided a complete visual record for tracking and monitoring changes over time and which could be suitable for automated image-processing, opening up the possibilities of further advances in inspection data processing, analysis and reporting.

5 SUMMARY OF PART 1 - VISUAL INSPECTIONS: PURPOSE, PROBLEMS AND POTENTIAL MITIGATIONS

It has been established that visual inspections play an important role in the current inspection regime, and that engineers are generally happy with the data they obtain using existing methods. The data is used to plan further inspections or investigations, and to plan maintenance work. However, the literature reports a number of issues and problems affecting visual inspections which suggests that the quality of data provided to bridge engineers is perhaps not as good as they believe, and could certainly be improved. A number of factors have been identified which influence the success of visual inspections, such as the inspector's fear of the inspection environment or eyesight, the physical environment in which the inspection takes place and the way the inspection is carried out

The problems with visual inspections are not confined to the collection of bridge data. The literature describes many instances where problems with visual inspection data have been encountered in other industries and applications. There are a number of measures which have been proposed to alleviate the problems and improve visual inspection data quality.

Technological approaches and tools have been successfully used to help collect visual condition data in a variety of fields and industries. Some applications (manufacturing, aerospace, food) have full control and are relatively straightforward computer vision problems; others (archaeology, accidents, construction, pavement condition monitoring) must operate in environments where there is less control over the orientation of the object, the scene background or the lighting, and are more akin to the requirements of bridge inspections.

There have been calls ((Middleton, 2004), (Woodward, 2006)) to develop suitable systems and methodologies which would enable technological tools to be used to assist and improve visual inspections on bridges. A similar process was undertaken between 15 and 20 years ago in pavement condition monitoring. Machine based surveys are now routinely performed on the majority of roads in the UK, and data from such surveys is accepted and used by those responsible for the maintenance of the road network. It is recognised that the problems faced in collecting data on roads and bridges are different, and that the move from the current situation where manual inspections are the norm, to one where a more technological approach is used will be a long process.

In order to be accepted by engineers, an Image-Based Inspection (IBI) system would need to produce data at least comparable to that currently obtained by traditional visual inspection methods, and would require ways of collecting, processing, analysing, interpreting and reporting this data. A number of researchers are investigating the use of image-processing tools to automatically detect and report defects such as cracks in images of concrete structures ((Abdel-Qader, et al., 2003), (Abdel-Qader, et al., 2006), (Adhikari, et al., 2014), (Jahanshahi, et al., 2009) (Li, et al., 2013) (Matsumoto, et al., 2014) (Moon & Kim, 2011) (Yamamoto, et al., 2014)), but little or no work has been undertaken to develop a standardised, methodical method for the collection of the images on which these tools can work.

5.1 Research question

The work carried out in Part 1 of the research has helped to properly define the research question:

Can systematically collected, high-resolution image data be used to enable General Inspections to be performed which provide at least as much information to engineers as traditional on-site General Inspections? If so, how can the data be collected, presented and interpreted, and what are the benefits of such an approach?

PART 2 – IMAGE-BASED INSPECTION SYSTEMS: REVIEW, DEVELOPMENT AND TESTING

Part 1 established that visual inspections play a vital role in the collection of bridge condition data and the management of the assets. It also showed that visual condition inspections are susceptible to a number of problems, resulting in subjective and variable outputs. A number of approaches for improving the quality of visual inspection data were discussed, as were examples of successful applications of these. Part 1 concluded that investigating the use of a technological solution to help the inspectors collect and interpret the necessary data would be beneficial.

Part 2 discusses the work performed leading to the development and testing of an Image-Based Inspection System (IBIS).

Chapter 6 discusses the requirements of any potential IBIS. This establishes through experimentation the way in which the size of feature which can be identified by inspectors varies with viewing distance and at different image resolutions, and considers the implications of this. Chapter 6 concludes by outlining a specification and list of requirements for an IBIS to be used for UK highways bridge GIs.

Chapter 7 reviews some existing systems and approaches which could be used to collect images or assist in a GI and discusses their strengths and weaknesses, and possible suitability for adoption and use as a routine tool for inspectors and engineers.

Chapter 8 covers the development of an image collection, display and interpretation system. This discusses the decisions made during the development, and explains why they were made, and why the alternatives were not.

Chapter 9 presents the results of the testing of the system, and the feedback received from practising engineers and inspectors who used it.

Chapter 10 presents an overview of the work done in Part 2 of the research, summarising the system requirements, the suitability and shortcomings of existing systems, the development of the prototype system and the results and feedback, highlighting the areas which require improvement.

The findings and conclusions of the work are presented in Chapter 11, followed by ideas for future research in Chapter 12.

6 IMAGE BASED INSPECTION SYSTEM REQUIREMENTS AND CAPABILITIES

The consultation found that photographs are taken in almost all General Inspections, but that there was no consistency in how this was done. In contrast to traditional GIs, images in an Image-Based Inspection (IBI) would be collected in a systematic manner, and would provide image data over the entire visible surface of the bridge. The images would be processed and aligned, and presented to inspectors for inspection. Obviously only defects which are visible within the images and detected during the inspection process will be reported, but this is the case with any form of visual inspection. Equally obviously, the success or failure of the IBI will depend on the quality of the images, which will have to have sufficient resolution, and be properly focused, illuminated and locationally referenced. The images should enable the inspector to view any part of the surface of the bridge at a level of detail sufficient to detect and identify defects of concern. However, an Image-Based Inspection System (IBIS) would have the advantage of producing a full image record of the condition of the bridge, enabling year-on-year comparisons of defect progression to be made. Additionally, the images could be shared between inspectors and engineers, easing collaboration and allowing second-opinions to be obtained, and the images could be used in conjunction with image-processing techniques to automate parts of the inspection and reporting process.

To be worthwhile any IBIS must produce results which are at least as useful and informative as those obtained from traditional inspections. This requires that the images show all defects which could reasonably be expected to be detected during a traditional inspection. The added value obtained during a Principal Inspection by being able to touch and feel the structure will be difficult to replicate using an IBIS, which will be purely visual in nature. This chapter will establish what the requirements of an IBIS are, if it is to be used to enable routine visual inspections, at a level of detail similar to that produced during a traditional GI, to be performed using the images alone, with no need for the inspector or engineer to visit the bridge.

If an IBIS is to deliver bridge condition data then there are a number of areas which must be considered to ensure that it produces data which meets the requirements of the engineers. These include:

1. Feature visibility requirements.
2. Practical requirements for data collection.
3. Image properties.
4. Practical requirements for data analysis.

6.1 Feature visibility requirements

The purpose of the images is to enable an inspector to undertake a GI and complete an inspection report without needing to visit the bridge. In order to assess whether or not this is feasible it is important to determine what is currently delivered by a traditional GI.

6.1.1 What does a traditional GI detect and report?

Appendix B discusses the outputs available from a traditional GI in more detail, but in summary an inspector considers each element of the bridge, and provides a brief report on the severity, extent and type of any defect seen, as well as an initial estimate of the type of work required to address the defect, the cost, and the priority of the work. The inspection report is usually accompanied by a number of photographs to document the general view and appearance of the bridge, as well as specific defects. The image record is not comprehensive.

6.1.2 What must be seen in order to complete a GI report?

In order to complete a GI report the inspector must be able to see all external surfaces of bridge. Obscured parts of the bridge (hidden, for example, by vegetation or signage) cannot be inspected. The inspectors look for signs that any previously required maintenance has been carried out properly, and check for new defects. The precise type of defect looked for, and its importance will depend on its location and the construction and design of the bridge. The nature of the inspection means that only visual defects, or visible manifestations of hidden defects, can be detected.

The inspection report form requires information on the individual elements of the bridge. The inspectors complete the parts of the form which apply to the bridge being inspected. In order to determine whether any part of the bridge requires maintenance or further investigation the inspectors must be able to see defects such as cracks, spalling, staining, efflorescence or impact damage, and must be able to report where on the bridge any defect is found well enough that another inspector or engineer can unambiguously and reliably locate it at a later date.

6.2 Practical requirements for data collection

In order to be adopted as a routine tool an IBIS must be able to operate under similar conditions to other routine bridge inspections. The physical process and requirements of image collection also place restrictions on the data collection and the placement and operation of the system.

6.2.1 What are the constraints imposed by the needs for a practical routine inspection method?

IBI is proposed as an alternative way of undertaking routine UK highway bridge inspections. These usually take place with no traffic management or access equipment, and are generally, according to the consultation responses discussed in Chapter 2, undertaken in 30 to 60 minutes. There are many more bridges than bridge inspectors and consequently the time spent on-site at each inspection must be kept as short as possible, while still collecting sufficient data and detail to enable an inspection to be carried out. Traditional routine inspections are quite a resource efficient method of collecting condition data as all that must be paid for is the travel to and from the site, and the inspector's time in performing the inspection and producing the report. In spite of the lack of equipment, access and short time on site, a GI provides information on the condition of all visible and accessible parts of a structure. This will vary from bridge to bridge, and some parts of the bridge will be easier to inspect than others, and will consequently be inspected in more detail.

An IBIS will need to operate under similar conditions: no traffic management or access equipment; minimised time on site. Ideally the image collection would take no longer on site than a current GI. Any increases in the time taken to inspect a bridge must be justified in terms of the increase in the functionality and usefulness of the data provided. Additionally, the time required to process, present and inspect the collected data offsite must also be minimised. The collection and processing of the data should be automated as much as possible to keep these processes fast and efficient, but all accessible and visible parts of the bridge must be included in the data collection. The equipment required must be affordable so that the basic cost of collecting condition data is not radically altered. Some increase in cost may be acceptable if the data produced is helpful and leads to improvements in the asset management of the structure.

A number of techniques and approaches to the processing of image data would be simplified by the use of targets permanently fixed to the surface of the bridge. Similarly, if the locations of the image collection positions were permanently marked then the time taken for the on-site system setup would be vastly reduced.

However, in order to meet the requirements of developing a system with no additional constraints or requirements to those on a traditional GI it was decided that these would not be used.

6.2.2 What are the limitations imposed on the system in terms of dealing with different bridge designs?

The need to operate without traffic management limits the possible places from which images can be collected. The system must operate without impeding, distracting, or disrupting traffic flow in any way, and the operation of the system must be safe for operators and the public. This essentially means that the data collection could take one of two routes: collection from the side of the road on footways or verges; or collection from a moving system which does not impede traffic.

The system will have to deal with a variety of bridge types and designs. Some of these will provide more of a challenge than others. Clearly the system will not provide information on the condition of hidden elements, and will only show features which have been imaged, but these limitations hold for traditional visual inspections. Obstructions on site, or more complicated bridge design features such as piers or support structures with more than a single visible side (as shown in Figure 32), are relatively easy for inspectors to deal with in a traditional inspection. The inspector can simply walk around the pier and inspect it from all sides, and can also easily look behind it to see parts of the structure which may be hidden by the pier when at the initial inspection location. The IBIS will need to collect data from multiple locations and display them appropriately, and will also need to take additional images to show any obscured parts of the structure. This requires additional image collection locations, resulting in more time on site.

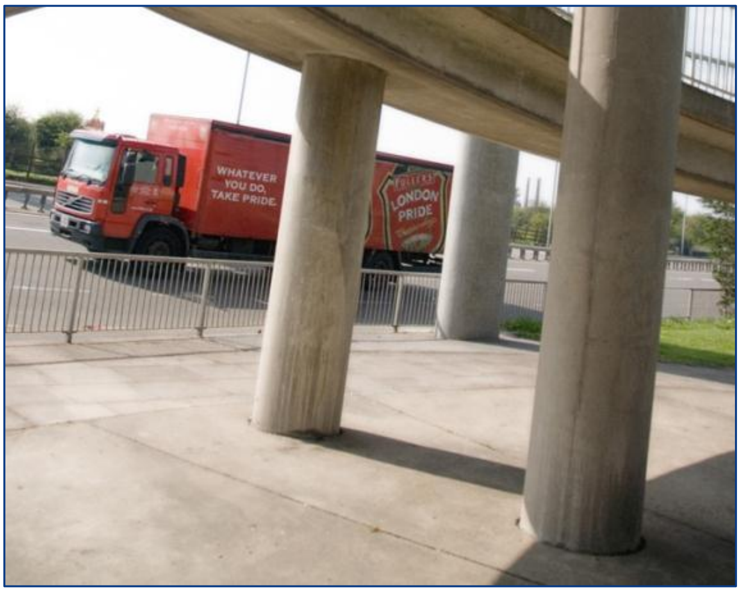


Figure 32: Example of feature which may be problematic for an IBIS, but straightforward for a human inspector.

6.3 Image properties

6.3.1 What are the constraints placed on the system imposed by the image collection process?

Ideally the collection of images would be a simple process using either a vehicle mounted camera which automatically collected images as it passed through or around the bridge, or a handheld camera which the inspector could use to snap images with little or no constraint on the image collection process. However, if the images are to be of acceptable standard, show adequate detail, and represent the size and shape of features accurately and consistently then the image collection process is necessarily more complicated.

For images to provide faithful representations of scenes certain criteria must be met. The following summary is necessary in understanding the decisions leading to a proposed specification for an IBIS.

6.3.1.1 *Lighting*

The scene being imaged must be adequately illuminated. Too much light will overexpose the image (Figure 33, left), while insufficient light will result in underexposed images (Figure 33, right). Both over- and under-exposed images will fail to show details which may be of interest to the inspector.

Figure 33: Example of over- (left) and under- (right) exposed images.

The need for the system to operate with no traffic management or disruption precludes the use of flash illumination and makes it difficult to use any form of illumination routinely. To simplify the development and demonstrate the potential for an IBI approach the decision was made to operate the IBIS with no artificial illumination of any kind, and make use of natural light.

6.3.1.2 *Field Of View*

The area which will be captured in an image is known as the 'Field Of View' (FOV). If the IBIS is to collect images of all visible parts of the structure then it follows that the FOV of the camera must either include the entire structure, or that a number of images must be taken. The larger the FOV of the camera, the fewer images will be needed to cover the whole bridge.

The physical dimensions and the number of individual pixels in the camera sensor are constant for any particular camera model. The angular FOV of a given lens of fixed focal length does not change. If the camera and lens are used to take an image of a plane surface from a distance of 10m away, and another image of the same plane surface from a distance of 5m away, then the parts of the surface which are included in the images will be different. Figure 34 illustrates this.

Assuming that the camera FOV (θ) remains constant, if the surface being imaged (represented by the rainbow coloured rectangles) is located at distance A, then only the two central bands will be included in the image. If the surface being imaged is at distance B then the four central bands will be imaged. Because the same number of pixels is available to represent the imaged scene, each pixel will represent a smaller area when the image is collected at point A, resulting in a more detailed image of a smaller area.

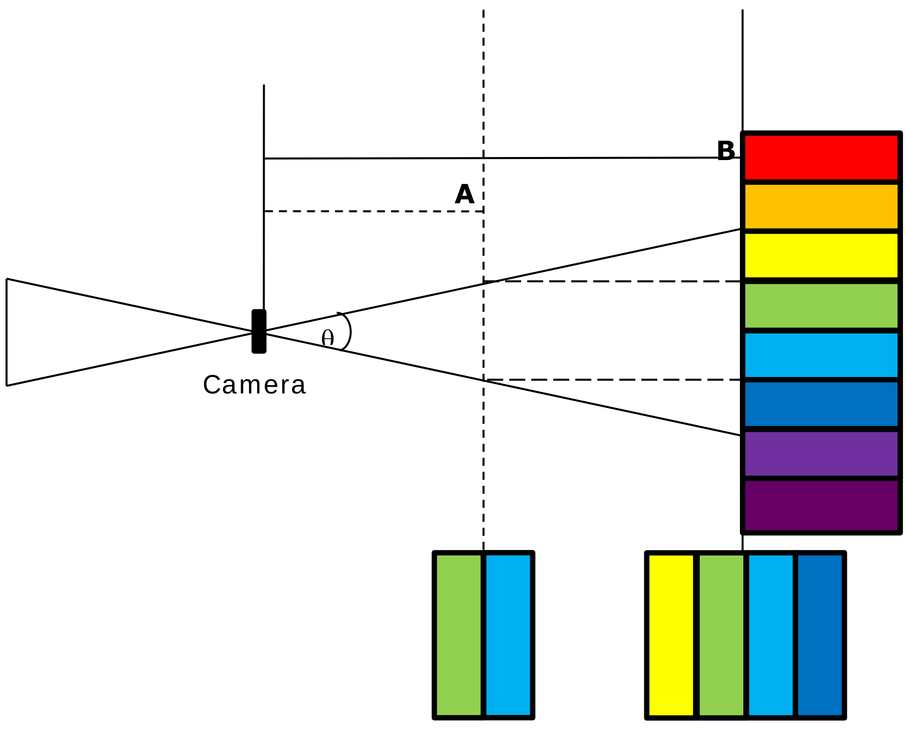


Figure 34: Demonstration of effect of imaging distance on area imaged.

It is therefore important to make sure that the images of the bridge will be collected at a distance which will produce sufficiently detailed images. In order to increase the level of detail in the images there are two things which can be done: the camera can be moved closer to the bridge, or the camera could use a lens with a narrower FOV. Moving the camera closer to the bridge is not always possible due to traffic, obstructions or the size of the bridge.

6.3.1.3 Angle of view

The angle at which the image is taken can have a great effect on the usefulness of the image. If the image is taken at a particularly oblique angle then the area of the scene represented by each image pixel will vary. Pixels representing parts of the scene which were closer to the camera will represent a smaller area than those from further away.

The images in Figure 35 show two views of the same part of a bridge. The image on the left has been taken from close (approximately 2m) to the bridge at a steep viewing angle. The image on the right has been taken from approximately 12m away, with the camera pointing more perpendicularly to the imaged surface. Despite being taken from farther away the image on the right gives a more easily interpreted impression of the condition of the wingwall.

Figure 35: Different views of the same part of a bridge showing the effect of imaging angle.

6.3.1.4 Resolution

The resolution of an image is related to the level of detail which can be seen within the image. A higher resolution image will show more detail than a lower resolution one. There are a number of factors which influence the resolution of the image: the camera sensor; the lens; the camera-object distance.

For a given camera sensor, moving closer to the scene, or choosing a lens with a longer focal length, makes the area of the scene within the camera FOV smaller, and means that each sensor element represents a smaller area of scene, producing a more detailed image. Changing to a lens with a longer focal length consequently has the effect of either producing more detail in the image obtained, or enabling an equally detailed image to be obtained from further away.

The camera sensor can be thought of as an array of individual sensor elements. Light from the scene gets focused by the lens and falls on this array. Each sensor element records the amount of light which it detects, which is then converted into an image. If this array was 1000 x 1000 then there would be a total of 1 million sensor elements, and the resultant image would have 1 million pixels. In practical terms the camera sensor cannot be changed, other than by selecting a different camera.

If the hypothetical 1 million pixel sensor above was used to image a scene measuring 1m x 1m then each pixel would represent the light detected from an area of 1mm x 1mm. If the camera was used to image a scene of 0.5m x 0.5m then each pixel would represent light from an area of 0.5mm x 0.5mm. The image requirement is to show features as small as 0.4mm (Chapter 2). This does not mean that there must be 1 pixel for every 0.4mm of scene area. Dark, sub-pixel size features will affect the light detected by each pixel, and reduce the reported pixel value compared to its' neighbours, meaning that the feature will be visible in the output image. Further detail on image resolution and visual acuity is discussed in Section 6.3.2.

6.3.1.5 Focus

Perhaps most crucially, the images must be properly focused. It does not matter how carefully the scene is lit, or what the sensor size of the camera is, if the images are not properly focused then the light from each part of the scene will be spread over a number of sensor elements, resulting in blurry images in which fine details cannot be resolved or detected.

Ensuring all images are in focus is difficult without manually focusing the camera for each image. The Depth Of Field (DOF) of a camera is the distance between the nearest and farthest parts of a scene which are displayed sharply. Only a single distance can be precisely focused at a time, but the decrease in sharpness at either side of this focused distance can be steep or shallow, meaning that more or less of the scene can be tolerably sharp.

Even when viewing planar objects such as bridge abutments, if the camera is not moved to be perpendicular to the plane being imaged, and held at a constant camera-object distance for all images, then some of the scene will be closer to the camera than others. If the difference in this camera-object distance exceeds the DOF, then parts of the image will appear unfocussed.

The DOF can be increased by decreasing the aperture size of the camera. Decreasing the aperture size lets less light in to the sensor, making the image darker, or requiring additional light sources or a longer exposure. If a longer exposure is used then the image will be more susceptible to blurring due to movement or small vibrations.

6.3.2 Required level of detail – visual acuity and resolution

The information visible in the images must be sufficient to enable the identification of defects to a level of detail comparable to that achieved in a General Inspection. However, there is little guidance available in the literature to advise on what a suitable image resolution may be.

As discussed in Section 3.1, Megaw (1979) reported that the inspector's vision is an important factor in how well an inspection is performed; however there is no vision requirement in the regulations on visual inspection on UK highways bridges. The questionnaire (Question 1.5) performed for this work found that 66.7% of respondents would accept a system which detected cracks of 0.4mm or wider. The responses to Question 1.3 indicated that there is confidence that inspectors can detect these, however the limitations of the questions posed in the consultation meant that no data was available regarding the distance at which inspectors would be expected to detect such details.

Testing this hypothesis – that visual inspectors see all (or most) of the defects that are of concern to the engineer, and that they can detect cracks of 0.4mm or wider successfully – and determining at what distances they can do so, in controlled conditions is not easy. Ideally a large number of inspectors would inspect a bridge independently of one another, and would record the position of every defect and crack present on the bridge. The results of the inspections would be compared against a reference data set which contained the positions, and widths of all cracks. However there are a number of practical problems with this including finding a bridge containing the correct number and distribution of fine cracks, aligning the inspectors output with the reference data set, collecting the reference data set in such a way as to ensure all cracks were included, accurately measuring the crack widths for the reference data, and physically getting enough inspectors to the bridge to perform their inspections.

An experiment was therefore conceived and performed which would test the ability of 'inspectors' to detect and resolve fine features at a range of distances, and in images of different resolutions. The experiment, was specifically designed for this research, as was one of the test targets (T_A) which was designed to mimic the type of defect which an inspector would have to detect when undertaking a visual inspection. The findings from the experimental investigation were used to inform the selection of appropriate image resolution levels for a working Image Based Inspection System, and demonstrate that the chosen resolutions would enable the detection of details at least as fine as those detectable from typical inspection distances. The work aimed to see whether or not inspectors could see more detail when presented with images rather than inspecting on-site, and to investigate the effect of different image resolutions on the amount of detail seen, and also wanted to show whether or not the inspectors showed more consistency in what levels of detail could be seen when looking at images compared to inspecting on-site.

6.3.2.1 Methodology

As noted previously GIs are performed with no special access equipment or traffic management, and the inspector does not have to get within touching distance of the structure. In terms of inspection distances, a distance of 12m is probably the upper limit of what might be deemed acceptable. An inspector would try to get closer to the bridge than this wherever possible, but in cases where there are obstructions or impediments this may be as close as they can get: wingwalls up overgrown embankments may be hard to access; to observe a parapet 6m above the pavement avoiding oblique viewing may require the inspector to stand 10m back, which produces a viewing distance of 12m (examples shown in Figure 36).

Figure 36: Images taken from 12m from bridge to illustrate what a 12m viewing distance can show.

A 6m inspection distance (Figure 37) may be experienced when inspecting the soffit of a structure, particularly when looking at the part of the soffit above the carriageway from a viewing position on the footway.

Figure 37: Images taken from 6m from bridge to illustrate what a 6m viewing distance can show.

Even in cases where the access to the bridge is good a 3m inspection distance (Figure 38) will be used frequently. If the clearance of the bridge is 5m, which is common on many highways bridges, then the inspectors head is unlikely to ever be closer than 3m to any part of the soffit, or to the upper parts of the abutment. Even on lower bridges it will be difficult to get closer than 3m to many parts of the bridge such as the soffit above the carriageway, parapets, wingwalls, or the upper part of abutment.

Figure 38: Images taken from 3m from bridge to illustrate what a 3m viewing distance can show.

Viewing distances of 12m, 6m and 3m were chosen to be representative of the types of distances at which bridge inspectors typically have to undertake GIs.

Targets

Three target-types were chosen for the experiment: standard opticians' LogMAR eye-charts (L_A and L_B, Figure 39); a Tumbling E's chart, with varying contrast between the test objects and the backgrounds (T_A, Figure 40); and a target specifically designed for this research which displayed a grid containing lines of specific and known thicknesses and orientations (E_A, Figure 41).

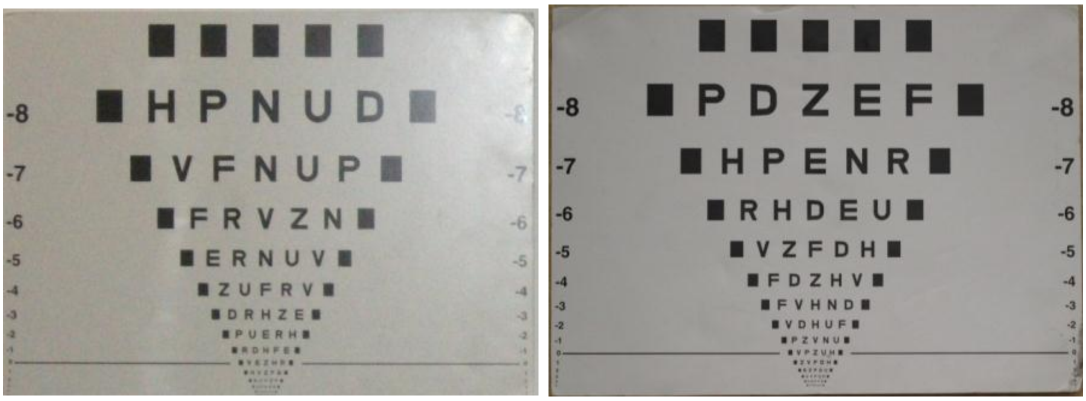


Figure 39: Standard opticians' charts used (L_A on left, L_B on right).

Figure 40: Tumbling E's chart with varying object-background contrast ratios (E_A).

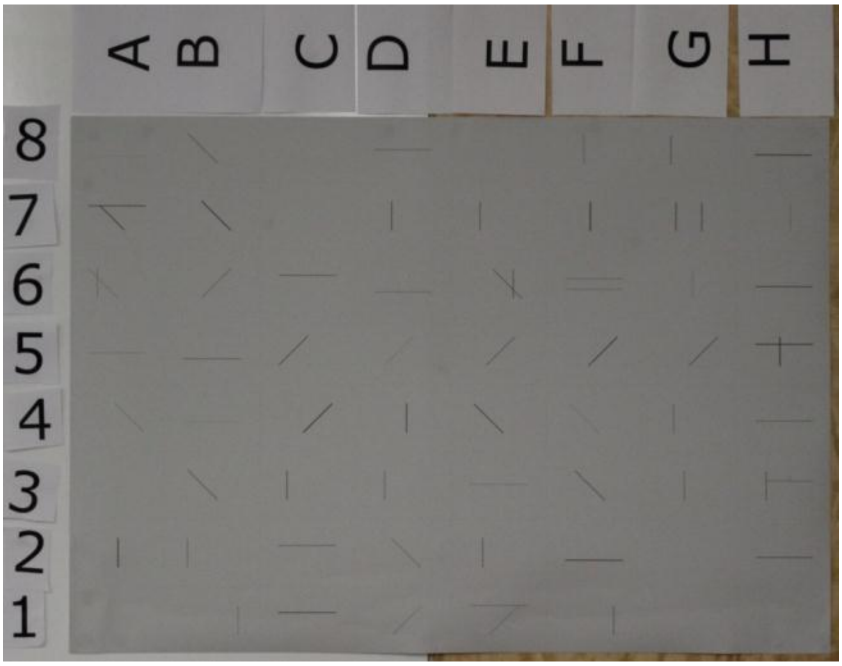


Figure 41: Array of lines of known thickness and orientations (T_A).

The LogMAR (LOGarithmic Minimum Angle of Resolution) charts were used in two ways. Chart L_A was used to establish a baseline for the participants' eyesight (corrected if necessary) and to confirm that all participants had eyesight which fell in the normal range. Chart L_B was used to determine how much detail could be read on the chart at the selected range of distances and image resolutions. The data obtained on chart L_B were used in the calculation of the results. When viewing charts L_A and L_B the test participants were asked to write down the letters they could see on the chart.

The tumbling E's chart was used to determine how well the test participants could resolve fine details in an image. The participants were asked to view chart E_A and draw an arrow on the record sheet indicating which way the E was pointing (a normal E was defined as pointing to the right) was defined as pointing downwards). As well as the change in size of the E's on the chart, the grey levels used for the background and the test object were varied on the chart. The effect of contrast on the ability of participants to correctly determine the orientation of the target was not investigated in this work.

Chart T_A was designed specifically for this work. The chart contained an 8x8 grid of cells in which lines of known thicknesses were printed. Most cells contained a single line, eight cells contained two lines and eight cells contained no lines. The distribution of line thicknesses is shown in Table 8.

Table 8: Number of lines of different thicknesses present in chart T_A

Line thickness (mm)	Number of cells
-	8
0.07	7
0.14	7
0.21	7
0.28	7
0.35	7
0.42	7
0.57	7
0.71	7
Total	64

Chart T_A was designed in order to test how well the participants could identify the presence of thin features. This simulated the task of detecting the presence of a crack on a bridge. The background of the chart was shaded a mid-grey, and the 'cracks' were black, to better replicate cracks on a concrete bridge. Participants were asked to draw the lines as they saw them on T_A.

Experiment location and conditions

The experiment was carried out under controlled lighting conditions to ensure consistency throughout the experiment. The collection of data took place over a number of sessions, and a light meter was used to make sure that the light in the room remained consistent throughout. The lighting in the room was deliberately chosen to be quite 'dingy', but not dark, and resemble typical lighting conditions encountered under a bridge on an overcast day. Light levels were controlled using blinds in the test room.

Experiment procedure

The room was set up as shown in Figure 42, and Figure 43. Lines were marked on the floor at positions P_0, P_1, P_2 and P_3. These were measured to be distances D_0 (3m), D_1 (12m), D_2 (6m) and D_3 (3m) from the targets (Table 9).

Participants were given a series of records sheets to complete, and were first positioned at point P_0, where they recorded what they could see in target L_A from a distance of 3m (D_0). They then recorded what they could see in targets L_B, E_A and T_A from position P_1, then P_2 and finally P_3.

Table 9: Viewing distances and locations

Viewing Position	Viewing Distance	Distance
P_0	D_0	3m
P_1	D_1	3m
P_2	D_2	6m
P_3	D_3	12m

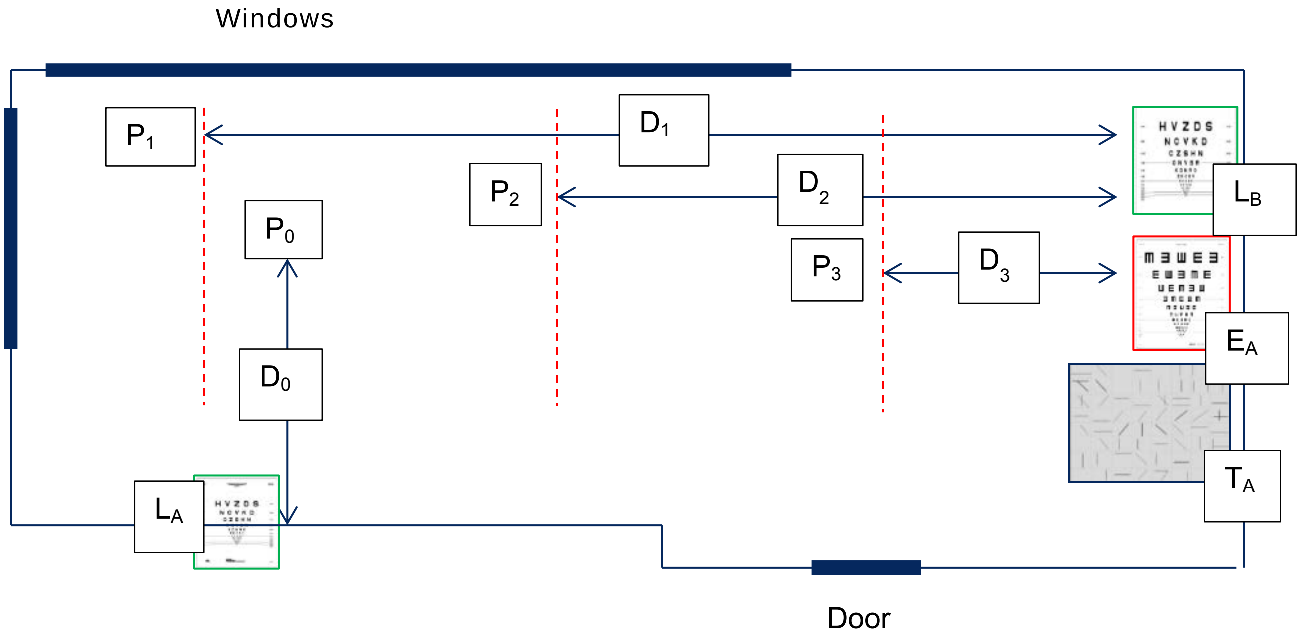


Figure 42: Room layout and experimental set up for visual acuity on-site data collection.

Figure 43: View of room set up for collection of acuity and image resolution data.

Following the on-site part of the experiment each participant was supplied with images of the targets L_B, T_A and E_A which had been processed to show detail at either 1 or 2 pixels per mm (shown below as Figure 44). That is the images were scaled such that features within the images which were known by measurement to be, for example, 20mm in actual size were represented by either 20 (at 1 pixel per mm) or 40 (at 2 pixels per mm) pixels in the image.

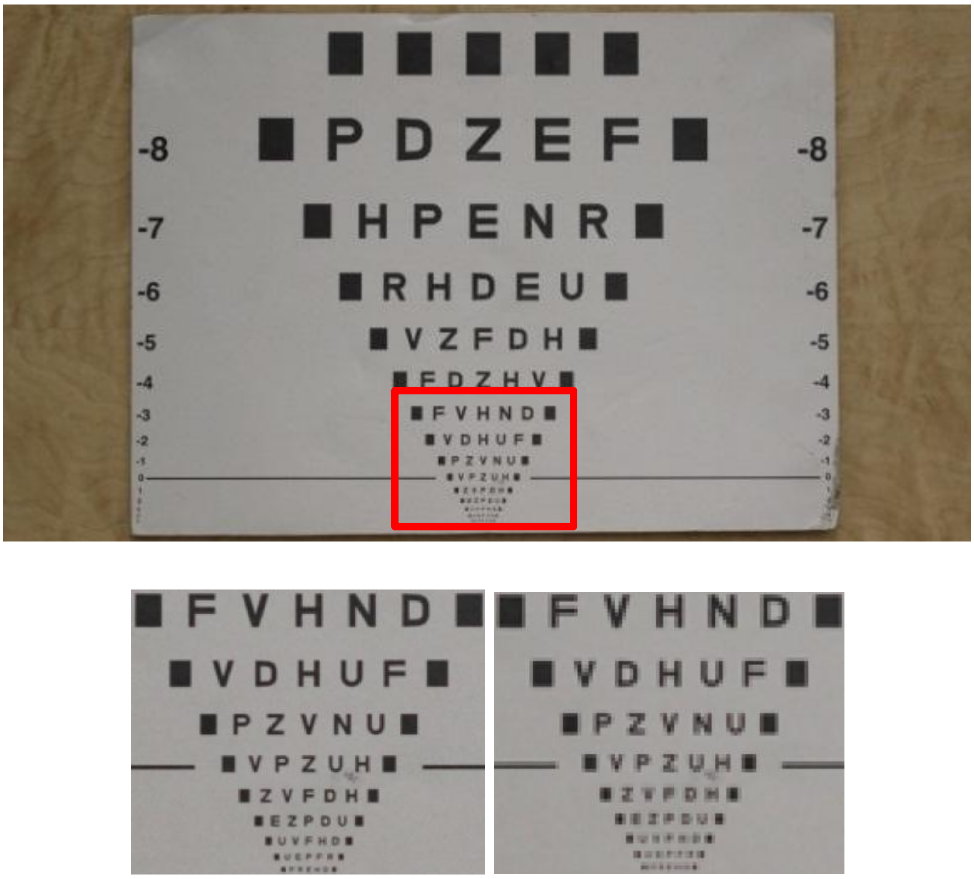


Figure 44: Image of eye-test chart, with detailed view presented below at (from left) 2 pixels per mm, 1 pixel per mm.

Test participants

Following advice, and power analysis (Cohen, 2013), from TRL's statisticians on the number of participants required in order to produce statistically robust results it was recommended that in order to be able to assign statistical significance to results which differ by 30% (i.e. a score of 90% compared to a score of 60%) a total of 40 participants would be required. These participants were duly recruited from within TRL. Very few of the test participants had any experience in bridge inspection. This was not felt to be a problem as the test was to determine the levels of detail which could be discerned on-site and in images, and not the interpretation of the detail seen.

The results obtained on chart L_A were used to calculate the basic visual acuity of the test participants. The distribution of these is shown in Figure 45, along with data from the study performed by Moore, et al. (2001). The Moore study involved practising inspectors undertaking inspections under test conditions on a number of bridges. The inspectors taking part in the Moore study were assessed in a number of ways, including having their eyesight measured. Although the details of the experiments carried out in the current research and the Moore work are different they both make use of data recorded based on what inspectors can see. The eyesight of the participants taking place in the current study is seen by inspection to be similar to that of the sample of practicing inspectors used in the Moore study (Figure 45).

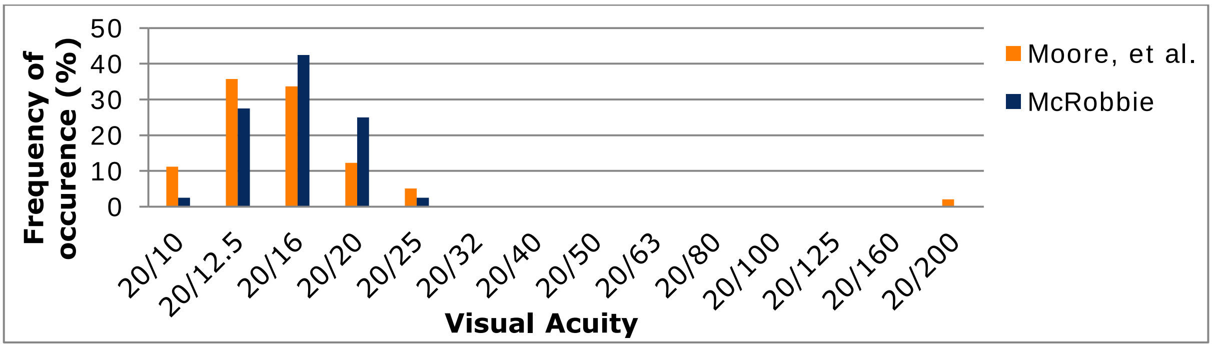


Figure 45: Distribution of participant visual acuities in this work, and in work by Moore, et al. (2001).

The participants were split into four groups for the image-based work, and were given different images depending on what group they were in. Table 10 shows which groups got which images, and how many people were in each group.

Table 10: Image resolutions assigned to groups

Group	Chart L_B	Chart E_A	Chart T_A	Group size
1	1 pix/mm	2 pix/mm	1 pix/mm	10
2	1 pix/mm	1 pix/mm	1 pix/mm	10
3	2 pix/mm	1 pix/mm	2 pix/mm	10
4	2 pix/mm	2 pix/mm	2 pix/mm	10

6.3.2.2 Results

For each target, the percentage of target objects of each size which were correctly identified at each distance and image resolution were calculated.

Figure 46 shows how each individual letter on chart L_B was identified at each different viewing distance and image resolution. It is clear that as the test participants move closer to the target, the better the participants do at identifying smaller letters. This is an entirely expected result. It is also clear from looking at Figure 46 that the participants were more successful at identifying small letters when looking at images of 1 pixel per mm resolution than they were when looking at the target itself from a distance of 3m, and even more successful when images of 2mm per pixel were used.

12m	a	b	c	d	e
-8	100	100	100	98	98
-7	100	100	100	100	95
-6	85	95	95	95	95
-5	20	73	25	63	63
-4	18	15	18	13	2.5
-3	0	0	0	0	0
-2	0	0	0	0	0
-1	0	0	0	0	0
0	0	0	0	0	0
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0

6m	a	b	c	d	e
-8	100	100	100	100	100
-7	100	100	100	100	100
-6	98	100	100	100	95
-5	100	100	100	100	93
-4	98	63	98	95	93
-3	33	68	55	65	60
-2	7.5	20	5	7.5	10
-1	0	0	0	0	0
0	0	0	0	0	0
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0

3m	a	b	c	d	e
-8	100	100	100	100	100
-7	100	100	100	100	100
-6	100	100	100	100	100
-5	98	95	100	100	100
-4	100	100	100	100	100
-3	100	100	93	100	100
-2	80	98	98	98	98
-1	80	30	25	70	70
0	18	18	18	15	20
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0

1pix/mm	a	b	c	d	e
-8	100	100	100	100	100
-7	100	100	100	100	100
-6	100	100	100	100	100
-5	100	100	100	100	100
-4	100	100	100	100	100
-3	100	100	100	100	100
-2	100	100	100	100	100
-1	100	100	100	100	100
0	95	100	100	100	100
1	90	35	35	80	90
2	0	40	30	30	25
3	5	0	10	0	0
4	0	0	0	0	0
5	0	0	0	0	0

2pix/mm	a	b	c	d	e
-8	100	100	100	100	100
-7	100	100	100	100	100
-6	100	100	100	100	100
-5	100	100	100	100	100
-4	100	100	100	100	100
-3	100	100	100	100	100
-2	100	100	100	100	100
-1	100	100	100	100	100
0	100	100	100	100	100
1	100	100	100	100	100
2	95	100	100	100	100
3	100	100	100	100	100
4	45	65	75	65	35
5	35	5	15	15	35

Figure 46: Detection rates of each individual test object on chart L_B at (from left) 12m, 6m, 3m, and in images at 1 pixel per mm and 2 pixels per mm.

Figure 47 shows how the overall percentage of correctly identified targets, which is referred to as the Probability of Detection (POD), varied on chart L_B at the different viewing distances and image resolutions. The increase in POD as the participants moved closer is apparent, as is the higher POD obtained when assessing the images of the targets. For example, letters in row 9 on the eye-test chart were not correctly identified by any of the participants at 12 or 6m viewing distances, and only 17.5% were correctly identified at a 3m viewing distance, but 99% were correctly identified in the images at 1 pixel per mm, and 100% were correctly identified at 2 pixels per mm.

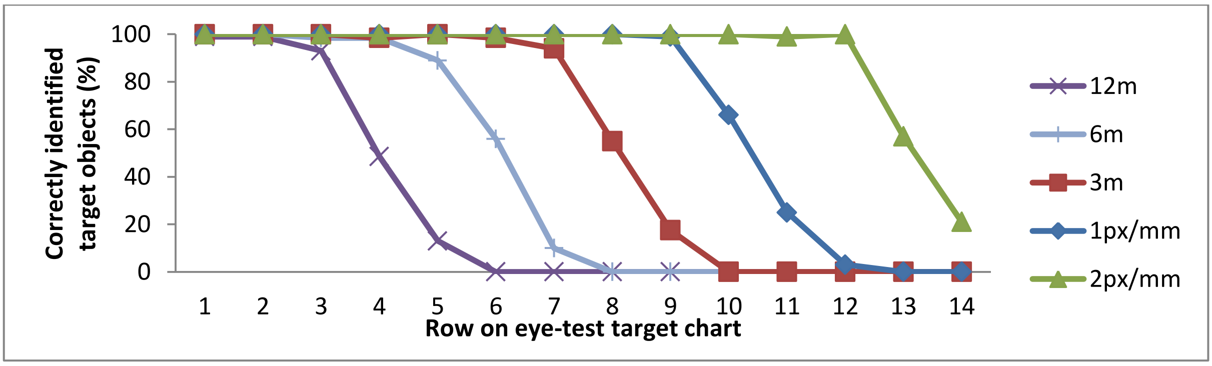


Figure 47: POD of test objects of different sizes on chart L_B at 12m, 6m, 3m, and in images at 1 pixel per mm and 2 pixels per mm.

A similar progression can be seen in Figure 48, which shows the POD for each row on Chart E_A. As was seen on chart L_B, the increased POD for smaller objects as the participants moved closer is clearly visible as is the increased POD when using the higher resolution images.

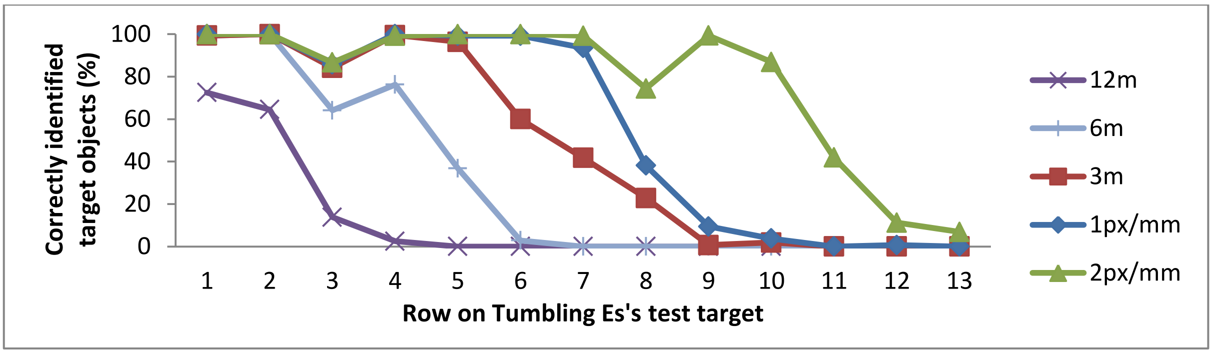


Figure 48: POD of test objects of different sizes on chart E_A at 12m, 6m, 3m, and in images at 1 pixel per mm and 2 pixels per mm.

The results of the tests on Chart T_A are shown in Figure 49. The broken red line marks 0.4mm, below which it is acceptable to the engineers (according to the consultation results) to fail to detect a defect. The results show that the participants struggled to detect the lines at 12m, and to some extent 6m, but could correctly identify the orientation of all but the very finest lines from 3m away, and detected all lines in the images at both 1mm and 0.5mm resolutions.

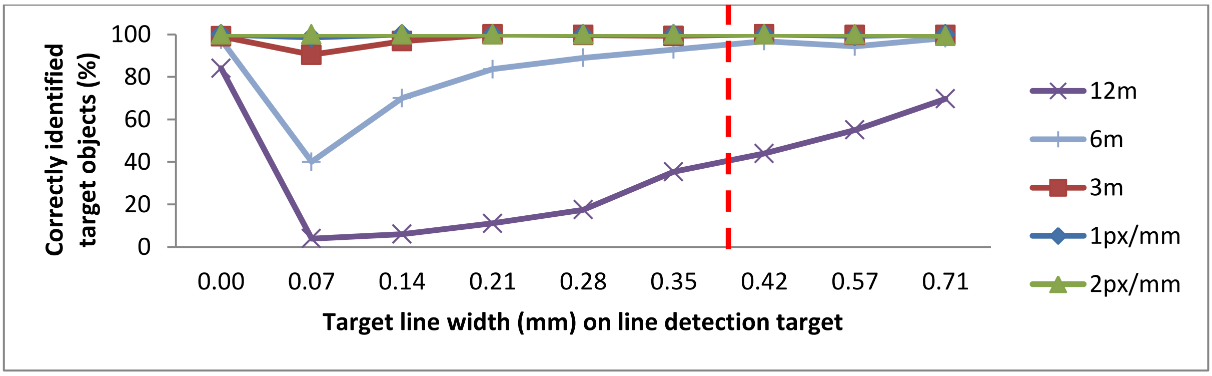


Figure 49: POD of test objects of different widths on chart T_A at 12m, 6m, 3m, and in images at 1 pixel per mm and 2 pixels per mm.

This also shows that the participants had little difficulty in identifying those cells containing no lines (0.00mm line thickness) even at 12m. This implies that inspectors are unlikely to report features and defects which are not really there, and inspection errors are more likely to be the result of failing to see something (false negative), rather than reporting something which is not there (false positive).

In addition to examining the POD of targets of different sizes, McNemar's test on paired differences was used to establish whether or not the results were significant.

Table 11 shows the 2x2 contingency tables for each of the targets used. These tables show how many individual targets were detected both at 3m and in images of 1 pixel per mm, how many were undetected in both conditions, and how many were detected onsite, but missed in the images, or vice-versa.

Table 11: 2x2 tables showing paired data and results for each target used in the experiment

L_B		3m onsite	
		Y	N
Image	Y	939	54
	N	21	386

McNemar's χ^2 statistic	14.52
p-value	<0.001
Odds Ratio	2.57
95% CI	1.55 - 4.26

E_A		3m onsite	
		Y	N
Image	Y	672	223
	N	27	878

McNemar's χ^2 statistic	153.66452
p-value	<0.001
Odds Ratio	8.26
95% CI	5.54 - 12.31

T_A		3m onsite	
		Y	N
Image	Y	1194	19
	N	1	2

McNemar's χ^2 statistic	16.2
p-value	<0.001
Odds Ratio	19
95% CI	2.54 - 141.93

These figures reiterate the fact that there is more chance of detecting any of the target objects in the images than onsite. The results of these tests show that the results are statistically extremely significant (p-values well below 0.001) and that there is an exceptionally low chance of obtaining the results by chance. The null hypothesis, that it doesn't make a difference whether the inspector is onsite or viewing images, can therefore be rejected.

6.3.2.3 Discussion

Clearly the experiment is artificial in nature as the test lines do not directly compare with real features, and the viewing environment did not fully replicate the conditions encountered during a GI. However, the work does demonstrate that inspectors may fail to properly identify features of similar sizes to those viewed as being important to the engineers – at a 12m viewing distance only 44% of lines of thickness 0.42 mm were correctly identified (Figure 49). The consultation found that engineers would expect features of 0.4mm or wider to be detected during a GI. Also, the test establishes that good quality images collected at 0.5mm or 1mm resolution provide sufficient detail to allow an inspector to perform an IBI and detect features of a size considered important to engineers.

It is true that inspectors will not carry out many inspections from 12m, or 6m by choice, and that there will be places on a bridge where an inspector can, and will, get very close to the surface of the structure. In these places the inspector will have an excellent view of the surface of the bridge and will be able to detect very thin cracks, thinner than would be visible in images of 0.5 or 1mm resolution. However these areas will be limited, and are generally not the areas which are of most concern to engineers. The inspector will therefore be basing their report on an inspection which has looked at different parts of the bridge in different degrees of detail: abutments next to a footway from ground level up to approximately 3m may be very closely inspected, while a much longer inspection distance may be used for the soffit of the same bridge. When performing an IBI, the resolution and detail available to the engineer will be constant over the whole bridge for all inspectors, providing a level of consistency which is not present in traditional inspections.

In addition to the improved consistency of information available to the inspector over the entirety of the bridge it has also been demonstrated that finer features can be resolved when looking at images of targets presented at 1mm per pixel than could be resolved when viewing the target from 3m. Presenting the image of the target at 2pixels per mm enables even finer details to be resolved correctly.

6.3.2.4 Implications

Images at 1mm per pixel, supplied over the entire surface of the bridge, should enable an inspector to undertake an Image-Based GI. If the resolution was improved to be 2 pixels per mm, or 0.5mm, them the detail available to the inspector would be even better, enabling finer features to be detected. However, this would quadruple the amount of data to be stored, and would require the use of longer lenses. The FOV of images taken with longer lenses would be smaller, meaning that more images would be required. A compromise must be reached between the desire for very high resolution images, and the desire for the image collection to be as quick as possible.

Note that an image resolution of 1 pixel per mm at the surface of the bridge does not mean that only features greater in size than 1mm will be visible, as was shown by the visual acuity experiment in which lines of width 0.07mm were successfully detected when looking at images at this resolution. This was mentioned in Section 6.3.1.4 and has been proved by experiment here.

Regardless of the quality of the images, and the levels of detail contained therein, if the final interpretation of images is still performed by a human inspector then the inspection results will still be subjective. The report will still rely on an inspector's opinion on the importance of a given feature. However, the improved consistency in viewing angles and detail available over the whole surface of the bridge will reduce some of the variability.

A traditional inspection has two sources of variability:

- whether the inspector will see a particular feature;
- the inspector's opinion of the feature once it has been seen.

The adoption of an IBI approach should reduce the first source as the data available to the inspector will always be good enough to enable the detection of defects of the sizes which are expected to be detected in a GI, regardless of where on the bridge the data is from.

6.4 Practical requirements for data analysis

Once the data has been collected it must be presented to the inspector (or an automated inspection system) for analysis. In order to enable this analysis to take place the images must provide as clear a view of the bridge as possible, in which the sizes, types and locations of any feature or defect can be accurately identified. This information must enable the inspector to complete an inspection report.

Because similar looking defects can have very different implications for the condition of the bridge depending on where they are located, the inspector must be able to accurately locate each image on the bridge as a whole and consider the context of what is seen. The location of each defect must be known accurately enough that the same part of the bridge can be looked at using images from other inspections to enable the progression of defects to be monitored. Additionally the processing and presentation of the images must allow the inspector to assess the visual condition of the whole bridge, with no gaps in the image record, or, where such gaps are present, they must be clearly marked in the results so that those interpreting and revisiting the data can distinguish between parts of the structure which were not inspected, and parts of the structure which were inspected, but where nothing of interest was seen.

6.5 Requirements for an Image-Based Inspection System

Table 12 provides a summary of suggested IBIS requirements if it is to collect and display data suitable for use in completing an Image-Based GI report. In addition, there are a number of recommendations that should be considered if the system is to be practical and pragmatic enough to be accepted and adopted by commissioners of bridge inspections and users of bridge inspection data, and if the data is to be used in making real advances in the way routine visual bridge inspections are performed. These are summarised in Table 13.

Table 12: Requirements for an Image-Based Inspection System suitable for use to complete General Inspections

System aspect	Requirements
Data collection	No special access or Traffic Management. No disruption or distraction to traffic. System must be safe for operators and public. Images must be recorded of all visible parts of bridge that would be normally included in a traditional General Inspection. The system must be able to operate on a range of different bridge types and designs.
Data delivered	Must provide a full image record of whole surface of structure, excluding obstructed parts. Images must provide clear views of all parts of bridge. Images must be well lit. Images must have a minimum resolution of 1 pixel per mm. Images must be properly focused. Image pixels must represent areas of constant and consistent size over whole bridge (or over elements of bridge).

System aspect	Requirements
	Image display system used by inspectors to complete inspection must display aligned images with no gaps between images, or duplications of imaged features. The image inspection system must allow the inspector to identify and record the location, type and severity of any defects, within the individual image, and within the context of the bridge as a whole, to within 0.5m of actual position on bridge. Image views must be consistent enough that year on year comparisons can be made in the certainty that any apparent changes are genuine and not merely a result of different imaging conditions.

Table 13: Practicality issues which must be considered if IBIS is to be adopted by bridge inspection community

System aspect	Recommendations
Time	Time on site should be minimised – c.f. average of 30-60 minutes for a GI. Time to process data ready for inspection should be minimised.
Ease of use / required expertise	There are two possible approaches to the complexity of the system and the required expertise of the operator. One way would be to outsource the collection of inspection data to specialised contractors who collect and process data and supply results, which could be either images and data ready for an inspection, or a full inspection report. This approach would allow the system to be quite complex and require a high degree of training for the operators. The alternative approach would be for a system which was much more simple and straightforward to operate, which would reduce the required expertise of the system operator, and hence reduce the cost of the survey. Such a system

System aspect	Recommendations
	may require no more than a couple of days training.
Data processing	Data processing and alignment should be as automated as possible and require a minimum of human intervention at any stage. Data processing should be done in such a way that 'corrections' can be made to the output if any are needed.
Cost	System must not be significantly more expensive than a standard inspection and any increase in cost must be justifiable.
Suitability of images for further automation	The images must be suitable for use in an image-processing based automated inspection system.

7 EVALUATION OF SUITABILITY OF EXISTING TECHNOLOGIES FOR UNDERTAKING ROUTINE IBI

In this chapter a range of potential image collection and processing approaches are presented and assessed against the requirements presented in Chapter 6 to determine if there are any existing systems or system components which could undertake Image-Based Inspections with minimal further development.

Some of the systems discussed are potentially useful for the image collection tasks, while others could be used for processing and display. The assessment of the systems considers the collection and display separately. It was possible to undertake practical trials of a number of the systems, but due to time and resource restrictions it was not possible to do this for all systems. Therefore some of the assessment has been undertaken as a desk based exercise using whatever information was available.

7.1 Potential approaches for image collection

7.1.1 Hand-held camera

Description of method

The simplest and cheapest approach to collecting the images would be to simply use a standard digital camera and no other equipment. The person collecting the images could then follow a basic protocol to ensure that all surfaces were imaged, and the images could be organised and aligned back in the office.

7.1.1.1 Hand-held camera – system details and assessment

Figure 50 presents a series of images collected using a hand-held camera. These were taken by simply walking around the structure and photographing each face at progressively closer distances, with specific defects and features being photographed from close range.

Figure 50: A selection of images of a bridge taken with a hand-held camera with only guidance provided to operator to ensure full coverage.

Each image shows a portion of the surface of the bridge, but viewed as a series of individual images, they are hard to interpret. Inspectors found it hard to keep track of where they were looking at on the bridge, and the changes in viewing angle and the size of the area imaged made it hard to determine the scale of feature seen, or how it compared to other features elsewhere on the bridge.

Advantages of method

- Requires no special training or equipment;
- Image collection could take place very quickly;
- Image collection can be nimble and agile and overcome obstacles to obtaining images of hard to reach elements;
- Duration of the site visit could be kept to a minimum.

Problems with method

- Hard to keep track of which part of the bridge is being viewed, particularly when looking at close up views;
- Hard to determine level of detail presented without features within each image to provide scale or context;
- The viewing angle, and the area within the field of view, changes from image to image;
- Hard to ensure full coverage of the bridge;
- Hard to ensure images collected at adequate resolution.

Additionally, aligning and displaying the images correctly would be difficult with no information about where each image was collected from. It is true that software exists (for example Photosynth – see Section 7.2) which can use information contained within the images to identify common features and back-calculate the image collection positions, and even calculate the 3-D shape of the imaged objects or sense. However these rely on the presence of sufficient, unambiguous, distinct features within the images which can be used in the processing calculations. This is discussed further in Section 7.2.

7.1.2 Tripod mounted camera

Description of method

Systems which fit in this category include basic cameras mounted on tripods which must be manually controlled, and which collect images when instructed (ScanSites: 7.1.2.1), automated pan-tilt units which calculate the required camera orientations and control the image collection (GigaPan: 7.1.2.2), and laser scanners synchronised with cameras which produce detailed 3-D point clouds of the scene (7.1.2.3), and can combine these with image data.

7.1.2.1 ScanSites CR – system details and assessment

The French company Sites has produced a camera based inspection system called ScanSites (Sites, 2010) which has been developed to inspect large structures such as dams, cooling towers, etc. The aim of the system is to detect, identify and map defects. A simpler version of the system, ScanSites CloseRange (or ScanSites CR) has been developed for inspecting smaller structures, such as the type of bridge common on the UK network.

The system (shown in Figure 51) comprises a camera mounted on a tripod, controlled by an operator. The operator is able to move the camera orientation to provide views of the structure. During the inspection an inspector monitors the camera view on a screen and uses their judgement to identify any defects present. When a defect is spotted the operator can record the type, position and extent of the defect using the system software, and can record images showing the defect. These images are stored in a database with details of the defect.

ScanSites undertook surveys and inspections on a number of bridges in the UK as part of a demonstration for this research.

Figure 51: ScanSites CloseRange system showing operators, tripod mounted camera and mounting, and laptop display used to control system and view images.

Images are only recorded when the inspector deems it necessary, therefore no full image record is taken of the structure. Also, the movement of the camera is controlled manually, and there is no way of guaranteeing that all parts of the structure are covered. If the inspector moves the camera too far there may be uninspected areas. Similarly if the inspector either fails to see, or fails to record a defect, then that defect will remain unreported and unrecorded with no way of reassessing the images to determine whether or not it is of concern. It is important therefore that the inspector involved in collecting the data is competent.

Figure 52 shows a selection of images of bridge defects taken using the ScanSites CR system (left) along with images taken at resolution of 1 pixel per mm using a more traditional camera.

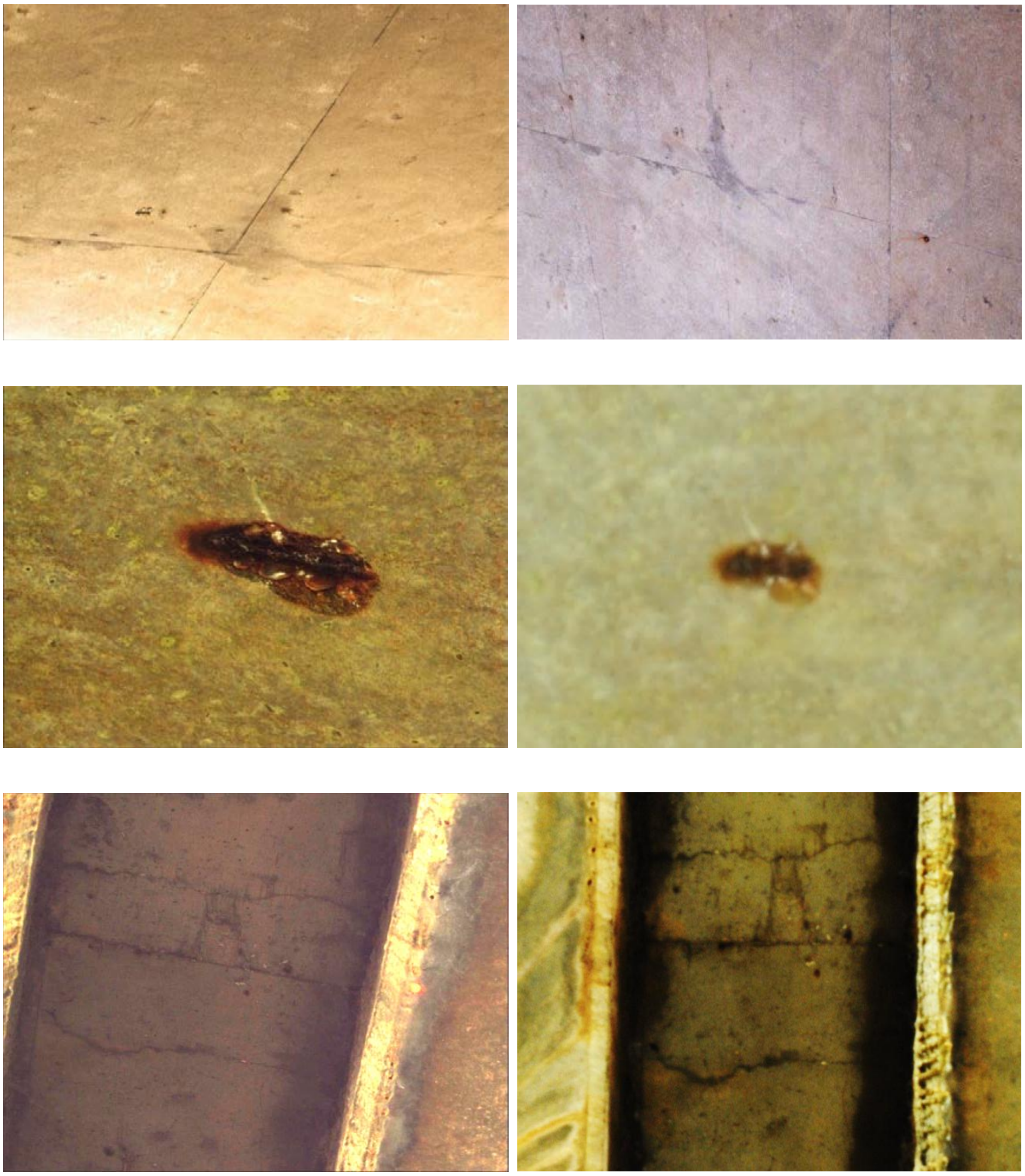


Figure 52: Example images taken using the ScanSites CR system (left) and traditionally collected images at 1 pixel per mm of the same locations.

The same features can be identified in the images seen in Figure 52 provided by the ScanSites system, and the traditional camera. The ScanSites images, particularly the one of the rust staining, are better quality and show more detail than the images at 1 pixel per mm.

Benefits of method

- Can use long lens – enables inspection from far away, or high levels of detail;
- System orientation recorded for each image enabling location of defects on structure to be mapped;
- Can see detail on large structures that would otherwise require special access;
- Produces image record of detected defects;
- Maps defects to structure;
- Can produce automated quantified reports of what defects are present.

Problems with method

- Image record only partial – restricted to images deemed worthy of recording by onsite inspector;
- Relies on subjective assessments on site to record;
- No way of knowing if whole structure has been inspected.

The system is effectively an excellent way of providing the inspector with an improved view of a structure which would otherwise be difficult to inspect without specialist access equipment. However the system does not provide a full record of the condition of the bridge for later interpretation or analysis, and the decision on whether any part of the bridge is affected by defects, and when to record images is purely down to the inspector onsite.

The system is undoubtedly useful for inspecting the types of structures for which it has been designed, and could be used as part of a bridge inspection regime, particularly on hard to inspect bridges, or parts of bridges, but it is not suitable for routine use on the majority of bridges on UK highways.

7.1.2.2 GigaPan Epic – system details and assessment

Carnegie Mellon University and NASA have developed the GigaPan system (GigaPan, 2009). This includes a robotic camera mount (several different models are available) which controls and adjusts the camera orientation, and triggers the collection of images, and software which stitches the individual images together into a single high resolution, gigapixel image. A GigaPan Epic was tested in this research, and was combined with a Nikon D30 camera to collect images of a number of UK bridges.

The GigaPan Epic robotic mount consists of a camera mounting plate, a control panel and electronics, two motors to control vertical and horizontal rotation of the camera, and a robotic 'finger' which presses the camera shutter button (Figure 53).

Figure 53: GigaPan Epic, with camera attached.

The system takes a few minutes to set up for each camera/lens combination, to ensure that the field of view of the images is known, in order to calculate the amount by which the camera orientation must change between images to produce a series of images with adequate overlap. The camera orientation for each individual image is not directly recorded, but it is possible to estimate this later using outputs from the stitching and processing software. Unfortunately this does not always produce accurate results (discussed later in Section 7.2.1).

The system is powered by AA batteries which are convenient and easy to obtain. However, the system drains the batteries fast, particularly when carrying heavier loads. As the batteries drain the capability of the system to move to the correct location and hold the camera steady is diminished. Additionally replacing the batteries is difficult to do without moving the camera position and orientation, meaning that image collection must often be disrupted and restarted when battery changes are required.

Benefits of method

- Quicker than manual movement of tripod based camera;
- More systematic and methodical than manually moving camera on tripod;
- More systematic and methodical than hand held camera – easier to guarantee full coverage;
- Repeatable – can repeat surveys with same system settings and record same images;
- Produces ordered image set where relationship of images to neighbours is known;
- Can estimate bearings and elevations of individual images (reliant on stitching software producing suitable output - Section 7.2.1);

- Requires little training or expertise to set up and use.

Problems with method

- Cannot adjust image parameters individually;
- Motors relatively weak and suffer from slippage – this results in the actual system orientation differing from assumed orientation;
- System is powered by AA batteries, and requires frequent changes of these;
- Establishing accurate bearing and elevation for each image relies on outputs from stitching software (Section 7.2.1). These outputs are not consistent from imageset to imageset, introducing uncertainties in camera orientation information.

The effective payload of the GigaPan Epic was limited by the relatively weak motors used to control the orientation of the camera. This meant that the system was not quite robust enough to be used in the IBIS. However, the principles of systematic image collection combined with automated camera orientation and triggering were found to align very well with the requirements of the IBIS as established in Chapter 6. Such capabilities were therefore important in the development of the IBIS (Chapter 8).

7.1.2.3 Riegl LMS-Z360i – system details and assessment

TRL own and operate a Riegl LMS-Z360i laser scanner (Figure 54). This system is predominantly used to collect data at collision incidents. The system can create 3-D models from the point cloud data it records.

Figure 54: Riegl LMS-Z360i laser scanner as operated by TRL.

The system uses a Class 1 laser, meaning no traffic management or closures are required, and has a quoted measurement range of approximately 200m with an accuracy of ±12mm. Experience within TRL suggests that it is possible to achieve higher accuracies by combining multiple scans at a single location.

To obtain the vertical scan the scanner utilises a rotating mirror with a range of 0° to 90°, a minimum angle step of 0.01°, and an angular resolution of 0.002°. The horizontal scan uses a rotating optical head with a range of 0° to 360°, a minimum angle step of 0.01°, and an angular resolution of 0.0025°. The actual resolution and extent of the scan can be adjusted within the control software. The user can increase the resolution of the scan and improve the output without negatively affecting the file size by confining the scanner to a small area. Additionally, the data can be post-processed to reduce the scan resolution and the size of the output datafile.

The system includes a Nikon D100 camera with a fisheye lens. A number of images are taken during a scan (currently seven photographs for a full 360° scan rotation) which are stitched together and overlaid onto the data points providing colour for each point.

As part of a demonstration of the system capabilities undertaken for this research images and laser shape data were recorded on a bridge local to TRL. This involved collecting data from five separate locations around the bridge. The image on the left of Figure 55 shows data recorded from a single position. The image on the right shows data from the highlighted area following the removal of unnecessary data. This process of data removal is known as ‘cleaning’.

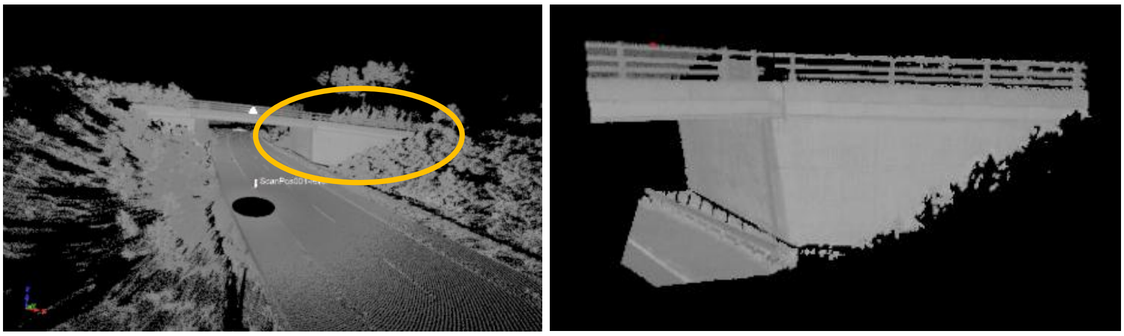


Figure 55: Full data collected using scanner at Scan position 1 (left) and following cleaning process to remove extraneous data (right).

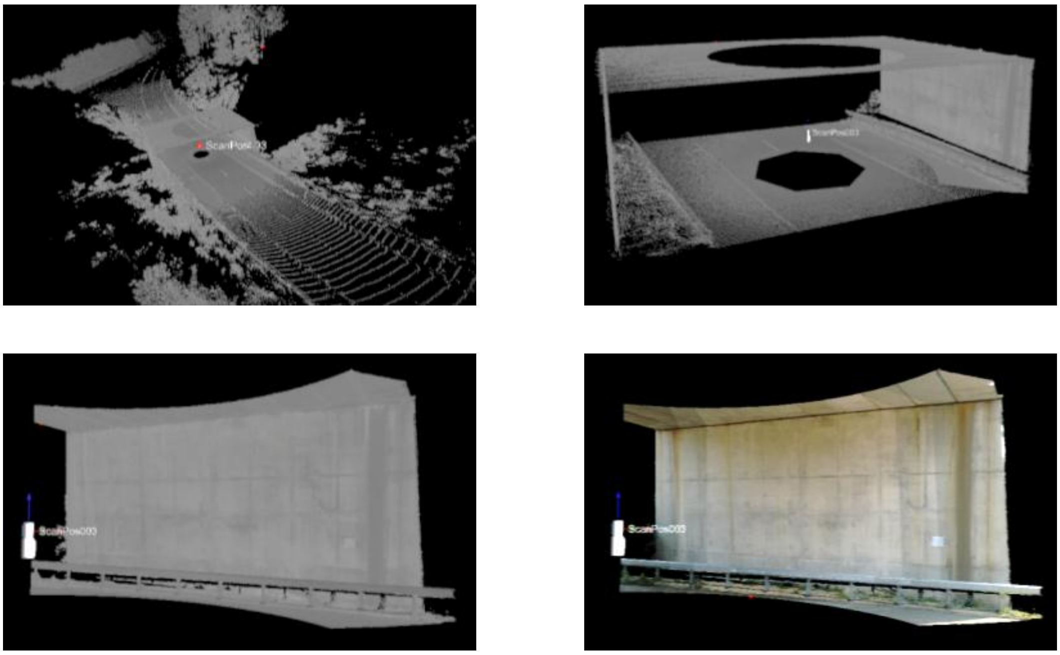


Figure 56: The scan data obtained from a single position in different stages of post-processing. Scan position was directly under the bridge approximately in the centre of the road.

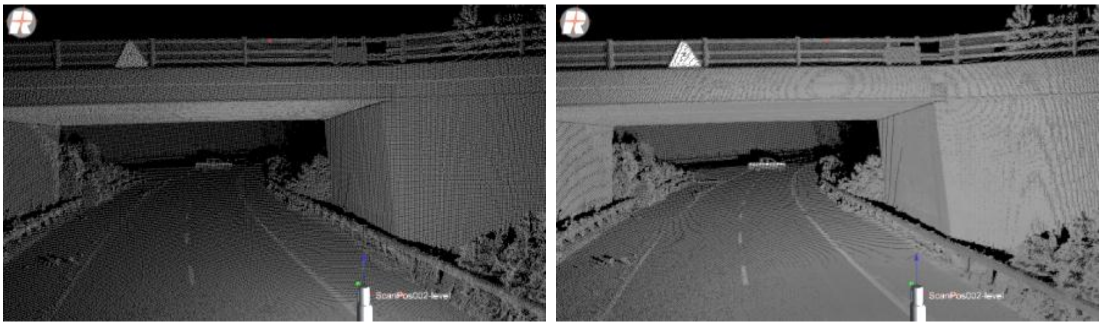
Figure 56 above shows the data from a single scan. Each of the images shows a different stage of the post-processing (full data (top left); cleaned data (top right); focusing on abutment (lower left); colour information added (lower right)). At each scan location, scans of different resolutions were performed. Changing the resolution of the scan changes the time taken to record the data and the quality of the outputs, as shown below in Table 14.

Note: not all scans included the same area of the real world: the scans at 0.1^{o} and 0.2^{o} were full 360^{o} scans (although only part of the data from these scans is shown below in Figure 57); the scan at 0.035^{o} was a scan of one of the wingwalls; the scan at 0.01^{o} was of an area of abutment approximately 1.6m x 1.5m in extent.

Table 14: Effect of changes in scan resolution on time and data produced

Resolution setting	Number of points	Time to scan	Data shown in…
0.2^{o}	810000	90 seconds	Figure 57 (left)
0.1^{o}	3240000	6 minutes	Figure 57 (right)
0.035^{o}	3183404	11 minutes, 29 seconds	Figure 58
0.01^{o}	6269575	12 minutes, 20 seconds	Figure 59

The difference in the density of the point count can be clearly seen in the definition of the data (Figure 57).



0.2° resolution 0.1° resolution

Figure 57: Comparison of two different resolutions of scan data, from scan position 2.

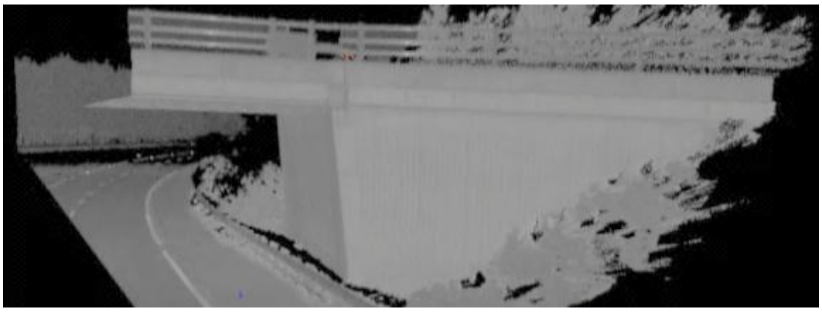


Figure 58: Scan of a section of the bridge from scan position 2 and a resolution of 0.035°.

Figure 59: High resolution scan at scan position 5 of a section of abutment.

The target sheet visible in Figure 59 was fixed to the abutment to help gauge the scanners ability to record detailed features. In addition to the A4 sheet, a 30cm ruler was also attached to the abutment. The image on the left of Figure 60 shows an enlarged view of the target as recorded, the image on the right shows the same target imaged with a normal camera at a resolution of 1mm per pixel.

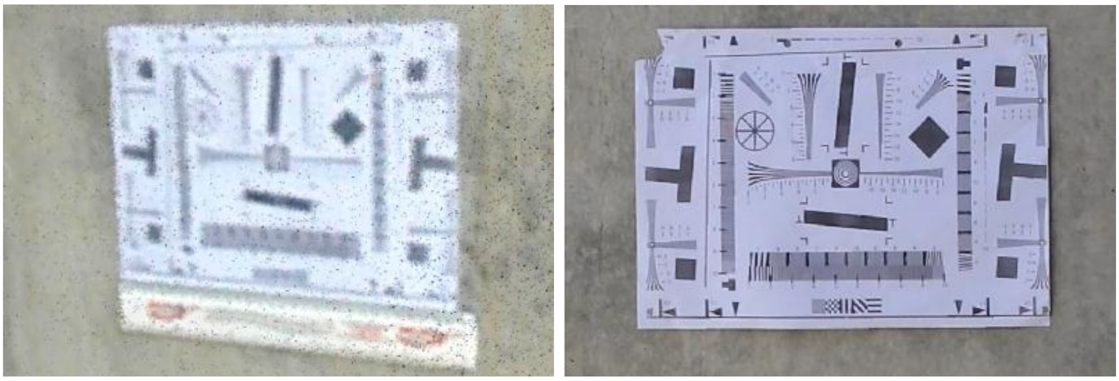


Figure 60: Enlarged view of the high resolution scan data for the target fixed to the abutment (left), and image showing same target at 1mm per pixel.

As can be seen in Figure 60, the resolution in the Riegl system image is not as clear as the 'normal' image. Given that the system uses seven images taken with a 6 megapixel Nikon D100 camera (3000 x 2008 pixel sensor) to provide image data for a full 360^{o} scan, it is no surprise that there is inadequate detail in the images to enable the detection of small features. This level of data would be inadequate for performing an image based inspection.

Benefits of method

- The scanner can be used (from a safe location) without requiring any road closures, while traffic is flowing;
- Can collect a large amount of data from a single position;
- Can combine data from multiple scans and multiple positions to produce 3-D models;

- Can combine 3-D shape data with colour data from integrated camera to produce more photo-realistic models.

Problems with method

- The resolution of the data produced by the scanner (both image and shape data) is not adequate for measuring the widths of smaller crack or distortions in a structure;
- The system requires a long time to collect data at higher densities and resolutions;
- Processing the data to produce potentially useful models, with extraneous features removed, and data from multiple scans merged is a complex, time-consuming and skilled operation that requires expertise and training.

It must of course be noted that this application (producing high resolution data which enables image-based inspections of bridges to be performed) is not what the Riegl system has been designed for. It can produce very impressive models for visualisation, reconstruction and simulation of scenes, and for these purposes the images can be suitably and acceptably photorealistic. However, when images are required which enable fine details to be detected, the system does not provide adequate levels of detail.

If the system was reconfigured with higher density point cloud data, and improved camera and lens combinations then it could be possible to obtain the required levels of detail. However, the cost of the system, and specialised skills required to operate it, and process the data would make such a system more suitable for specific site investigations on bridges already known to need investigation, rather than use as a routine inspection tool for a bridge network.

7.1.3 Boom mounted

Description of method

The camera would be mounted on the end of a boom, or remotely controlled arm which would manoeuvre under the bridge, enabling the camera to get close to the underside of the bridge.

Such a system could not be operated without requiring a closure or traffic management, disrupting traffic considerably more than a traditional GI. This makes it unsuitable for a routine visual inspection tool as defined in Chapter 6. Therefore these systems were not considered for further investigation or development as a routine visual inspection tool.

Benefits of method

- The camera can be positioned close to many parts of the bridge which would otherwise be difficult to inspect;
- This is particularly true for large bridges which are high above the ground, or over water;
- The orientation and position of the camera can be recorded for each image which will help in the alignment and processing of the images.

Problems with method

- Unless the camera movement is automated then the image collection relies on the operator positioning and orienting the camera manually using a display screen to monitor the view, as with ScanSites;
- This process will be susceptible to human error making it hard to guarantee the complete coverage of the whole bridge;
- While the system will enable good close views of the underside of the bridge deck, other parts of the bridge may be harder to access using a boom;

- The system will require a closure or traffic management in order to operate and will cause significant disruption to traffic.

7.1.4 Vehicle mounted

Description of method

Information collected by vehicle mounted systems, such as those described in Section 4.3.4, helps monitor pavement condition. This information is collected at traffic speed and typically consists of laser measurements of shape, geometry and texture, and images used to identify pavement surface defects. If a similar approach could be used to collect data on bridges this would be a potentially efficient method for collecting inspection data. To achieve this the camera could be mounted on a vehicle which would travel under and/or around the bridge, collecting images whilst travelling. The vehicle could be either a wheeled vehicle such as a car or van (DIFCAM: 7.1.4.1), or an aerial platform such as a UAV (Aerial drone: 7.1.4.2).

7.1.4.1 DIFCAM – system details and assessment

The DIFCAM (Digital Imaging for Condition Asset Monitoring) system has been developed by a consortium involving NPL, Omnicom and Atkins (NPL, 2013). The system combines images from 11 individual 24 megapixel cameras and a rotating laser scanner. These instruments are mounted, together with powerful flash illumination on top of a vehicle fitted with location measurement systems. DIFCAM was designed to collect condition data on rail tunnels, and detect changes in tunnel condition by comparing data from different inspections. The vehicle on which the system was mounted was a road-rail vehicle, which could operate on railway tracks.

It was not possible to undertake a practical assessment of the capabilities of the DIFCAM, or to look in detail at the images or results obtained. The assessment presented here is based on information obtained in the available literature ((http://projects.npl.co.uk/difcam), (McCormick, et al., 2013)), and in conversation with the lead system developer (McCormick, 2014).

The system aimed to eliminate some of the problems affecting traditional inspections, specifically to reduce the exposure of inspectors on track, and to tackle some of the subjectivity inherent in visual inspections. DIFCAM combines the image and laser data, along with information about the vehicle movement to produce high resolution 3-D models of the tunnel, which can be aligned and compared with previous inspection results. Although designed for rail tunnels, the system could be adapted for use on other asset types where traditional inspections are problematic or dangerous. The system has been demonstrated to successfully record data at speeds of approximately 1 ms^{-1}, and provides images with each pixel representing areas <=1mm.

Benefits of method

- Collecting images from a moving platform speeds up the collection process considerably;
- Raises the possibility of potentially mounting the image collection kit on existing survey vehicles making the collection of bridge images as routine as it is on pavements;
- Enables comparison of inspection data from survey to survey;
- Provides a full image and 3-D record of the internal surfaces of a tunnel;
- Safer for inspectors;
- Quantitative, objective measurements of defect size and extent possible.

Problems with method

- Movement path of vehicle, and speeds of 1 ms^{-1} would disrupt normal flow of traffic and require traffic management or closures;
- It would be much more difficult to maintain focus at speed on different parts of a bridge, which would be at different distances from the camera;
- Survey methodology currently requires the vehicle to run on rails to ensure it follows a consistent path through tunnel – this restricts current system to use in rail environment only;
- The way in which the data is collected (radially outwards along the line of travel) means that whilst the internal surfaces of a tunnel can be well surveyed, surfaces which are perpendicular to the direction of travel, such as parapets, wingwalls, etc. would not be surveyed.

Although the system collects data at approximately 1ms^{-1}, which is faster than a traditional GI, the data collection methodology requires that the vehicle moves under the bridge or tunnel in such a way as to interrupt the normal flow of traffic. The system would therefore require a closure or traffic management in order to operate. The system is therefore not yet suitable for routine visual inspection on UK highways bridges.

7.1.4.2 Aerial drone – system details and assessment

LCPC (now IFSTTAR) in France have developed an inspection system mounted on a radio-controlled drone, or an Unmanned Aerial Vehicle (UAV). The drone has been equipped with various systems to help provide a more stable platform for the inspection system. The system was developed for use on large, hard to survey structures, but can be used on any structure where access is feasible.

The system is based on the use of a radio-controlled helicopter, as shown in Figure 61. The helicopter is two metres long, and has a rotor diameter of 1.8m. The helicopter can fly at speeds of up to $10ms^{-1}$, for up to an hour.

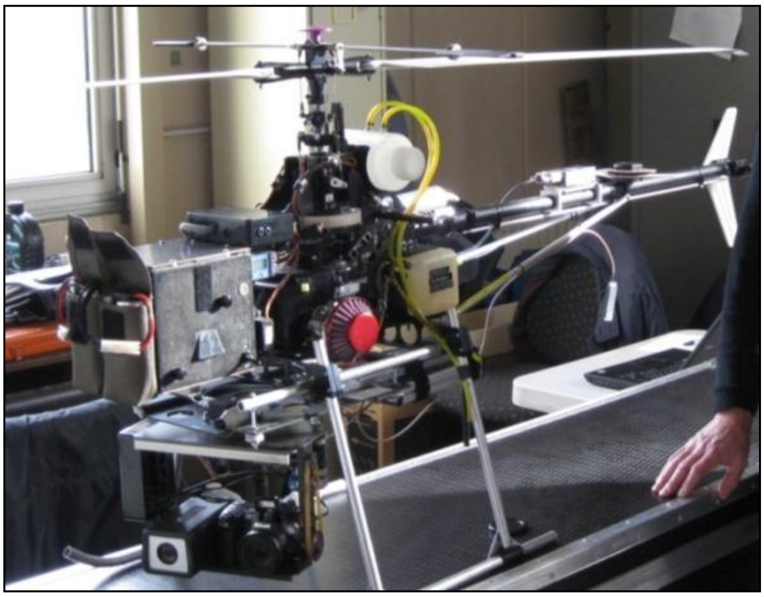


Figure 61: LCPC drone.

The helicopter carries a number of cameras to enable the inspection to take place. These include a drone camera, which provides an overall view of the drone surroundings, an inspection camera, which provides a continuous stream of video (0.8 megapixels) and can be oriented independently of the helicopter, and a still camera (currently an 8 megapixel Nikon Coolpix 8700) which can be controlled remotely. Both the still camera and the video stream are located in a gyrostabilised turret mounted under the control unit (Figure 62). The drone can be fitted with a laser distance measurement unit, and/or radar to determine the platform's range from the structure being surveyed.

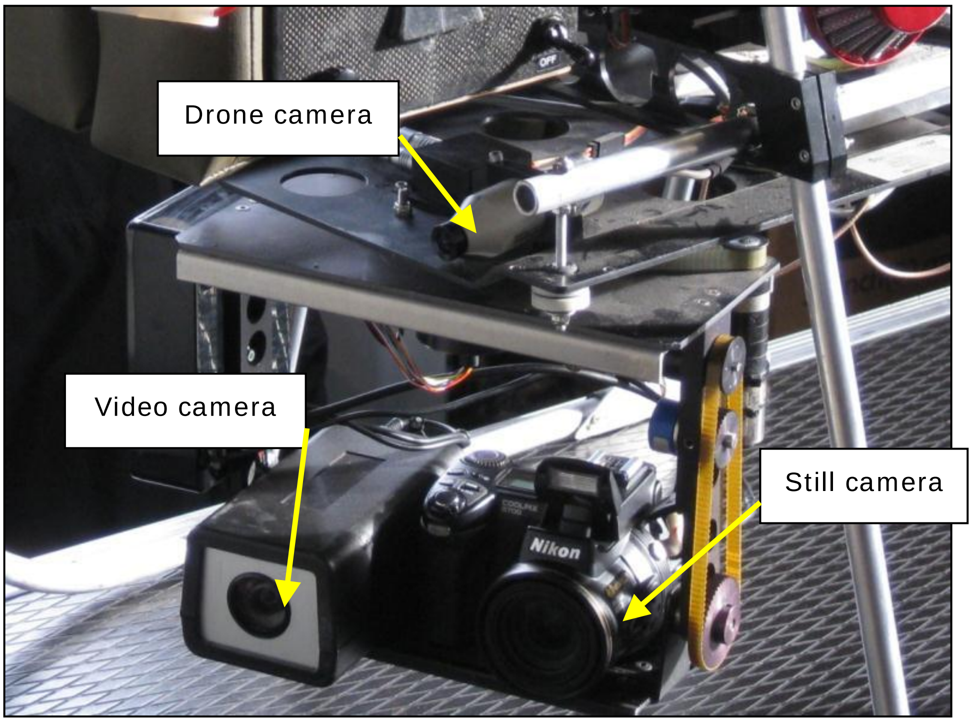


Figure 62: Inspection camera and still camera mounted on gyrostabilised turret.

The system is controlled from a suitcase control system, and a laptop, as shown in Figure 63, and can be flown in three modes:

- Manual control;
- Assisted control;
- Fully automatic.

Figure 63: Control station for system.

Flying the drone manually requires high levels of expertise, however the assisted control mode allows the system to translate simple commands of 'up', 'down', 'left', 'right', etc. into full control commands for the flight systems. This can be done with relatively little training. Flight in the fully automatic mode relies on the production of a flight plan which uses GPS data to store the positions and flight routes of the drone. Using an aerial imaging system means that views of structures can be obtained which would otherwise be impossible, or very difficult to get, and which would require specialist access arrangements and equipment.

The system requires an experienced engineer/inspector to watch the video to determine the condition of the structure, and where still images should be recorded. This decision making process is fully manual. The movement of the platform can make it hard to focus correctly, degrading the quality of recorded images.

The system has a number of limitations relating to where it can and cannot fly. For example it cannot fly over roads carrying live traffic; cannot fly near power cables; requires line-of-sight to control; cannot fly near airports; requires good GPS in fully automated mode; cannot fly under structures without manual control; cannot fly closer than 8-10m to a structure for safety reasons; cannot fly in winds of more than $10ms^{-1}$, or in gusty conditions.

Benefits of method

- Views which would be otherwise impossible are achievable;
- Can work on large structures where access is difficult or dangerous;
- Provides video record of survey (but at low resolution).

Problems with method

- Requires inspector to view images and decide what to take images of and what to view further;

- Only records images when requested;
- Produces a partial image record;
- Image focus can be poor due to platform movement;
- Regulations restrict where system can fly;
- Practical issues restrict where and when platform can fly;
- Risk of system failure and crashing means that in order to operate near roads, closures would be required to ensure traffic would not be involved in any collisions with the platform.

The use of UAV mounted inspection systems may be worthwhile on certain structures, particularly large ones where inspection must take place at height, or in other potentially hazardous environments. 'UAV inspections', or inspections based on images collected using UAVs have already been undertaken successfully in the UK. For example, Historic Scotland used this approach to inspect Stirling Bridge (BBC, 2011). This inspection was a special inspection, following up on issues uncovered during a GI.

However the restrictions on where and when such systems can fly, coupled with the partial image record and requirement for an inspector to inspect the structure via a video screen onsite means that such systems are not suitable for routine visual inspections on UK highway bridges. Nonetheless, the recent and ongoing growth in the proliferation of UAVs, and the advances in UAV technology, has brought these platforms much more into the limelight. UAVs have now moved from being essentially a niche, specialist, and expensive approach, to being mainstream hobby devices. Consequently the legislation regarding who can fly them, where and for what purposes are likely to change in the future as the regulatory bodies try to adapt and amend legislation which was never intended to cope with the availability and ease of use of such devices.

7.1.5 *Summary of image collection systems against IBIS requirements*

Table 16 shows a summary of how the image collection systems assessed meet, or do not meet, the requirements stated in Chapter 6. Due to space constraints some of the entries in Table 16 are explained in further detail in Table 15.

Table 15: Key to terminology in Table 16

Table text	Meaning
Yes	Have demonstrated capability to meet this requirement.
Usually	Have demonstrated capability to meet this requirement, but exceptions can occur resulting in failure.
Likely	Have not demonstrated capability to meet requirement, but expectation is that it should meet requirement, with little extra development.
Possibly	Have not demonstrated capability to meet requirement, but no theoretical reason has been found to indicate it cannot be done.
Unlikely	Current knowledge and theory suggests system cannot meet requirement using existing approach without significant development.
No	Have demonstrated inability to meet this requirement.

Table 16: Summary of system performance against system requirements

Requirement	Hand–held	Manual tripod	Automatic tripod	Vehicle mounted
Example of system	Camera	ScanSites CR	GigaPan Epic; Riegl	DIFCAM; Drones
No traffic management or special access arrangements needed?	Yes	Yes	Yes	Unlikely
No disruption or distraction to traffic?	Yes	Yes	Yes	Unlikely
Safe for operators and public?	Yes	Yes	Yes	Yes
Record images of all visible parts of structure?	Yes	Usually	Yes	Usually
Applicable on different bridge types and designs?	Yes	Yes	Yes	Yes
Delivers full image record?	Yes	Usually	Yes	Yes
Provides clear and consistent views of all bridge?	Usually	Yes	Yes	Yes

Images well lit?	Usually	Usually	Usually	Usually
Images of suitable resolution?	No	Yes	Yes	No
Images properly focused?	Yes	Yes	Yes	Yes
Image resolution and pixel size constant for whole bridge?	No	No	No	No
Images accurately located within 0.5m of actual position?	Likely	Yes	Usually	Yes
Image views consistent year on year?	No	Yes	Yes	No
Image display with no gaps in image record?	Usually	Usually	Yes	Possibly
Image display with no duplication of image features?	No	Possibly	Usually	Likely
Image display system enables recording of position, type and severity of defects?	No	No	No	No

7.2 Potential approaches for image processing and display

There are a great variety of software tools and techniques available which can be used to process and align images and present them as 2-D panoramic scenes, or create full 3-D models from the image data. A full review of the capabilities and methods used in such systems is outwith the scope of this thesis, but a few packages were selected based on a review of the basic techniques used, the availability of software, and the system cost and compatibility with available images and IT equipment. Use of an "off-the-shelf" software solution for the image processing and alignment requirements of the IBIS would provide substantial efficiencies in cost and time in the development of a working IBIS, although it would also offer less control and customisation of the functionality and customisation of the capabilities and working environment.

The systems assessed can be split into two main groups: those that produce a 2-D reconstruction of the images, or those that produce 3-D models of the data.

Techniques requiring the use of target objects to be placed in the scene, or which required detailed knowledge of the camera and lens calibration parameters were not used as such approaches would not be compatible with the goals of the IBI which require no special site preparation or modification prior to inspection.

7.2.1 Two-dimensional image stitching techniques

Description of method

This type of software attempts to take a series of images of a scene and merge them to produce a single output image. Examples of this include the GigaPan Stitcher software, and Microsoft ICE (Image Composite Editor). Figure 64 shows example of a series of images, and the resultant panoramic image produced using GigaPan Stitcher version 2.3.0307.

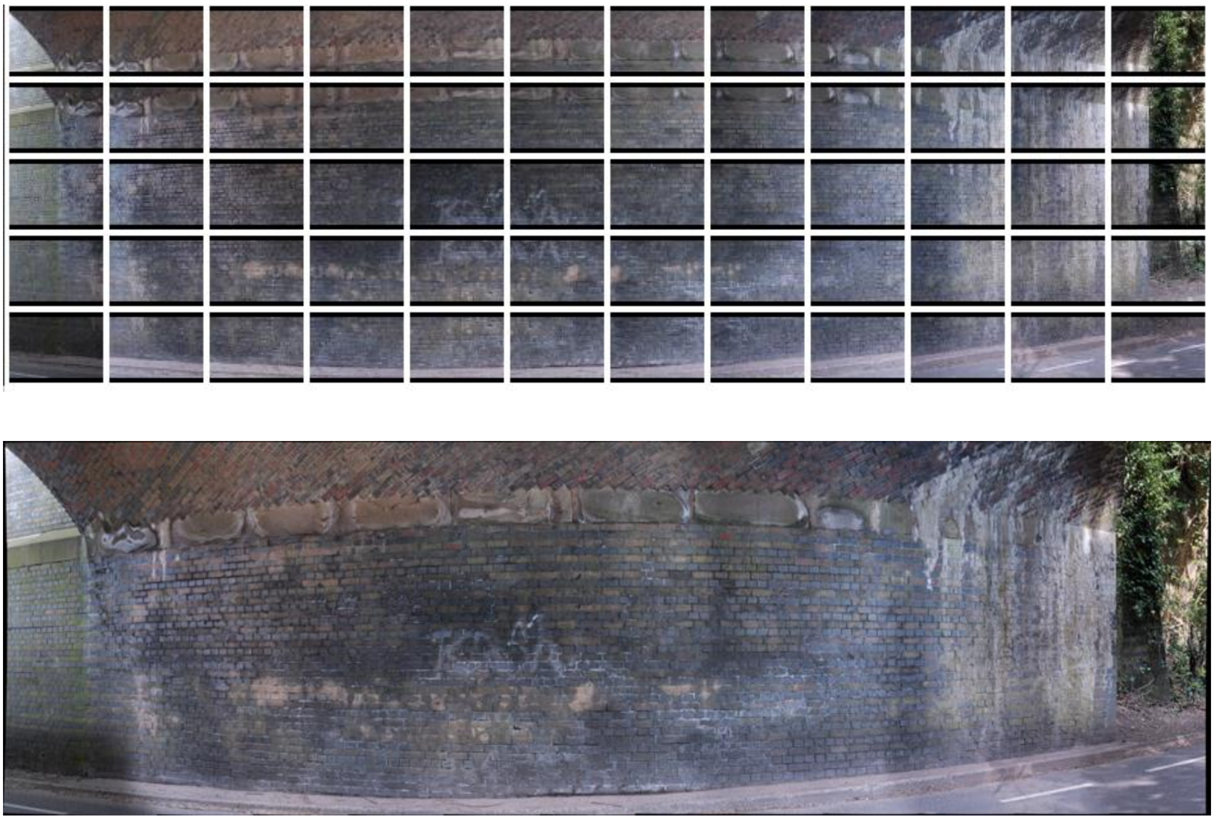


Figure 64: Display of 60 individual images and resulting panoramic display produced with GigaPan Stitcher.

The software works by defining features within images, and then identifying other images exhibiting similar feature patterns. The matching feature patterns are then aligned and the images blended to produce a single output image with no visible seams.

However, it can go wrong as illustrated in Figure 65 and Figure 66. Mis-stitching errors like these have a number of potential causes, such as the inability to detect enough identifiable and unambiguous features in a scene. This can be a result of there being too little (for example wide expanses of blank uniform concrete), or too much (for example repeating patterns as found on good condition masonry surfaces) information in the scene. In these cases the system can struggle to decide which instance of a feature matches another instance of the feature, and makes mis-stitching errors.

Figure 65: Panoramic image produced by GigaPan Stitcher, with close-ups highlighting mis-stitching of images (left), and showing actual appearance of surface (right).

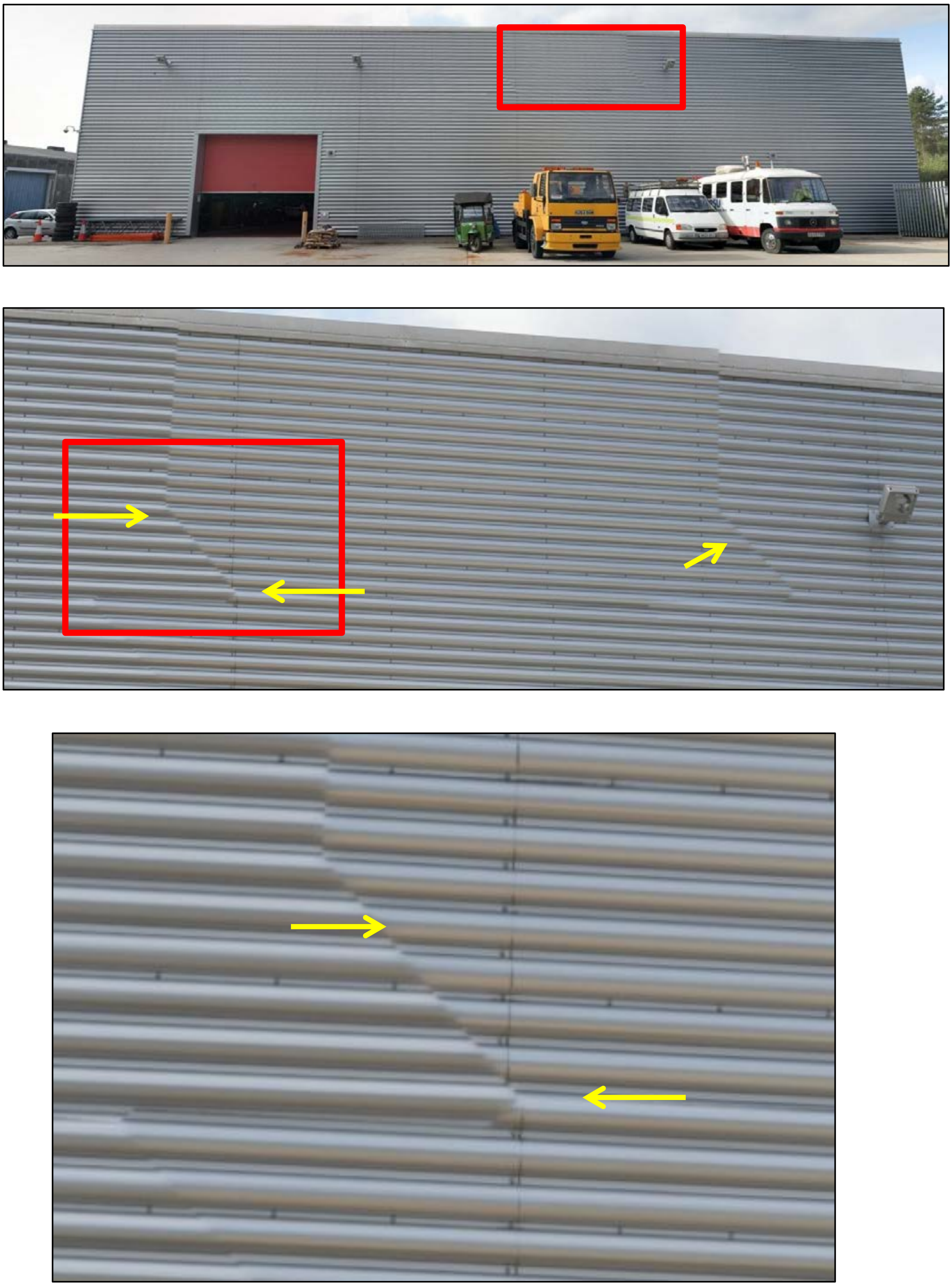


Figure 66: Panoramic image created using GigaPan Stitcher, showing mis-alignment of image features.

Mis-stitching errors such as those shown above can be hard to detect without carefully scrutinising output images, and even then, in the absence of identifiable features and obvious mistakes it can be hard to identify when things go wrong.

An extreme example of image mis-stitching was seen in an experiment conducted using imaging test targets such as shown in Figure 67.

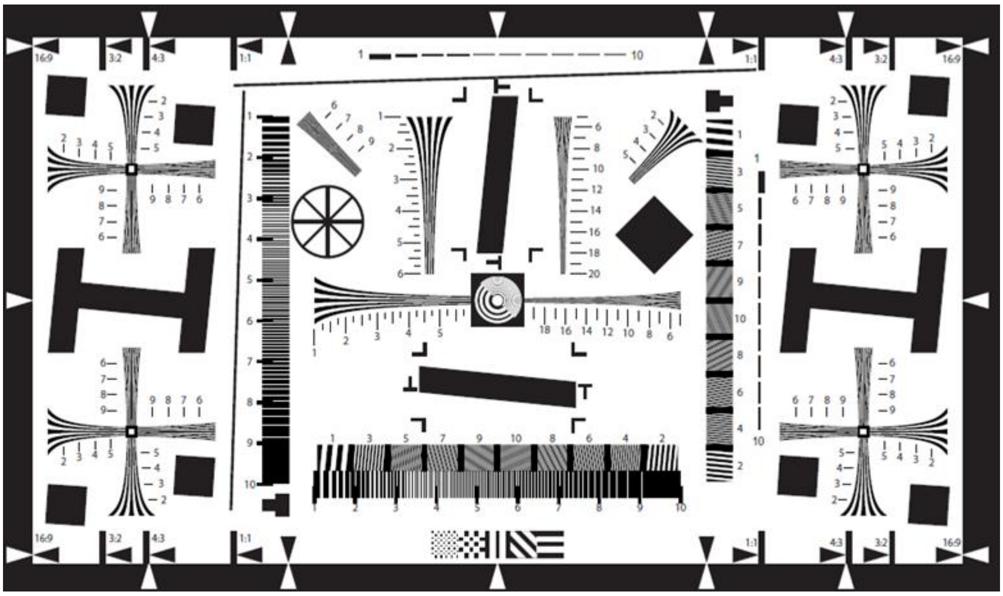


Figure 67: Example of test sheets used to assess automated image stitching capabilities.

Sixteen A4 sized targets were fixed to a wall and imaged using a Nikon D60 mounted on a GigaPan Epic. The individual images collected are shown in Figure 68.

Figure 68: Sixteen individual images of test targets used to test alignment.

Figure 69 shows the stitched image produced by GigaPan Stitcher, and also by Microsoft Image Composite Editor (ICE).

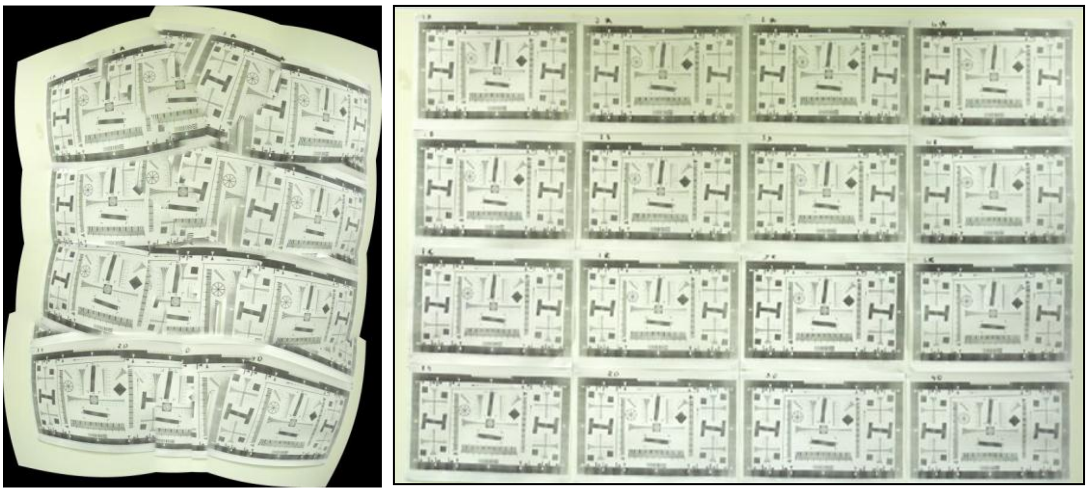


Figure 69: Result of stitching together 16 individual images of test targets using GigaPan Stitcher software (left) and Microsoft ICE.

Clearly the image shown on the left of Figure 69 is not an accurate representation of the scene, and demonstrates the unsuitability of GigaPan's Stitcher software for use on bridges containing many similar repeating patterns. There are, however, other software applications available for stitching images together, some of which, such as Microsoft's Image Composite Editor (ICE) (Microsoft, 2010) have less of a problem stitching images of repetitive patterns together (right of Figure 69).

Benefits of method

- Established technology;
- Cheap;
- No development costs or effort needed;
- Produce excellent results on suitable images.

Problems with method

- Systems have not been developed to cope with scenes in which almost all features match other features (masonry) or in which there are very few identifiable features (concrete);
- Auto-stitching can struggle with too many or too few features;
- No way of correcting or over-ruling mistakes.

Relying on third-party software, whether it is GigaPan, ICE, or another system, means that the image stitching and viewing will not be under the full control of the user, and if the system cannot deal with the images there will be no way of overcoming the problems. Additionally, the blending of the images may remove small detailed features such as cracks which the inspector would have been interested in. As the software was not designed for this application there is a high likelihood that they will fail to deal with the varying types of bridge image that they may be needed for. It therefore appears that the use of third party image stitching software is unlikely to provide the solution to the problem of displaying the bridge images.

7.2.2 Three-dimensional image-stitching techniques

Description of method

Using different, but similar approaches of identifying specific features in multiple images it is possible to calculate the 3-D shape of a scene. Such systems determine the 3-D location of the identified features, and use these to create point clouds of the scene, upon which they can display the rest of the image data, either as a full 3-D model, as can be achieved with software such as Autodesk 123D Catch® (Lo Brutto & Meli, 2012), or as a sort of 2.5-D model such as produced by Photosynth (http://www.photosynth.net/) in which the individual 2-D images are displayed having been aligned and oriented as if three-dimensional.

As part of the assessment of systems for potential use in routine visual inspections the capabilities of Photosynth were investigated. Photosynth is a web based system provided by Microsoft Live Labs. The application can create 2-D panoramas in a way similar to that described in Section 7.2.1, but can also produce more advanced pseudo-3-D reconstructions. These reconstructions are useful for displaying scenes where the images have been taken from different locations, showing different views of the scene. The system requires no special equipment, and there is no need for information about the camera settings, location, or orientation for any of the images. The system can use images from multiple sources in the creation of models.

The application looks for common features in the series of photographs, and uses these to generate a point cloud and 3-D model of the scene (Snavely, 2008). The system then aligns the images with the point cloud, and allows the user to navigate images in a way which gives a more interactive experience than simply clicking on an array of images side by side, or one after the other. The user can change viewpoint, or look round features as desired, as long as images are available and have been correctly aligned.

The Photosynth online documentation and help (http://photosynth.net/help.aspx) suggests that the feature matching algorithms may struggle when confronted with scenes containing too many or too few features. This means that Photosynth may struggle to accurately locate images of relatively blank surfaces, such as concrete, or highly patterned surfaces, such as a masonry structure, as was also seen with the 2-D processing software (Section 7.2.1).

To test the potential usefulness of the system a test was undertaken. A standard point and shoot digital camera was used to take 347 photos of a bridge following the advice on the Photosynth website, imaging out from the middle of the road under the bridge in a circle, then in from the edges of the bridge, then filling in gaps on the east and west approaches to the bridge. The image collection took approximately 45 minutes. The images were then supplied to the stitching software, which took several hours to process them and produce the output model.

Figure 70 shows some of the images presented within the Photosynth application. The images present progressively closer and more detailed images of the north east corner of the bridge, and within each display the main image can be seen, as can other images showing the same, or similar overlapping parts of the scene. Selecting these neighbouring images changes the display to focus on these images instead, and presents a new set of similar alternative images and views. This demonstrates how the images can be viewed and manipulated to see both contextual and detailed views of the structure. Figure 71 shows a plan view of the point cloud of the bridge, created using image pixel data alone.

Figure 70: Series of images, displayed in Photosynth browser window, moving progressively closer to part of east end of north abutment. Also shown is the point cloud of the bridge.

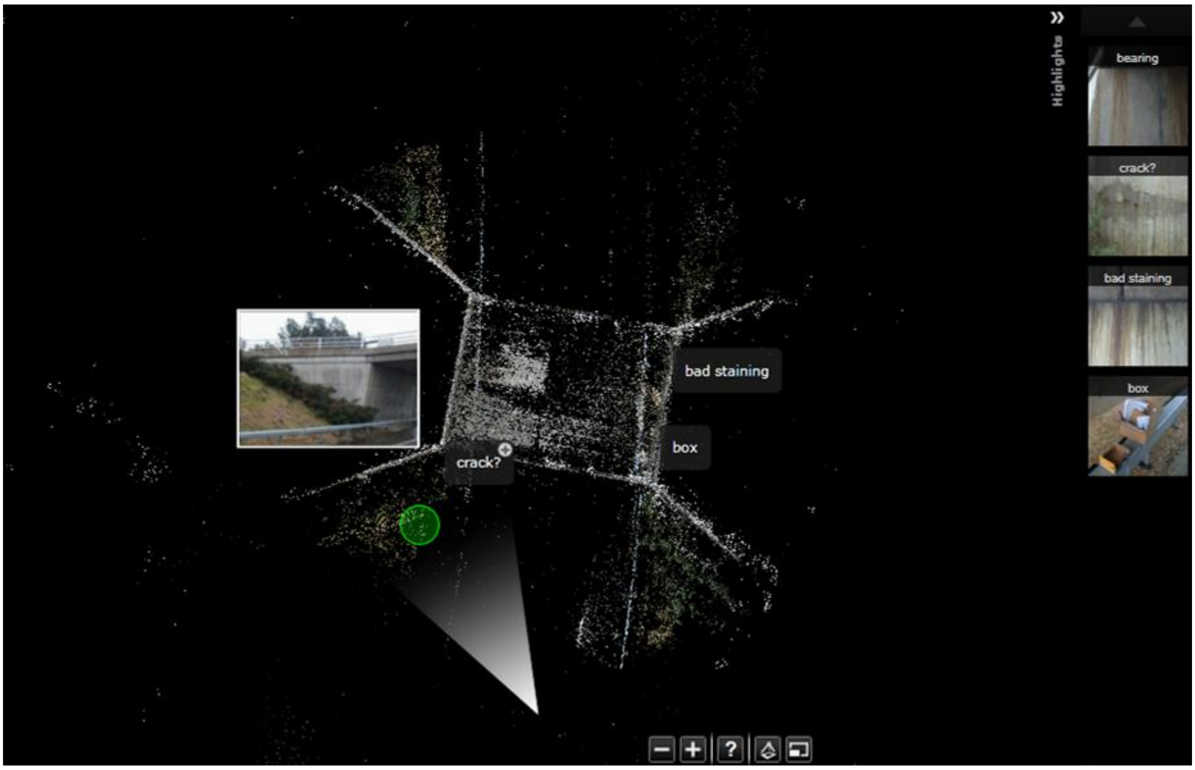


Figure 71: Point cloud of bridge showing a selection of 'highlight' views.

The green circle shows the location of the current image (which is displayed above the green circle). The white triangular shape shows the location from where the image was taken, and the field of view of the image. The smaller images shown on the right of the display show features which have been marked and labelled as 'highlights' by the inspector. These can be zoomed to by either clicking on the images, or by clicking on the point cloud tags.

Benefits of method

- The lack of requirement for information about camera position, or orientation means that such an approach would be compatible with free-form, unsystematic collection of images with normal cameras. This could be done as part of a standard GI;
- Interacting with the models (when they have been successfully created) enables inspectors to get a sense of being at the bridge;

- The system can incorporate images from multiple sources and cameras, and can provide more detail when necessary;
- Models are quite intuitive with very little practice (when successfully created).

Problems with method

- Struggles to create models if too many, or too few features in images;
- Mis-location of images can cause confusing effects and produce parts of the model which are hard to navigate;
- No way of correcting or over-ruling mistakes;
- Interface does not allow inspection results to be overlaid on the images or model, and producing inspection tools to work with 3-D models is not a trivial task.

Systems such as Photosynth can produce impressive visualisations of scenes, and where absolute accuracy is not required; these can be informative and help to mentally place a remote observer in a scene or location. However, they are susceptible to similar problems to the 2-D visualisation systems in that they can struggle to accurately and reliably locate images within their models, particularly when presented with too many, or insufficient features. It is also difficult to interact with the models and mark the locations of defects in quantitative and objective manners. It is felt that the benefits of the models produced are largely cosmetic and that adoption of such tools is, at the present time, unnecessary in routine visual inspection of bridges.

7.3 Evaluation of suitability of existing technologies for undertaking routine IBI Suitability of existing systems - Conclusions

None of the systems assessed are ready for use as off-the-shelf visual inspection tools for routine use on UK highways bridges to provide data comparable to that required in a GI.

Each of the systems had some clear benefits and features which could be useful, such as the levels of detail that could be obtained using ScanSites; the ease of use, and the systematic nature of the image collection of the GigaPan; the views obtained using UAVs; the combination of shape and image data of the Riegl; or the ease of production of 2-D panoramas offered by Microsoft ICE, or Photosynth.

However, each had significant drawbacks, making them unsuitable for use without modification. For example the GigaPan Epic cannot carry large weights, which restricts the detail it can provide on large bridges; ScanSites and UAVs do not provide full image records; automated image-stitching packages relying on identification of image features can go wrong when confronted with too many or insufficient features; the Riegl system provided inadequate detail for detecting fine defects of interest to engineers; DIFCAM would require causing disruption to traffic.

Consequently, in order to demonstrate that images can provide a viable source of information for inspectors, and that it is possible to collect and process such images routinely it is necessary to develop a prototype IBIS which will better meet the requirements outlined in Chapter 6.

8 IBIS DEVELOPMENT PROCESS

This chapter discusses the development of a prototype IBIS which was used to demonstrate the feasibility and practicality of the IBI concept, and demonstrate that images can provide a viable source of inspection data. The development built on the lessons learnt in the assessment of existing systems and considered data collection, processing, and presentation.

8.1 Brief outline of IBIS

The design of the IBIS, and the selection of appropriate hardware and techniques, is based on meeting the list of requirements noted in Table 12, Section 6.5.

The system is designed around the use of a tripod-mounted camera, which collects images from a number of Imaging Positions (IPs) situated around the bridge. These IPs are situated on verges or footways, meaning images can be collected without requiring roads to be closed. A series of images is collected at each IP. The process considers the bridge as a series of discrete elements or surfaces. For example, a simple bridge may be composed of two abutments, two wingwalls, two parapets, and a soffit.

In addition to the core IBIS hardware and data collection, images collected during pavement condition surveys using HARRIS2 were used where available to provide views of the pavement over the top of the bridge.

The images of each element are processed and displayed, and show the visual condition of the surface of the element at the time of collection. Inspectors can navigate the image display as appropriate, scanning for potential defects and zooming in to see detail where required, and can complete an inspection report in this way. Additionally, the inspector can mark locations on the images where defects are seen. This results in an automatically generated report showing the location and type of all defects on the bridge, as well as a quantitative breakdown of the area of the bridge affected by particular defects.

In line with the practical requirements of the system discussed in Chapter 6 the system was developed to require no permanent installations of markers or targets on or around the bridge, and also to operate without a flash or artificial illumination as far as possible. This is to avoid road closures or traffic distraction (a key requirement of the IBIS if it is to operate under similar conditions to traditional GIs).

8.2 Image collection

The core hardware of the IBIS is described in Section 8.2.1, followed by a description of the process and calculations involved in establishing which lenses to use, and where to site the system. A brief explanation of the role and collection of supplementary images, using pavement condition survey vehicles, is provided in Section 8.2.3.

8.2.1 Image collection hardware

The core IBIS collection hardware was developed to be simple to use, and require little training or expertise to operate. The key elements of the system hardware are illustrated in Figure 72.

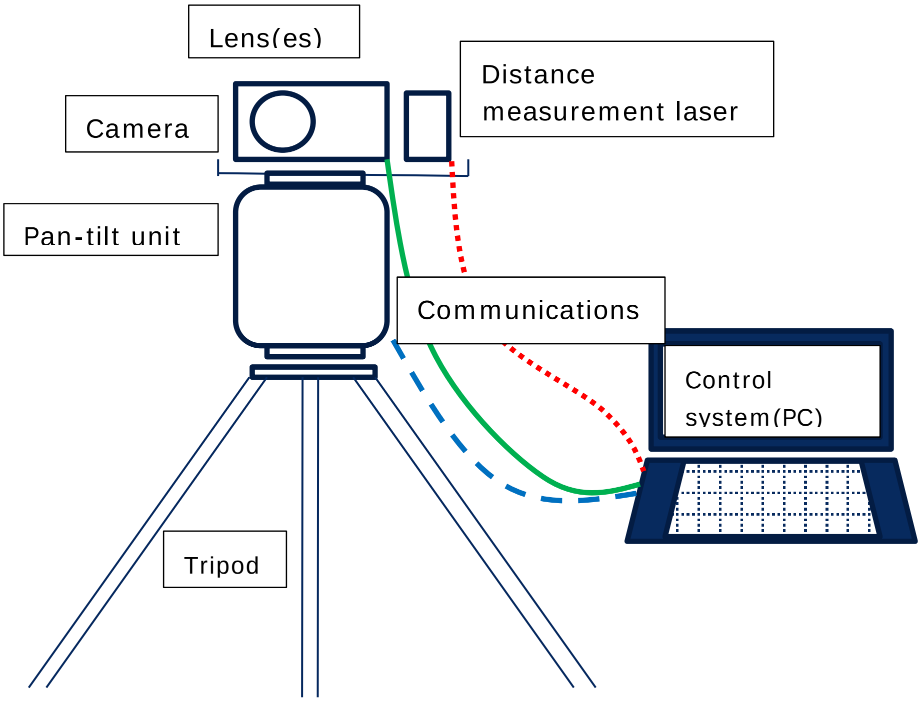


Figure 72: Schematic drawing of elements of system hardware.

8.2.1.1 Pan-tilt unit

One of the requirements for an IBIS identified in Chapter 6 was for the system to provide full image coverage, and for the images to be accurately located. A system which could be guaranteed to ensure the collection of images of the entire visible surface of a structure was required. This would have to control the camera position correctly to ensure that images were taken at the correct orientations.

Following some initial testing into the collection of images using a manual system it was recognised that an automated pan-tilt unit would be more efficient. Although there were definite limitations with some aspects of the GigaPan Epic system reviewed in Chapter 7, the automated camera positioning and systematic image collection functionality offered by the GigaPan Epic were identified as a basic starting point for the development of an IBIS which would meet the requirements identified in Chapter 6. Therefore, initial proof-of-concept testing of the IBIS and collection of the first sets of bridge images was performed using the GigaPan Epic, as shown in Figure 73.

Figure 73: Prototype image collection system showing camera mounted on GigaPan automated pan-tilt unit.

However, the GigaPan Epic was limited in its effective payload, and the range of compatible cameras was also restricted. These restrictions stemmed from the motors used in the system and also the image-triggering mechanism used in the GigaPan Epic.

The motors used for positioning the camera were AA battery powered and could not hold heavy loads in position, especially as the batteries drained. The GigaPan Epic claimed a payload limit of 0.68kg. However GigaPan systems are designed to be operated with the GigaPan unit itself horizontally levelled. In order to collect images of soffits it is necessary to adjust the orientation of the system by 90^{o}. This places a lot more strain on the system and it struggles to maintain position.

The collection of images was triggered by an actuator switch which was positioned over the camera shutter release button. When in the correct orientation this switch is activated and the 'robot finger' presses the button, triggering the collection of an image. Although adjustable, there were a limited number of small-to-medium cameras which could be controlled in this way as the 'robot finger' could not be positioned such that this approach would work on all cameras.

A replacement for the GigaPan Epic was therefore required. In order to meet the requirements outlined in Chapter 6, and build on the lessons learned in the initial experimentation, the following features and capabilities were sought after:

- Able to move and hold weight of payload: camera, lens, mountings and lasers.
    - Until the camera and lenses and other payload items were known, the exact weight of the payload was an estimate.
- Able to work when flipped on back to cover soffits.
    - The system must function correctly when operated with vertical and horizontal planes reversed. This means the basic methodology of operation must allow this, and also the motors must be strong enough to accurately maintain camera orientation when in this position.
- Able to be powered on site.
    - The system should preferably not require mains power. Although a generator could be used to supply 240V if necessary, it is preferred that the system could be powered via other means.

- Provide position information feedback.
    - The GigaPan system did not directly report the orientation of the camera for each recorded image. Instead the image stitching software estimated the total field of view of the panoramic scene and this was divided by the number of images to work out the orientations for each image. This had problems when the stitching software failed, and assumed that the movement throughout the scene was constant. It would be beneficial if the system could directly report the bearing and elevation of the camera for each image.
- Positional resolution.
    - The GigaPan Epic had horizontal and vertical positional resolutions of 0.36^{o}. Based on the requirement to accurately position and align images, and the performance levels obtained when using the GigaPan, it was decided that any replacement system for use within the enhanced IBIS should at least match this positional resolution.
- Ease of set up and handling.
    - Transporting, setting up, operating the unit should require little training, and should require no permanent installations or modifications on site.

Following a review of available systems a Clauss Rodeon ST (Dr Clauss Bild- und Datentechnik GmbH, 2011) was identified as meeting these requirements, and was procured (shown in Figure 74).

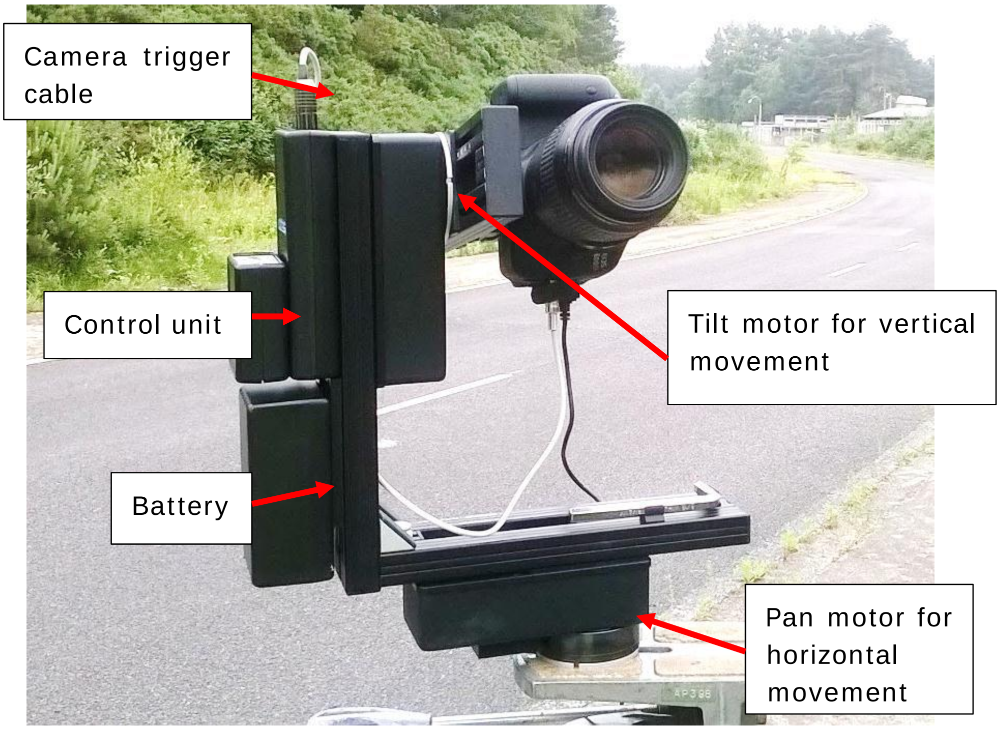


Figure 74: Clauss Rodeon ST with camera fitted.

Table 17 summarises the relevant specifications for this device, and for the GigaPan Epic used in the prototype system.

Table 17: Specifications for GigaPan Epic and Clauss Rodeon ST automated pan-tilt units

	GigaPan Epic	Clauss Rodeon ST
Payload	0.68 kg.	7.0 kg.
Power	6 x AA batteries.	11.1 V, 5200 mAh battery, or 12V plug in power cable.
Position information	None available directly.	Software reports bearings and elevations of camera positions.
Pan precision	0.36°	0.015°
Tilt precision	0.36°	0.005°
Triggering of image collection	Lever, controlled by on-board system.	Cable, controlled via Bluetooth connection to control device (PC or tablet).

8.2.1.2 Camera and lenses

The initial investigations into the practical use of an IBIS used a Nikon D30 DSLR camera and a GigaPan Epic. The adoption of the Rodeon ST pan-tilt unit meant that larger cameras and lenses could be used.

The key features for the camera were that it should have at least 10 million pixels; it should be compatible with a range of lenses with focal lengths spanning at least the range from 50 to 200mm; it should physically fit on the Rodeon ST; be light enough for the system to move and position it correctly; it should be compatible with the Rodeon ST remote triggering software; it should have lockable white balance and exposure settings, and autofocus capability.

Following a review of available and suitable cameras a Canon EOS 600D was chosen for use in the IBIS. This was compatible with the Rodeon ST cable triggering facility, had increased image resolution, and met all the other requirements. Two lenses were available for use during the duration of this research. One of these had a fixed focal length of 100mm; the other was variable in the range of 18 – 55mm.

Table 18: Specifications for Nikon D60 and Canon EOS 600D digital cameras (and lenses)

Facility	Nikon D60	Canon EOS 600D
Number of pixels	2592 x 3872 (10036224)	3456 x 5184 (17915904)
Sensor dimensions	15.8 x 23.6 mm	14.9 x 22.3 mm
Weight	0.522 kg	0.572 kg
Auto Focus	Yes	Yes
Exposure lock	Yes	Yes
White balance lock	Yes	Yes
Remote triggering	No	Yes

compatibility with Rodeon		
Lenses available in this research	50mm; 90mm; 105mm.	18 – 55 mm; 100 mm;

The increased pixel resolution of the Canon EOS 600D changes the maximum distance the system can operate at while still maintaining the required resolution following reprojection. Table 19 shows the maximum camera-bridge distances for the cameras used in the prototype and enhanced IBIS's for lenses of different focal lengths at which the required resolutions of 1 pixel per mm following reprojection can be achieved.

Table 19: Maximum camera – bridge distances whilst maintaining required image resolution of 1 pixel per mm with different cameras and lenses

	Maximum distance from bridge while maintaining required resolution	
Lens focal length	**Nikon D60**	**Canon EOS 600D**
50 mm	8.20 m	11.59 m
55 mm	9.02 m	12.75 m
90 mm	14.76 m	20.87 m
105 mm	17.22 m	24.35 m
200 mm	32.81 m	46.38 m
300 mm	49.2 m	69.58 m

As the camera orientation changes, moving from image to image, so too does the camera-bridge distance. If the camera focus is manually set, then the automated nature of the system means that it cannot be adjusted for each image. The differing distances at which different images are taken then means that some images are out of focus. This is illustrated in Figure 75.

A camera can be optimally focussed for objects at a specific distance. The particular combinations of lens, aperture size and speed produce a region around this specific distance in which objects will be tolerably within focus. The size of this region is known as the Depth Of Field (DOF) of the camera. By adjusting the aperture settings it is possible to adjust the DOF.

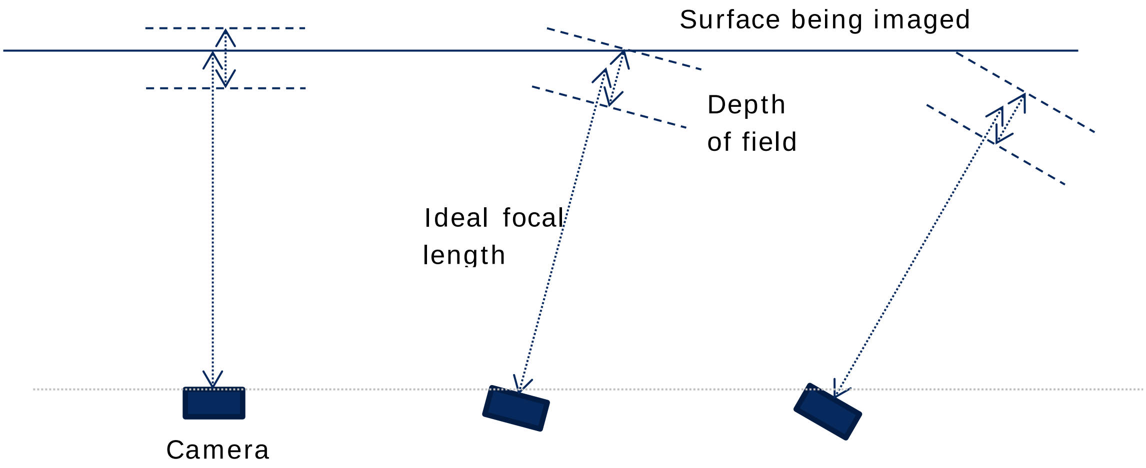


Figure 75: Depth of field.

If the camera uses the autofocus facility then this attempts to optimise the focus of each image, and fits with the automated nature of the image collection. However, the autofocus requires features to be present within the image field of view which can be brought into sharp focus automatically. This is not always possible, particularly when dealing with concrete bridges which can be large, relatively featureless expanses of grey. Therefore the autofocus cannot be completely relied upon. This can be countered by increasing the camera DOF, to increase the size of the region in which the image will be tolerably well focused. Decreasing the camera aperture size increases the DOF of the image, although this comes at a cost of allowing less light through to the sensor, resulting in darker images. The effect of this can be mitigated by decreasing the camera shutter speed, which opens the aperture for longer, letting more light through. This makes the images susceptible to motion blur, but for this application this is not a problem as the Rodeon ST is very stable and able to hold position throughout the exposure.

The Canon EOS 600D was able to give the aperture setting priority even when allowing some of the other functions of the camera to be automatically controlled. It was therefore possible to set up the camera so that it would use the autofocus functionality, while still maintaining a large DOF.

8.2.1.3 Distance measurement laser

The difficulties in aligning images when relying on image data alone were discussed in Section 7.2. If the camera position and orientation relative to the bridge are known for each image then this can be used to calculate the location of each pixel on the bridge surface, and the display can be adjusted accordingly. This is the approach taken by the laser-scanning Riegl system presented in 7.1.2.3, albeit with lower resolution images, and calculating the pixel positions in three, rather than two dimensions. A far simpler and cheaper approach would be to use a simple distance measurement laser to measure the perpendicular camera-bridge distance at each imaging position, and to combine this with the orientation information to calculate the distances required in the reprojection and alignment calculations. However, small errors in the system position or orientation relative to the bridge surface would affect the reprojection (Section 8.3.1) and alignment (Section 8.3.2) of the images as the wrong information about the camera-bridge stand-off would be used in the calculations.

Actual measurement information on where the IBIS was located in relation to the bridge for each image could be obtained if a distance measurement laser was incorporated in the system. Having such information makes the set-up and positioning of the system hardware at each IP simpler and faster, meaning the hardware can be set up in approximately the correct location and the measurements can be used in the calculations to produce the correct results. Initial testing with a hand-held, manually-operated distance measurement laser found that the integration of such data into the system would be beneficial, but that a more automated approach must be followed.

In order to provide useful information, and be properly integrated into the system a suitable laser must be capable of making measurements and transmitting or recording that data without requiring human interaction other than to start and stop the measurement process. It must be able to either make measurements on demand, or at regular intervals. The system must be able to make measurements in the range from 1 to 40m (the expected range of image collection distances), and each measurement should be accurate to within ± 5 mm, with a measurement resolution of 1mm. Additionally, the system must be able to operate on-site, ideally without requiring an external power source, and must be light enough to be mounted on the Rodeon ST.

Following a review of available systems it was found that an Acuity AR1000 distance measurement laser met the criteria and would be suitable for inclusion in the enhanced IBIS (Scmidtt Industries, Inc, 2014). The Acuity AR1000 was not the most accurate of the available lasers, and struggled to make accurate measurements at ranges over 30m in bright sunlight, but crucially it was possible to trigger and record measurements via an RS-232 connection to the control PC, and did not require a button-push for each measurement. Figure 76 shows the Acuity AR1000 laser mounted on the Clauss Rodeon automated pan-tilt unit.

Figure 76: Acuity AR1000 mounted on Clauss Rodeon.

The Rodeon ST would have been easily capable of carrying and moving both the camera and laser simultaneously, but this would have introduced errors in at least one of the systems due to their movement relative to the surface. In order to collect accurate laser distance measurement data it was therefore necessary to remove the camera, and replace it with the distance measurement laser. This ensured that the rotation of the Rodeon moved both the camera and the laser in such a way as to ensure the sensors remained fixed in space at the central node of the rotating system. This was easily done using quick release plates which meant the system orientation was minimally disturbed during the swapping operation. It is recognised that this process of swapping the distance measurement laser and the camera at each IP is not a practical long-term approach for an operational IBIS system. However, it is a viable approach as a method of demonstrating the concept of using direct distance measurements in the image reprojection and alignment calculations.

8.2.1.4 Control and Communications

The system is controlled using a laptop PC, although a suitable tablet may also be used. The limits of the scene of interest for the Rodeon ST are input to the Rodeon control software (RODEONmodular). This requires the user to enter the horizontal field of vision for the scene, and the vertical limits of the scene. The software also requires the user to specify how many images to take both horizontally and vertically. The software calculates and reports the maximum focal length of lens which will provide full scene coverage using these settings. If the lens being used has a focal length equal to, or shorter than, this then the images will cover the whole scene with adequate overlap for processing and alignment. The control software can also set parameters such as how long to remain static before, during and after image collection, how many images to take, and how quickly the motors move the camera between image-collection orientations. The control PC communicates the information to the Rodeon ST unit about where to move, when to stop, and when to take an image via a Bluetooth connection.

The Rodeon hardware uses a cable connection to the camera to trigger the collection of individual images. These images are downloaded using the canon control software (EOS Utility) via a USB cable. This enables each image to be checked for quality as it is recorded, meaning that problems with image quality can be detected, and alternative images can be recorded without requiring follow-up visits to the site.

The distance measurement laser is controlled via an RS-232 connection between the sensor and the laptop. Use of a terminal emulator program such as 'hyperterm' enables commands to be sent to the laser which can start and stop measurements, and transfer the recorded data to text files for use in processing and analysis.

8.2.1.5 Tripod

A standard tripod, capable of being levelled, and adjusted for height, and able to support the weight of the IBIS (Rodeon ST + Camera + lens + Laser + mountings).

8.2.2 Imaging Positions and required lenses

In order to guarantee that the images will have the required resolution, and will cover the whole surface of the bridge it is necessary to make sure that the images are taken from the correct locations, using the correct lenses.

To do this requires some information about the camera sensor dimensions and number of pixels. A Nikon D60 DSLR camera has a sensor with 2592 x 3872 pixels, in a 15.8 x 23.6 mm sensor (Nikon Corporation, 2008). This would allow a 2.592m x 3.872m area of a bridge to be imaged at exactly 1 pixel per mm. However, when collecting multiple images at different camera orientations from a single IP the camera-bridge distance will change (illustrated in Figure 75). Therefore it is necessary to establish the maximum imaging distance which will be used at any imaging position, and ensure that the lens can deliver the required resolution at this distance.

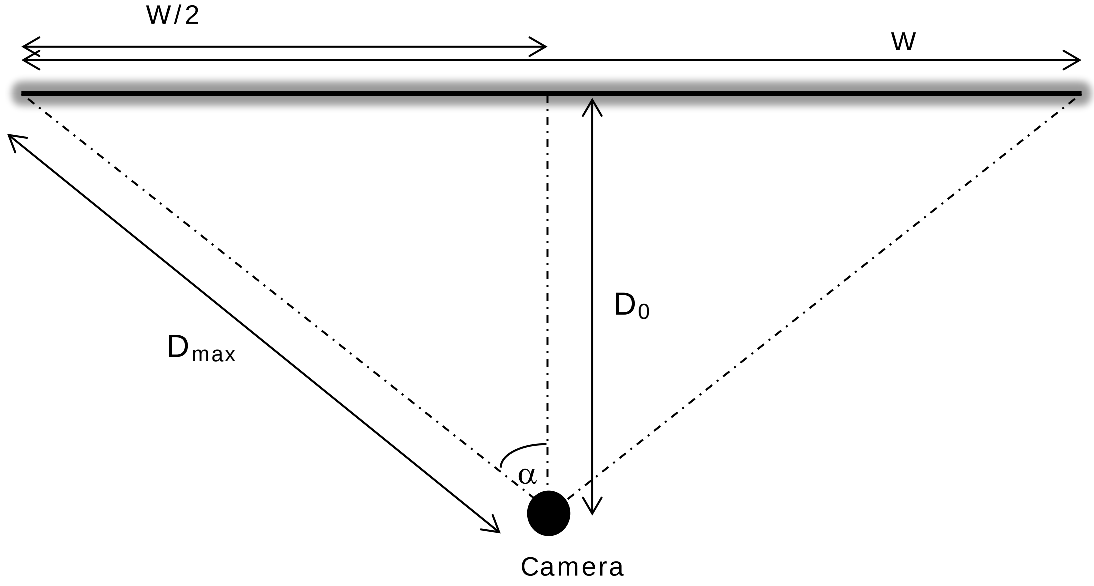


Figure 77: Change in camera-object distance with changing orientation.

Figure 77 shows how the maximum camera-object distance (D_{max}) increases at angle α compared with the camera-object distance when imaging perpendicularly to the surface (D_0). The change in distance can be calculated using Equation 1:

$$D_{max} = \sqrt{{D_0}^2 + \left(\frac{W}{2}\right)^2}$$

Equation 1

The ideal lens focal length required to produce an image of the required resolution is given in Equation 2:

$$F_{ideal} = \left(\frac{D_{max} W_S}{W_i}\right)$$

Where $D_{max} = maximum\ camera - object\ distance$;

$W_S = camera\ sensor\ width$;

$W_i = width\ of\ output\ image\ at\ desired\ resolution.$

Equation 2

This will produce a value of F_{ideal} in mm which is the precise focal length needed to produce images at the required resolution at D_{max}. If the actual focal length of the lens used is greater than or equal to this then all the images will have sufficient resolution to meet the requirements. The actual focal length used will depend on the available lenses.

The horizontal field of view of the camera using a given lens can be found using Equation 3.

$$FOV_H = 2\tan^{-1}\left(\frac{\frac{W_S}{2}}{F_{actual}}\right)$$

Where $W_S = camera\ sensor\ width$;

$F_{actual} = Actual\ focal\ length\ of\ lens\ used$

Equation 3

The width of the image collected perpendicularly to the bridge surface, at D_0, can be calculated using Equation 4.

$$W_{i0} = 2\left(D_0\left(\tan\frac{FOV_H}{2}\right)\right)$$

Equation 4

Similar calculations can be performed to ensure that the vertical field of view and the height of the images will meet the resolution requirements.

Once the overall FOV of the scene, and the FOV of individual images are known it is possible to calculate how many images are required to cover the whole scene, and the camera bearings and elevations needed to achieve this.

Spreadsheets have been developed which make use of the above equations (Equation 1 to Equation 4) to automatically calculate the optimum focal length of the lens required to collect images at a given output resolution when imaging surfaces of a bridge. These spreadsheets require information on the camera-bridge distance at each IP, the camera sensor dimensions and number of pixels in an image, and the size of the area being imaged. The calculations then establish the maximum imaging distance for the surface of interest, and the input resolution required at this distance to produce output orthoimages at the required resolution (1mm per pixel).

The possible viewing distances which can be used to image a given bridge are limited by the lenses available. If a particular surface is so far away from any possible imaging position that it would require a lens with a longer focal length than is available then it cannot be imaged at the required resolution. It may be that a lower resolution could be acceptable in such situations.

Knowing the available lenses, the required resolution, the camera sensor parameters, and the bridge dimensions and layout it is then possible to produce a plan showing the required image collection positions. These positions should be located on the footway or verges. Figure 78 shows an example of the imaging positions required for a simple bridge. Imaging Positions 13 and 14, which are shown here on the road, can be moved to a footway if required, or replaced by increasing the extent of the areas imaged by the wingwall IPs (3, 4, 5 and 6).

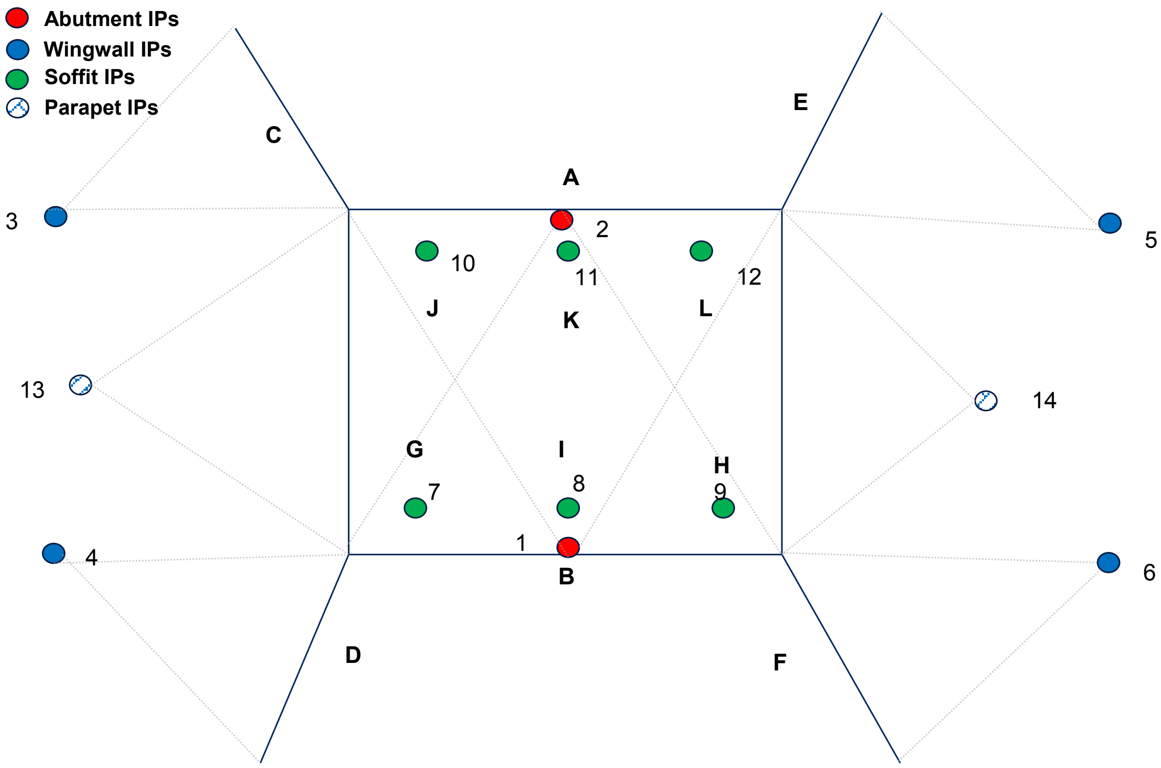


Figure 78: Imaging positions for IBIS.

Once on site, the pan-tilt unit is mounted on the tripod, and set up for the specific camera/lens combination being used. This involves using the control panel of the pan-tilt unit to find the limits of the scene of interest, and estimate how many image rows and columns are needed to provide full coverage. The control software then confirms the minimum lens focal length needed to ensure full coverage will be achieved. Assuming that the lens being used meets the requirements of the imaging setup then the image collection can commence. The pan-tilt unit controls the positioning of the camera, collecting images or making laser distance measurements as required, until the entire scene has been covered. The images are collected following the path shown in Figure 79. Once all images are collected at any given IP the system can be moved to the next IP where the next imageset can be collected.

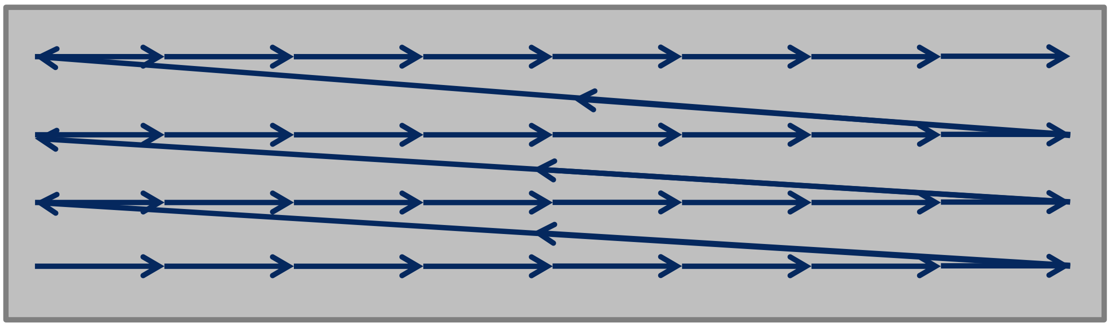


Figure 79: Image collection path taken by Rodeon ST during collection of scene data.

8.2.3 Supplementary images of bridge deck

The core IBIS hardware collects images of the bridge substructure. Feedback from bridge engineers and inspectors suggested that images showing the condition of the pavement over the top of the bridge would be beneficial as the state of the pavement here can give strong clues as to potential defects and problems affecting the bridge. For example expansion joints can be blocked with detritus, or pavement cracks can be allowing water ingress which can damage the structure. Such defects can often be seen from the top surface of the bridge before they become apparent from below.

One of the goals of the IBIS is that it should require no additional closures or access arrangements above those required for a traditional on-site visual inspection. It was impractical to gain access to the upper parts of the bridges and find safe and practical locations for setting up and operating the image collection hardware. This is also often the case when undertaking a traditional inspection.

To overcome this shortcoming another source of image data for the top deck of the bridges was sought and identified. Automated pavement condition monitoring systems (TRACS, SCANNER) collect data on most roads (in the UK). These collect downward (Figure 80) and forward (Figure 81) facing images of the road surface. Combining these images with IBIS images and inspection software enables inspectors to see the condition of the bridge deck, and to record the locations and types of defects seen.

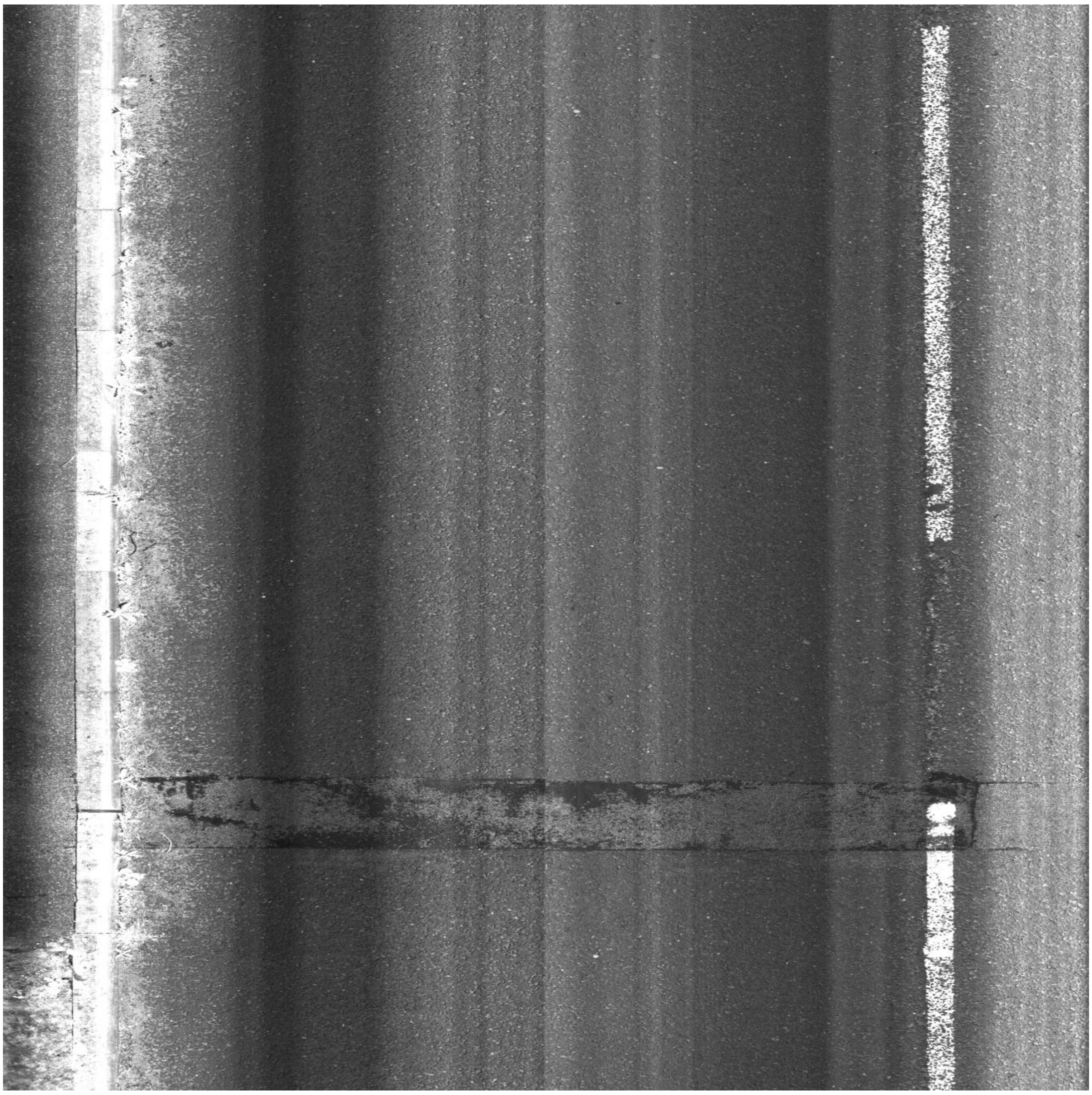


Figure 80: Downward facing images as collected by pavement condition survey vehicle.

Figure 81: Forward facing image as collected by pavement condition survey vehicle.

8.3 Image Processing

Raw images collected using the IBIS contain high levels of detail and can be searched for defects. However, to get maximum usefulness out of the images it is necessary to view them as an aligned and tessellated image set.

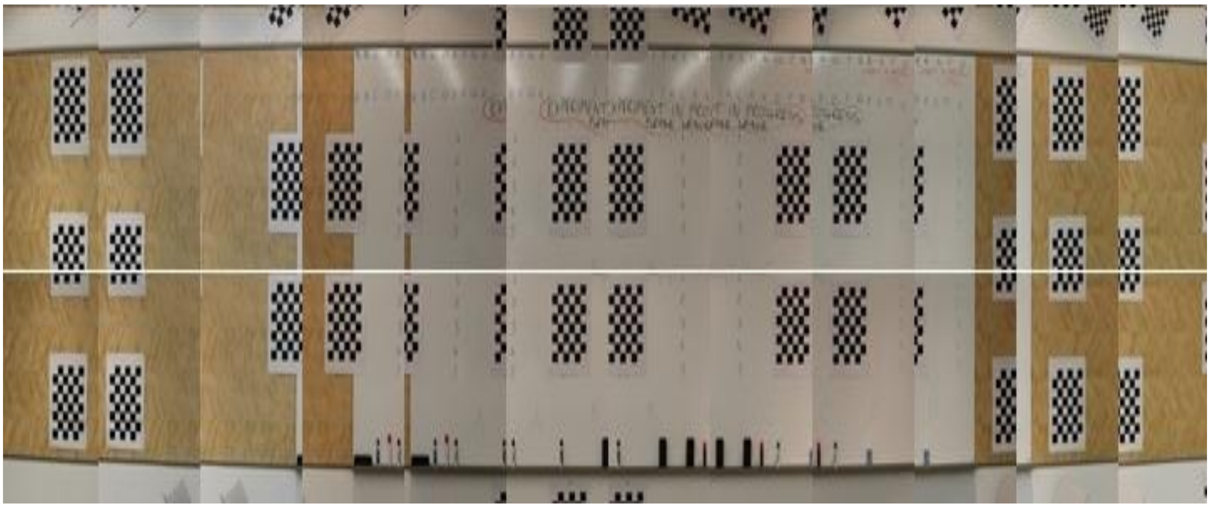


Figure 82: Tesselation of images as collected, demonstrating effects of perspective and visual confusion caused by overlaps in image resulting in multiple displays of features.

Figure 82 shows an image set from a single IP, which has been tessellated with no processing. The effect of perspective can be seen in the distorted horizontal features, and the confusing effect of features appearing multiple times due to image overlap are apparent.

Images collected using a camera adjusting its orientation around a single IP demonstrate the effects of parallax and perspective. Those parts of a bridge which were closer to the lens appear larger than parts which were further away. This results in the distortion of features, making it hard to accurately align and display the images if they are unprocessed. The overlap in the images, which is necessary to ensure that the whole surface of interest is imaged, also makes interpreting the raw images difficult as features are repeated multiple times.

To quantify the size of defects and objectively track their evolution from inspection to inspection it is important that all pixels in all the images represent a constantly sized area of the 'real world'. Additionally, to avoid confusion and distortion when viewing the images it is important that each image is presented with the effects of perspective and viewing angle removed, and that all the images are well aligned.

8.3.1 Reprojection and generation of orthoimages

Figure 83 shows how images taken at different orientations at a single IP represent 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.

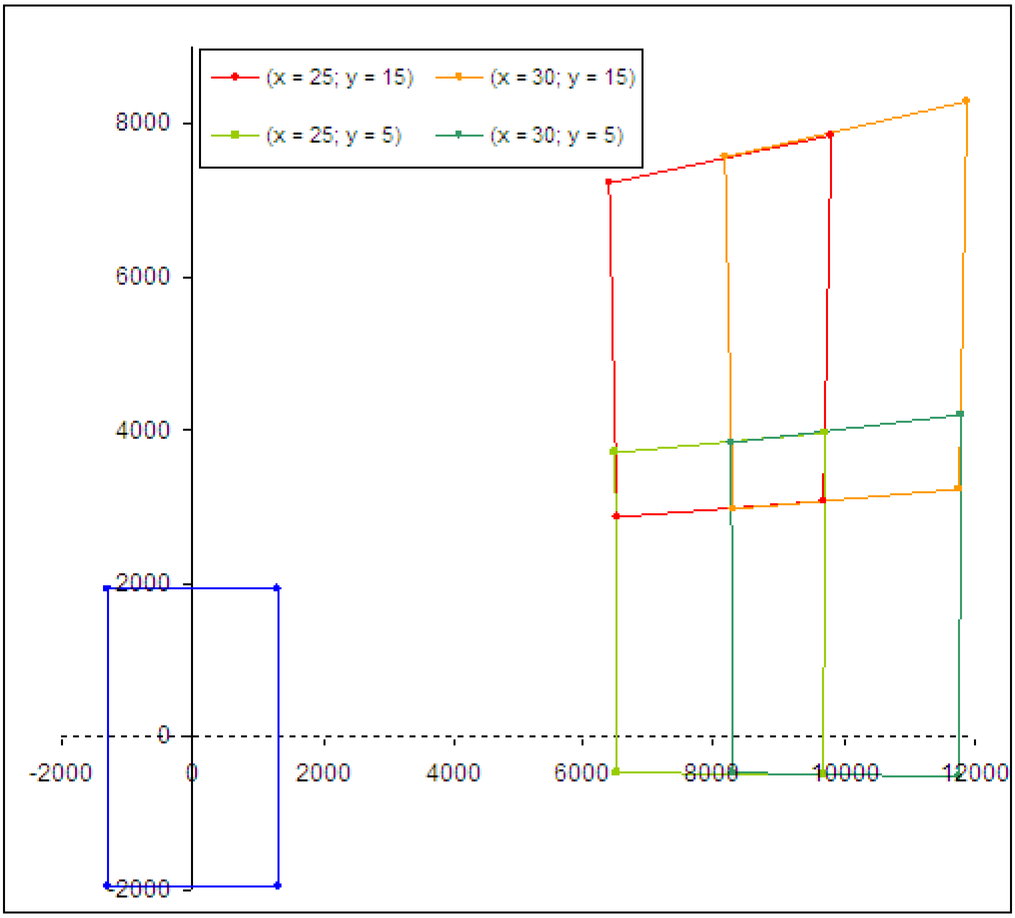


Figure 83: Illustration of how viewing angle can affect size and shape of view represented in image.

Information about the camera, lens, and the camera-bridge distance can be used to reproject and rescale these images and create orthoimages. These orthoimages show the imaged surface as if each image had been collected perpendicularly to the bridge surface, from a constant distance. The result of this reprojection is that all pixels represent a constant area on the bridge, and that the distortive effects of perspective are removed.

Additionally, as part of the image reprojection process it is possible to calculate the alignment coordinates of each image, meaning that instead of a tessellated display of images as shown in Figure 82 it is possible to calculate the overlap between images, and adjust the display accordingly.

Image reprojection is performed following the trigonometric principles discussed below. Figure 84 shows a set of diagrams which are helpful in understanding the concepts involved in the reprojection of images, using the example of calculating the horizontal components of the reprojection of a bridge abutment. Note that Figure 84 does 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.

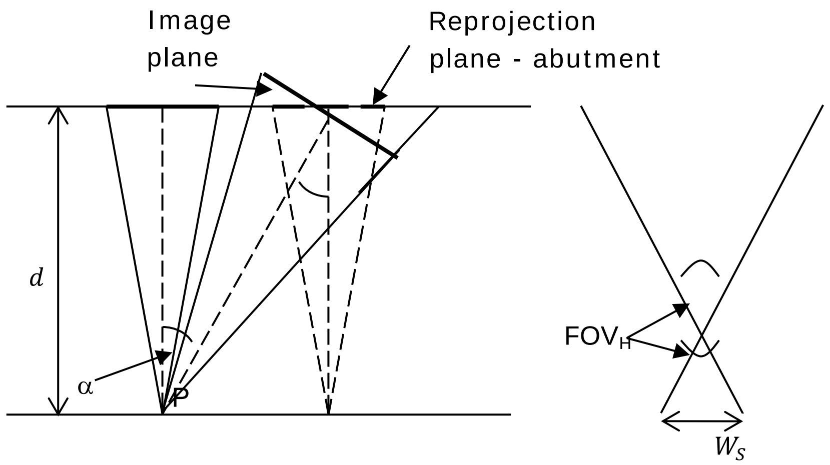


Figure 84: Illustration of some of the concepts and angles involved in image reprojection.

Image plane pan relative to projection plane: α;

Reprojection plane tilted at: β_r (not shown);

Image (camera) tilted at: β_I (not shown).

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

With a camera Field of View angle (FOV_H), and an image sensor width of W_S pixels, the camera-object distance, d, can be found, using Equation 5:

$$d = \frac{W_S}{2\tan\left(\frac{FOV_H}{2}\right)}$$

Equation 5

For an image tilted at βi 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 Equation 6:

$$x_r = d\cos\beta_i\sin\alpha + x_i\cos\alpha - y_i\sin\beta_i\sin\alpha;$$

$$y_r = d\sin\beta_i + y_i\cos\beta_i;$$

$$z_r = d\cos\beta_i\cos\alpha - x_i\sin\alpha - y_i\sin\beta_i\cos\alpha.$$

Equation 6

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 the relationships in Equation 7:

$$x'_r = x_r;$$

$$y'_r = y_r\cos\beta_r - z_r\sin\beta_r;$$

$$z'_r = z_r\cos\beta_r + y_r\sin\beta_r.$$

Equation 7

Then simple scaling using the ratio of d and z'_r (Equation 8) brings the x'_r and y'_r onto the $z = d$ plane and therefore these become the xy coordinates in the reprojected space.

$$x = x'_r \, (d/z'_r);$$

$$y = y'_r \, (d/z'_r).$$

Equation 8

By applying these equations to each pixel in the original image in turn, then a new, reprojected position of the pixel information can be found, and a new, reprojected image is generated. Each of the resulting images now has had the effects of perspective removed, resulting in undistorted images with horizontal and vertical features properly presented. Additionally, each pixel now represents the same area of the bridge surface, and the (x,y) coordinates of each image on the reprojection plane are now known.

Figure 85 shows a tessellation of nine individual images before (left) and after (right) the reprojection process. The perspective effect, making it appear as if the top of the abutment slopes down to the right, can be clearly seen in the left image. This has been removed from the reprojected images on the right. Therefore, by using the reprojection techniques developed within this research images can be converted into a view that appears as if the surface of the structure was surveyed at a constant distance, from a perpendicular position. This improves the quality of tessellation, and makes the tessellated outputs much easier to interpret.

Figure 85: Example of effect of reprojection - Mosaic of nine un-reprojected images (left) and the same nine images following reprojection (right).

8.3.2 Image alignment

To enable the inspector to view the images and determine whether and where any defects are located it is important to present the images correctly aligned and tessellated. Because the images are collected with each image overlapping its neighbours, if they are presented simply abutted up next to one another there would be confusing and disorienting effects where individual features could be seen multiple times in the display, as seen in Figure 82.

There are many existing software packages available for the alignment of images, but, as discussed in Section 7.2.1, none are totally suitable for the needs of this application. Most image alignment software relies on one of two main methods: images are aligned using only information and features contained within the images, with no knowledge of the camera position or orientation; or images are aligned based purely on knowledge of the camera parameters and position, with no consideration given to the contents of the images.

Unfortunately the first approach is unreliable on many images of bridges due to either excessive or insufficient pattern in the surfaces being imaged. This approach relies on the unambiguous identification of features and points in multiple images, which can then be matched to produce transformations enabling the images to be aligned (and scaled or rotated if necessary). This approach works very well in some situations and environments, but not all. Bridges often have too many features, all of which look very similar (masonry arches), or very few features, and vast expanses of relatively unchanging grey concrete. This makes such an approach prone to relatively large errors in alignment.

Additionally when imaging large surfaces multiple IPs are often required. Using panoramic creation software with images collected from more than one position results in panoramic scenes which are at best distorted (Figure 86), and at worst totally wrong.

Figure 86: Result of using panoramic creation software on images of soffit, taken from two IPs.

The alternative approach uses knowledge of the camera position and orientation at any given time. This gives reasonable results, and avoids catastrophic misalignments where images are located in totally the wrong place, but small measurement errors can result in misalignments (Figure 89).

Therefore, a hybrid technique has been developed in this research which produces improved alignment information. This process makes use of the camera orientation information to identify the positional relationships between the images (which image is next to which image), and to establish an initial estimate of how the images overlap. One of the images is then defined as having its position locked, while the other can have its position adjusted. A smaller region of the locked image is then selected for use in the cross correlation process. This sub-image is used instead of the whole image purely to make the calculations and processing more efficient. The region selected for this sub-image is chosen based on the orientation information, and should contain the region of overlap between the two images. A series of sub-regions, or templates, within the other image are also defined. These template locations are also selected based on the orientation information and should contain regions of overlap and features common to both images. Figure 87 shows an example of two images, and the regions selected for cross-correlation. By restricting the cross correlation calculations to regions which are known to include overlap based on camera orientation information the chances of correctly finding a match between the images are improved as the likelihood of erroneously matching another part of the bridge is lowered.

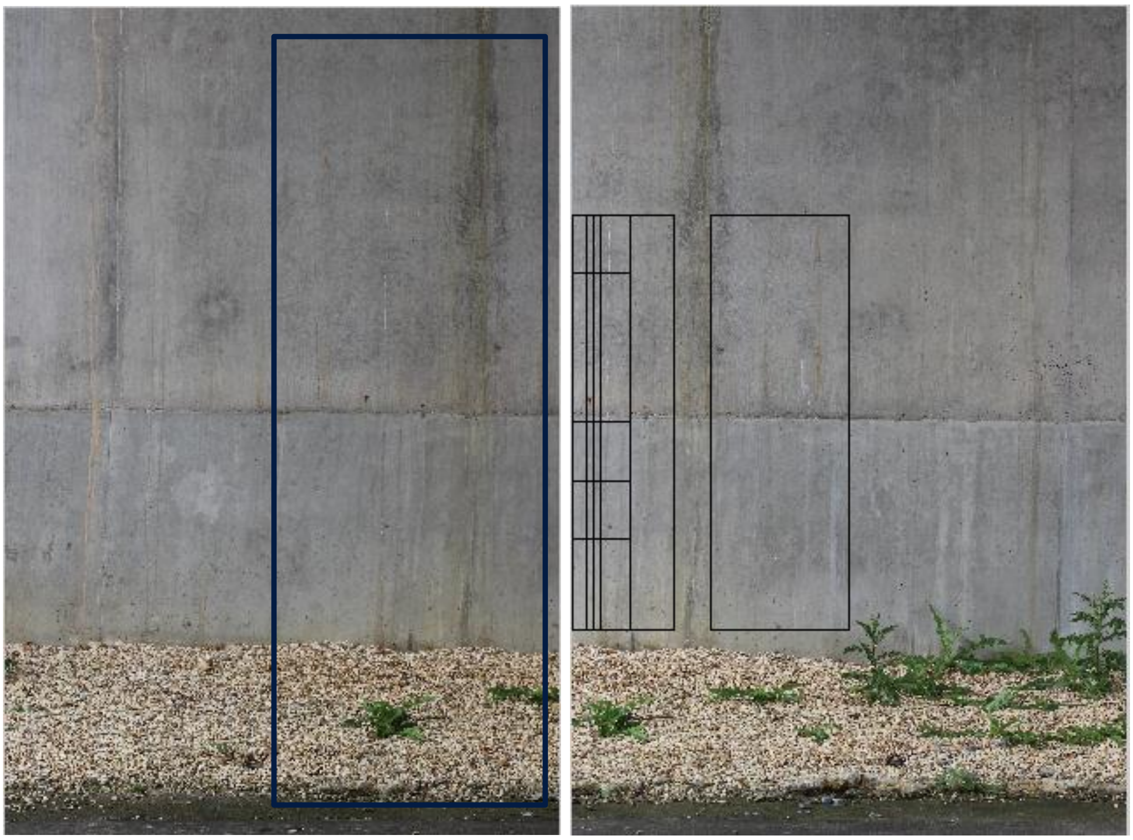


Figure 87: Two images showing defined regions of cross-correlation calculation as used in the alignment process to determine required adjustments in image position relative to one another.

The normalised cross correlation process first attempts to remove the effect of differences in the image brightness caused by changes in illumination. This is done using the formula shown below in Equation 9, which subtracts the mean pixel intensity of each sub-image from each pixel value, and divides by the standard deviation of the pixel intensity values within the sub-image (Lewis, 1995). The cross-correlation coefficients of the normalised data are then calculated.

$$\gamma(u,v) = \frac{\sum_{x,y}[f(x,y) - \bar{f}_{u,v}][t(x-u,y-v) - \bar{t}\,]}{\sqrt{\left\{\sum_{x,y}[f(x,y) - \bar{f}_{u,v}]^2 \sum_{x,y}[t(x-u,y-v) - \bar{t}\,]^2\right\}}}$$

Where $\bar{t}$ is the mean pixel intensity of the sub-image template, and $\bar{f}_{u,v}$ is the mean of $f(x,y)$ in the locked image.

Equation 9

The cross correlation coefficients are calculated for each of the sub-images in the non-locked image and produces a peak value where the two images are optimally correlated, and hence best aligned (as shown in Figure 88).

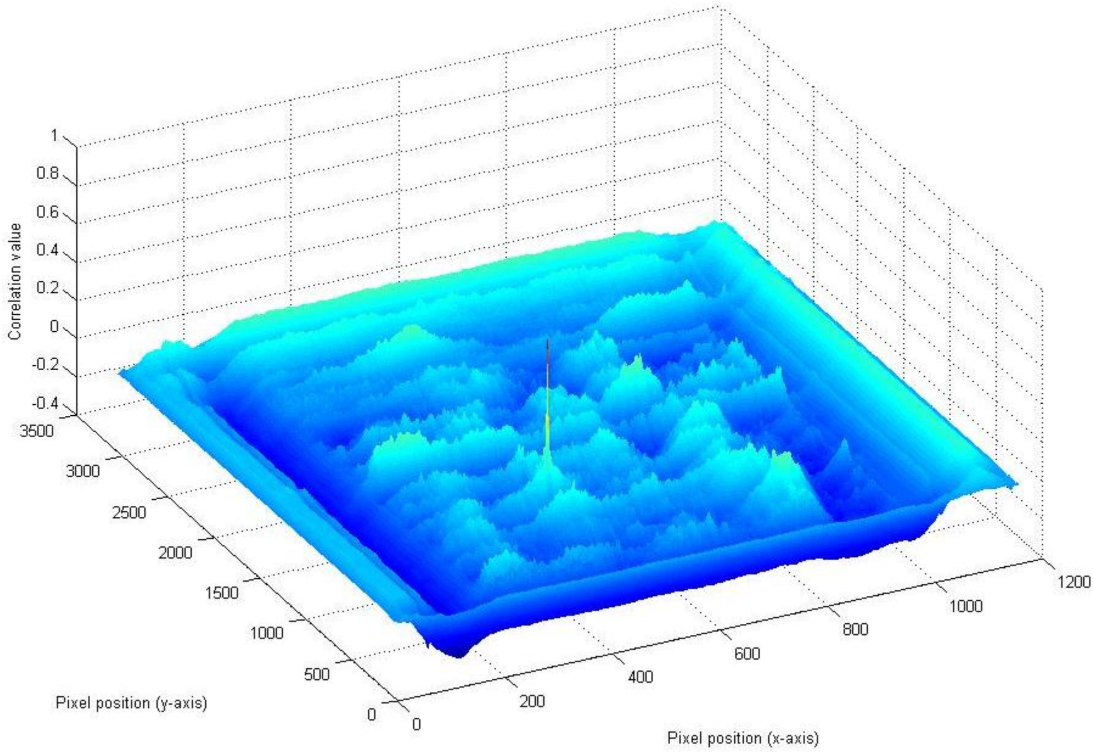


Figure 88: Correlation coefficients calculated by cross correlating one of the sub-regions shown in Figure 87 with the locked image (peak value at (430,1411)).

The position at which this peak correlation is recorded is converted to an image offset required to align the images. The multiple templates which are cross-correlated with the locked image sometimes differ in the image offsets which they produce. The image offset associated with the maximum correlation value is then used in the alignment process to adjust the position of the non-locked image relative to the locked image.

To improve the efficiency of the process the cross-correlation is not calculated for all the sub-images, unless the peak correlation coefficients found are below 0.8. If all the peak correlation values from all 10 sub-images are below 0.8 then the position of the image is not adjusted automatically. The position can still be adjusted by manually working out the optimal position and editing the image offsets file, but this reduces the possibility of images being grossly misaligned and producing confusing tessellations which are hard to correct. Cases where the cross correlation process fails may happen if the structure is particularly featureless, where errors in the image collection process mean that there is no, or insufficient overlap, or where the camera orientation data is incorrect.

This cross correlation process significantly reduces the errors in alignment, as can be seen by comparing Figure 89 and Figure 90.

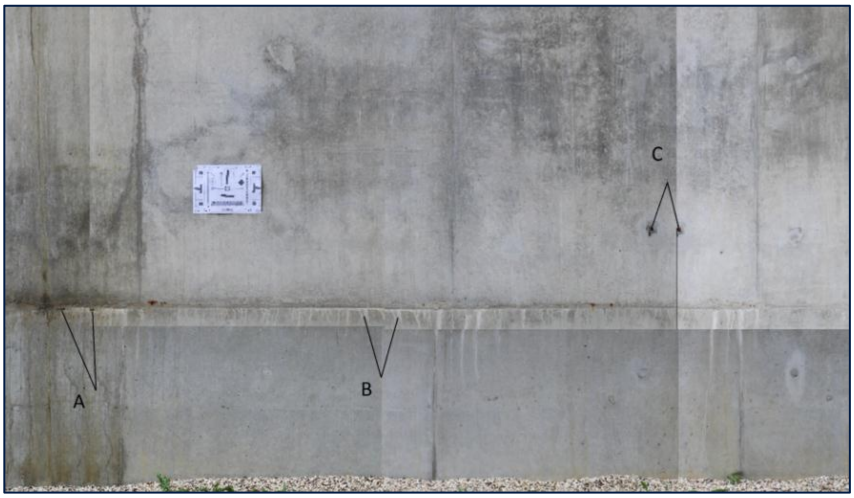


Figure 89: Alignment using camera bearing and elevation data.

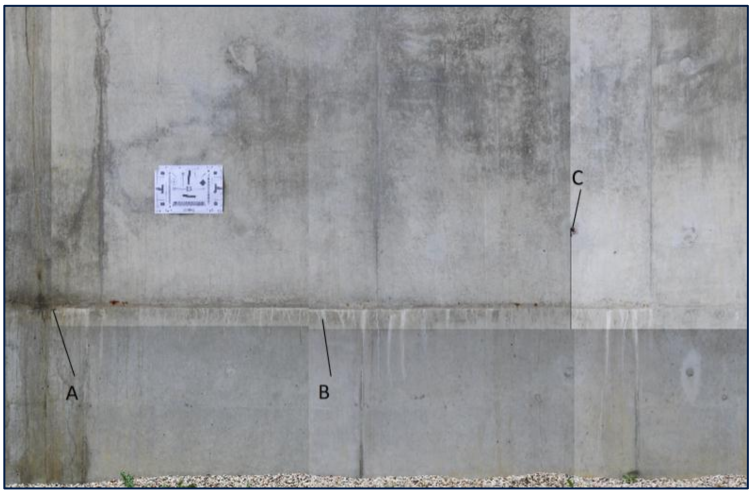


Figure 90: Alignment using camera bearing and elevation data, and image cross correlation.

8.3.3 Image illumination and colour balance

Tessellated images often show large changes in colour between neighbouring images (as shown in Figure 91). These were found to be off-putting and distracting when performing inspections. Additionally, some inspectors were concerned that they may make subtle changes in colour difficult to see and mask genuine differences.

Figure 91: Example of tessellated images showing large colour and intensity differences due to changing illumination conditions.

There are three problems with the image illumination visible in Figure 91. First there is the appearance of two images on the left of the tessellated display which are obviously darker than any of the other images; secondly, the concrete appears to take on a distinct greenish colour in parts of the bridge – this is due to mistakes being made by the camera automatic white balance settings; thirdly, individual images appear lighter at the bottom than the top, which is particularly apparent towards the top-right of the display.

In correcting these issues it is important not to introduce any artificial features or artefacts into the image as a result of blending the images, and care must be taken to ensure that the process used does not remove or hide any genuine features.

This is not a simple issue, and even professionally developed image blending and stitching software has problems in coping with large changes in image illuminations, as illustrated by the example shown in Figure 92, showing the same images as in Figure 91, but this time stitched using GigaPan Stitcher software.

Figure 92: Example of tessellated images showing large colour and intensity differences due to changing illumination conditions (GigaPan).

Here, although most of the images are smoothly blended into one another, there are still obvious differences in some locations where the input image illumination differed from its neighbours – the dark area on the left remains, as does the green tinge to some of the image, and although less dramatic than in Figure 91, the changes in image brightness from the top to the bottom of images can still be seen to give the upper right part of Figure 92 a somewhat stripy appearance.

Consultation with engineers and inspectors determined that whilst the changes in colour and illumination within the image sets could be unnatural and off-putting, they were not a major obstacle to the use of the images. Consequently it was decided that addressing this issue was not a research priority and effort was focused in other areas.

8.4 Image Presentation

Rather than developing an image display and interaction system from scratch it was recognised that it would be more efficient to use a modified version of a piece of proprietary TRL software named ChartCrack. This software has been developed over many years and has the prime purpose of allowing researchers to process and view pavement condition data, such as that collected during TRACS or SCANNER surveys. ChartCrack has the capability to load and display images, and provides an interface for user interaction with them. The image handling capabilities of ChartCrack were primarily developed in order to display downward facing images of pavement surfaces. These images can be manually inspected, and the locations of defects can be recorded by clicking on the image. The software can generate a report showing the location and type of any detected defects on the pavement.

ChartCrack was adapted to display and align images which vary in their *x* coordinate as well as the *y* coordinate (pavement images are displayed as a single long strip of images, one after the other, with no attempt to accurately represent corners or bends). The modification of the TRL software was carried out by TRL staff familiar with the complex program code.

The ChartCrack software was modified to read input files containing the image name and calculated alignment coordinates of each image. The need for this file was identified in the system process design, and the image processing code was developed in order to create the file automatically as part of the reprojection process. The images are then displayed, offset from a common origin point, ready for inspection and interaction. There can be over 100 images in an image set from each IP. Each image is typically between 5 and 10 MB in size. If the software tries to display all the images at once the computer must hold an extremely large amount of data in memory. This makes the system very slow to respond to user interaction or commands.

To mitigate this problem the software has been modified to present lower resolution thumbnail images to provide overall context for the surface being inspected, while the full images can be viewed in more detail. The lower resolution images are produced during the image reprojection process. The display software only loads the images required for the display at any given moment, so this reduces the amount of data in the computer memory, and makes navigating the images faster and smoother. Figure 93 shows an example screenshot of the software display, with the low resolution thumbnails showing the tessellated imageset on the left, and the detailed images on the right. An indicator box can be seen on the thumbnail display to highlight the parts of the structure shown in the detailed zoom view. This indicator box is present in the software, and changes size and moves around the thumbnails as the inspector zooms and pans the detailed images.

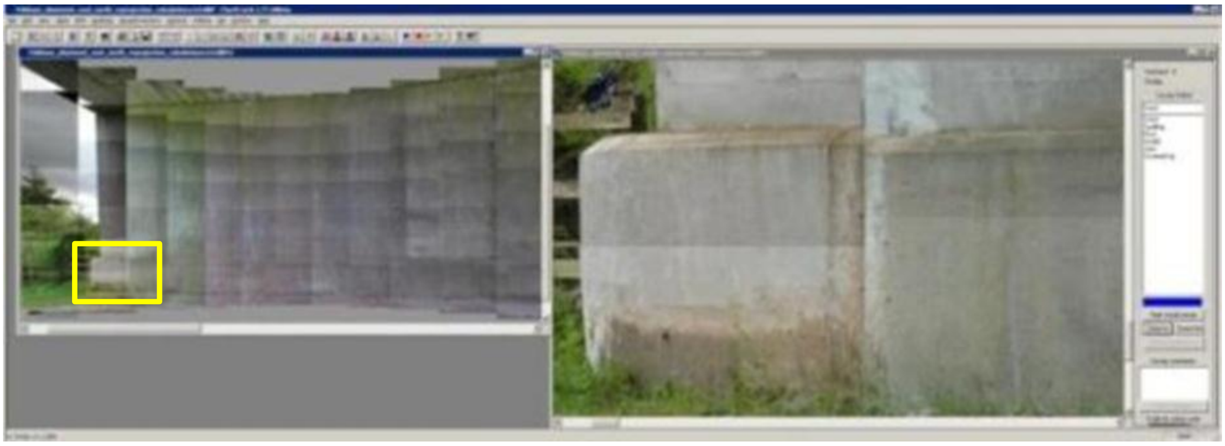


Figure 93: Screenshot of image-based inspection software showing zoomed out thumbnail view, and detailed section of images.

8.4.1 Inspection process

Inspectors can simply use the software to display the images, and complete a GI report based on this, but the software allows more interaction with the data. Inspectors sometimes draw sketch maps of bridge surfaces, upon which they mark the location and type of defects. This is more common in Principal Inspections, but is not unknown in GIs. Instead of having to sketch their impression of where defects are, and estimating the size and position of defects, the software allows the location, type and extent of any detected defects or features to be recorded. Defect recording is performed using a grid system, in which each grid cell is marked as either containing, or not containing, a defect. The software allows the inspector to look for defects, and to select any defect type from a menu on the right of the screen. The inspector then clicks on the screen where the defect is seen and the display is marked with a cross. These marked defects are used by the software to generate an output file showing the location and type of defects. This can be used for later analysis and to quantify the defects on the bridge. These files are known as 'defect maps'. The size of the grid squares used in this process can be controlled by the user, enabling the resolution and level of detail present in the generated defect maps to be altered as appropriate. If desired the inspector is able to open the individual images for inspection outside the ChartCrack software.

Figure 94 shows an example of a tessellated view of an abutment, and the zoomed in view with a defect (thin crack) marked on it. The zoomed out view shows where on the abutment the zoomed in image is located, and also shows where the crack has been marked.

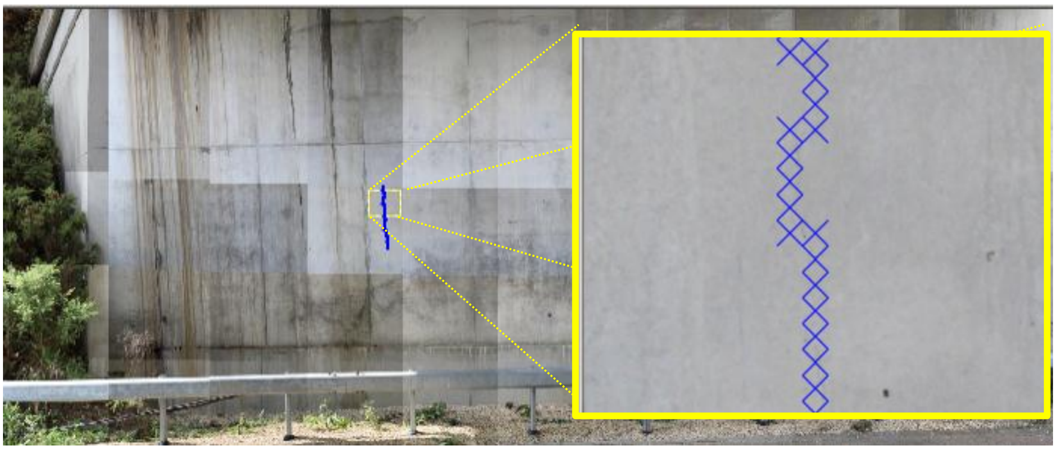


Figure 94: Tessellated view, with overlaid zoomed in image, showing marked defect location.

This information can be exported for analysis in other packages, compared against previous inspection results, or reloaded into the inspection software to allow the defect map to overlay the images, making it easy to see exactly why a particular grid cell had been marked as containing defects. The software also allows the inspector to mark any location in the images, and enter comments about the location. Such comments could be notes on what is seen, questions for other inspectors, or details of remedial work which may be appropriate.

The system can only record a single defect type in any individual grid square. Inspectors must therefore record the most serious defect present if more than one defect is located in the same location.

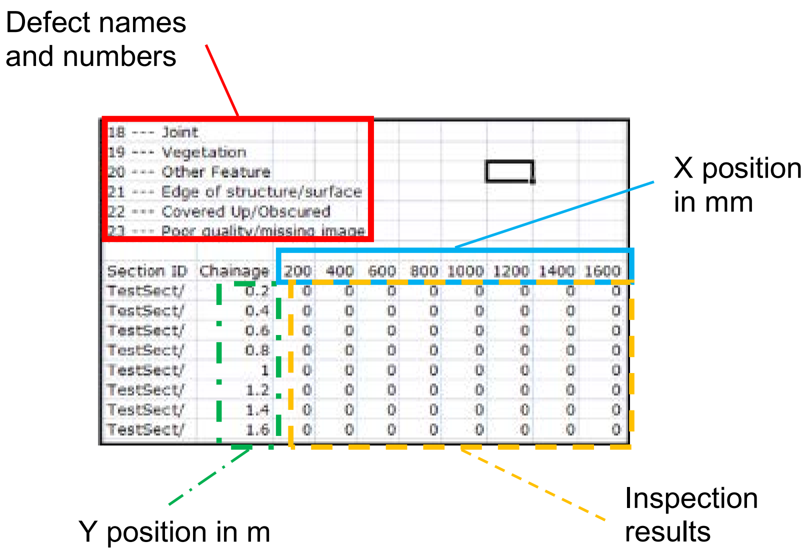


Figure 95: Example of data produced by inspection software, used to create defect maps.

Figure 95 shows the output from the inspection software. This is displayed as a screenshot showing the data in Microsoft Excel ®, although as the output is a simple text file it could be analysed in alternative packages. This shows the x and y coordinates of each grid cell on the surface being inspected, and shows the marked defect value for each cell. It can be helpful to use the conditional formatting functionality of Excel. This will colour the grid squares according to the defects reported, and produce a visual defect map of the part of the structure inspected, as shown in Figure 96.

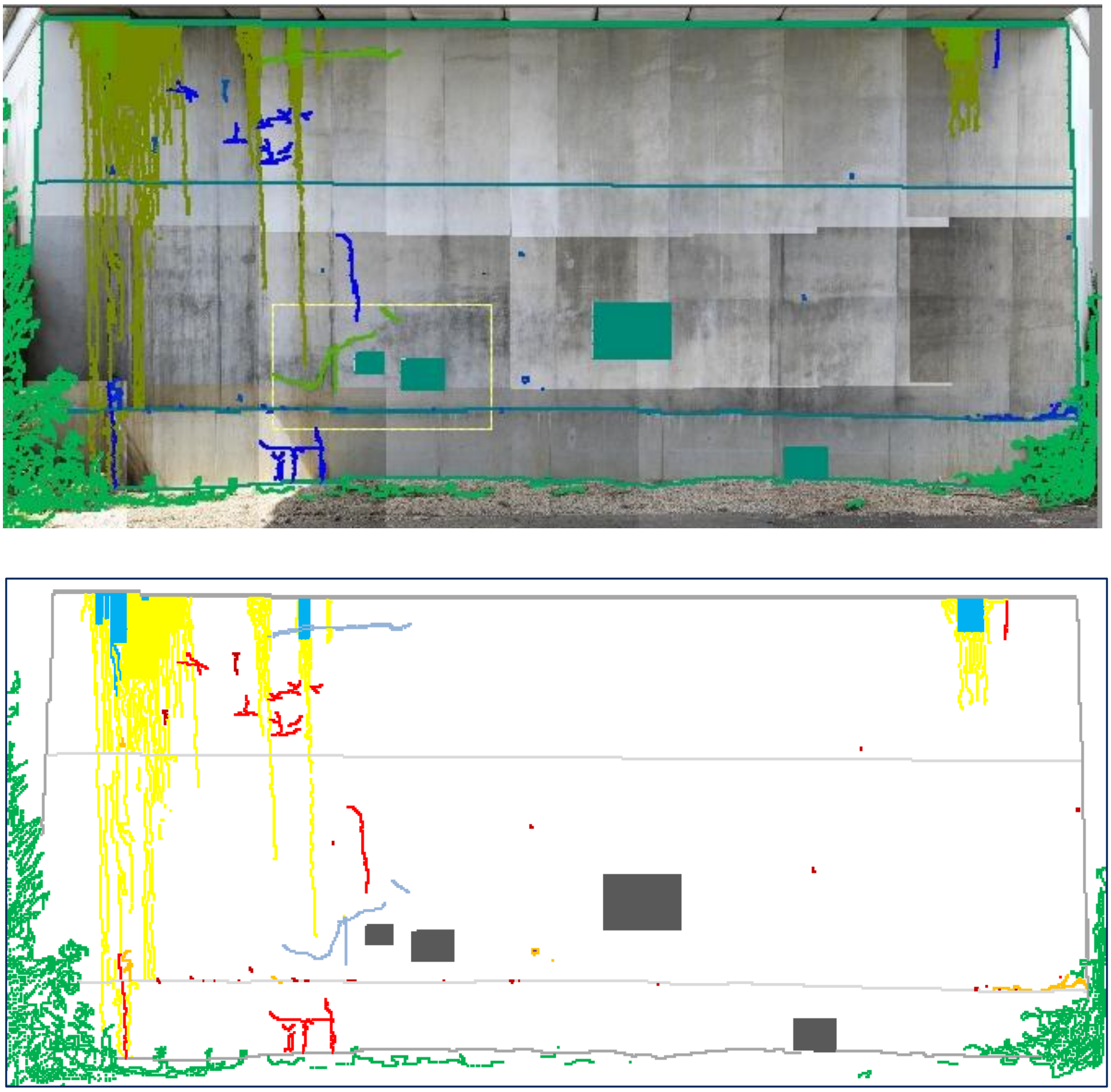


Figure 96: Example of defect map produced using ChartCrack, overlaid on images (top) and in spreadsheet form (bottom).

8.5 IBIS Summary

An IBIS has been developed that consists of a Canon EOS600D, and an Acuity AR1000 distance measurement laser, mounted on a Rodeon ST automated pan-tilt unit. This is attached to a tripod which is placed at various Imaging Positions around the bridge being inspected. The camera is compatible with a range of lenses enabling it to get detailed views of bridge surfaces from long distances. The pan-tilt unit has a working payload limit of 7kg, meaning it can easily cope with the weight of the camera and other hardware, such as the distance measurement laser. The pan-tilt unit is also robust enough for practical use on site, and can hold the camera steady while images are taken. The system is controlled using a laptop, which is used to set up the field of view of at each IP, and to control the movement and orientation of the camera, and trigger image collection. The PC also enables images to be checked onsite, ensuring they are of sufficient quality for later analysis.

The process of undertaking an IBI on a bridge can broadly be split into four phases: preparation; collection; processing; inspection. These are summarised in Figure 97 (which is intended as a schematic diagram of the overall methodology and operational stages involved in an IBIS inspection and is not a complete flowchart of all processes required). The preparation phase involves looking at maps and images of the bridge and its surroundings to establish the likely locations of the required IPs and the distances from which images will be taken. This enables appropriate lenses to be selected. The collection phase involves setting up the IBIS and using it to collect suitable images and laser distance measurements at each of the IPs in turn. Once all images and measurements are collected the processing phase can begin. This requires the operator to produce a batchfile for each IP containing the image filename, and the bearing, elevation and measured camera-bridge distance for each image. This is then used by the reprojection software to produce scaled orthoimages at the required 1 pixel per mm resolution, based on accurately measured information, and an alignment file for each IP. This contains the reprojected image filename, along with its alignment coordinates. The images are then ready for use in the inspection phase where ChartCrack can be used to detect and record defects, produce defect maps and reports, and enable the inspector to complete the GI report form.

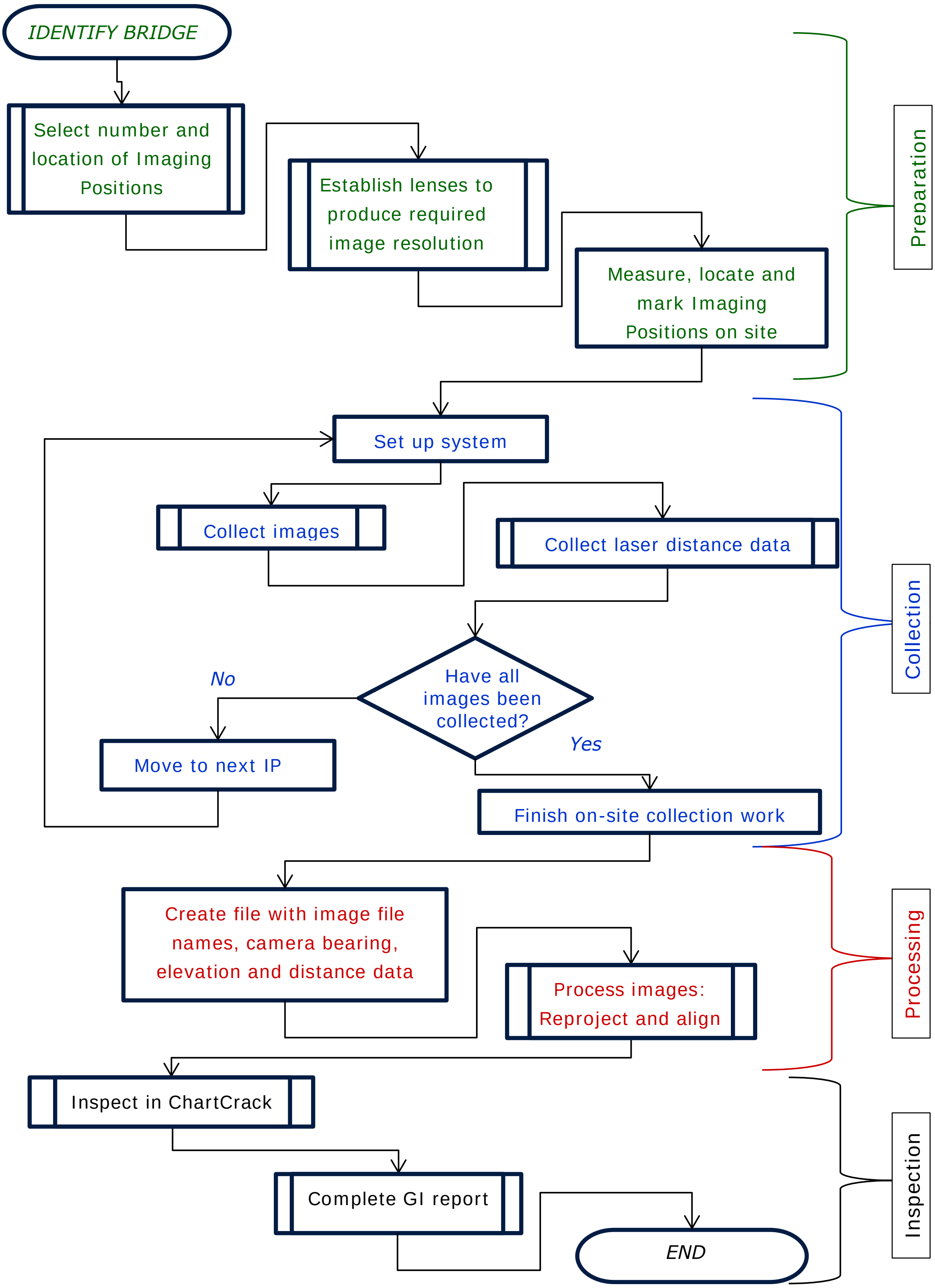


Figure 97: Overview of IBIS processes.

9 TESTING AND FEEDBACK

Having developed an IBIS (Chapter 8) it was then necessary to test it, and demonstrate that it was a practical and realistic way of collecting routine visual bridge condition data; that it met the requirements drafted in Chapter 6; and that the images provided were useful. Demonstrating the quality and detail of the images was particularly important: many of the requirements, particularly those to do with the system practicalities, are important in terms of the overall usefulness and usability of an IBIS approach, but fundamentally, if the basic images provided did not contain adequate detail then the entire IBI concept would fail.

The assessment of the prototype IBIS was performed in two parts:

- Determine that the system provided data which could be used to carry out a GI, and whether or not the results of the Image-Based GI were similar to, or better than, the results of a traditional GI – Section 9.2.
- Consider the requirements described in Chapter 6, to ensure it would be compliant with all the needs of a successful system – Section 9.4.

The assessment process used the criteria developed in Chapter 6 to provide a framework against which the performance could be judged, and also compared the results of Image Based Inspections against data produced using more traditional onsite inspection methods. A wider process of comparison of results obtained using IBI methods and those obtained using traditional methods would be useful and informative in determining the impact of IBI on inspection reliability, but the performance assessment performed as part of this research is adequate to demonstrate the potential of the concepts, techniques and systems developed.

9.1 Methodology

Using the prototype IBIS described in Chapter 8, images were collected on a number of in-service structures, and also under experimental conditions. The collection of data on in-service sites was to demonstrate the practicalities of the IBIS method in 'real-world' conditions, and to understand the limitations and constraints of the method and hardware. The experimental work undertaken in controlled conditions provided data which enabled specific features and aspects of the system performance to be judged.

9.1.1 In-service sites

Sites used in the development and assessment of the prototype are shown in Figure 98.

a) Frilsham

b) Stoke Bruerne

c) Woodford Halse

d) Little Cransley

e) TRL Test Track

f) Winnersh

Figure 98: Sites used in prototype IBIS assessment.

Bridges (e) and (f) were selected primarily due to their convenience for performing site visits and collecting images. Bridges (a) to (d) were selected as part of a related project into the use of automated bridge inspection techniques.

As well as collecting IBIS data on these bridges, existing GI reports were also obtained, thanks to Northamptonshire CC and Mott MacDonald. Furthermore, an independent inspector from Atkins undertook a series of highly detailed visual inspections on bridges (a) to (d), which provided more detailed defect maps than would be typically available from a GI. These inspections were specifically designed to provide data useful for this work. Four of the bridges (a, d, e, f) were simple concrete structures carrying a road over another road, one (c) was a double masonry arch carrying disused railway lines over a road, and one (b) was a precast concrete structure carrying a road over a canal. As the inspection process took place throughout the development and assessment of the IBIS not all assessments were carried out on all bridges.

A number of different inspectors were consulted at various stages throughout the development, implementation and assessment of the IBIS. For the assessment of the usefulness of the system outputs and methods, IBIS images and data were supplied to experienced inspectors and engineers who were asked to perform inspections and produce reports based only on the IBIS data. This included staff from LNEC (Laboratório Nacional de Engenharia Civil) in Portugal, who were working with TRL on an EU project (TRIMM WP3), investigating the potential for image-based inspection within the development of advanced methods of bridge monitoring.

The on-site assessment procedure was based on an enhanced General Inspection. This judged the visual condition of the structure at two levels of detail: providing a general assessment of the condition of the bridge and the individual elements comprising the bridge; and a more in-depth assessment giving details of any defects observed. This produced data at levels of detail greater than those offered by GIs, but did not require the specialised testing equipment needed for Principal Inspections.

The general assessment considered the structure as a whole, and as a set of individual elements (abutments, soffit, etc.). This categorised each part of the bridge using the scheme outlined in Table 20.

Table 20: General condition categories used in initial assessment of Image-Based Inspections

Category	Description
6 – Sound	No maintenance needed at moment, and no visible signs of degradation which will lead to maintenance within 5 years
5 – Good	No maintenance needed at moment, but one or two possible signs of degradation which may lead to maintenance being required within 5 years
4 – OK	No maintenance needed at moment, but several possible signs of degradation which may lead to maintenance being required within 5 years
3 – Poor	No maintenance needed at moment, but signs of degradation suggesting maintenance needed within 2 years
2 – Very Poor	Single area requires attention within 6 months
1 – Deteriorated	Multiple areas require attention within 6 months
0 – Severely Deteriorated	Requires attention urgently

The in-depth assessment involved noting and sketching the type, position and extent of a range of defects. The defects recorded included cracks, damp areas, spalling, rust staining, exposed reinforcement, as well as other defects. On-site, this was done by the inspector making measurements, taking photographs, and producing sketch diagrams showing the presence of defects on pre-printed sheets.

This information was then converted into the same format as the defect maps produced during the image-based inspection process.

Offsite, this involved using ChartCrack to inspect the processed and aligned images provided by IBIS, and mark the positions and types of defects. As part of the IBIS procedure, ChartCrack automatically produced defect maps showing the location of defects.

The results of the on-site and IBIS inspections were compared to determine whether the reported general condition of the bridge was similar regardless of the inspection method used.

In addition to the qualitative assessment, LNEC inspectors were supplied with images which contained the same visual acuity targets used in Chapter 6 to determine the required image resolution. The inspectors were asked to complete the same tasks as the test participants, and record the letters seen on the eye-test chart (L_A and L_B), and the orientation of lines on the visual acuity target (T_A). Figure 99 shows the images used to complete the tests on L_A, L_B, and T_A.

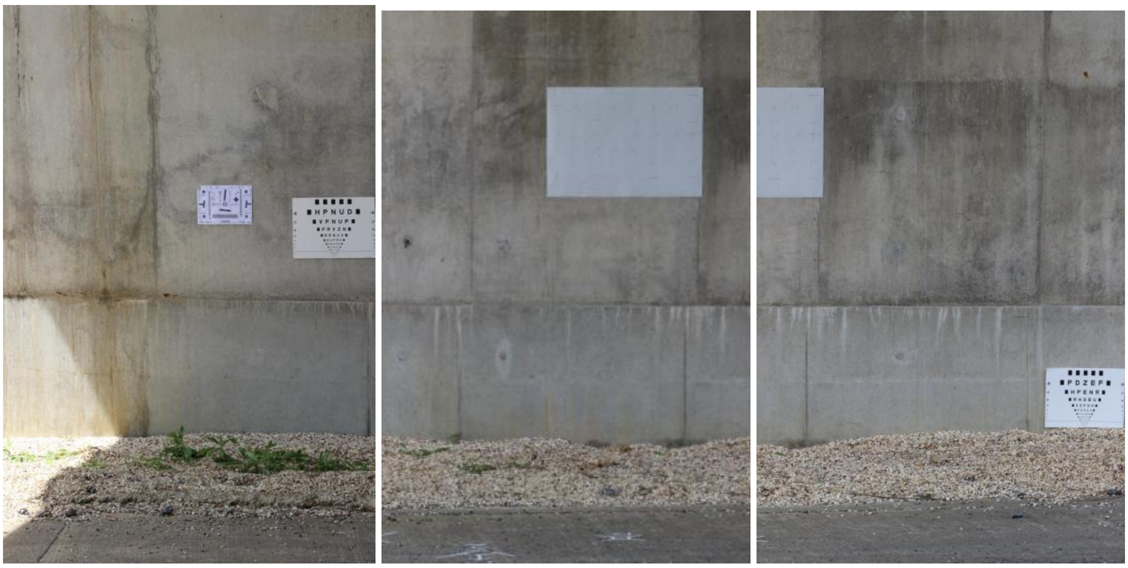


Figure 99: Images used by inspector to complete visual acuity tests using actual IBIS images.

9.1.2 Laboratory testing

To demonstrate the effect of image reprojection, and confirm that the image reprojection methods were being correctly applied, an experiment was undertaken in a controlled environment.

The experiment used a series of targets with known properties, which were fixed to a wall. The camera was set up 5m perpendicularly from the centre of the wall, with a 100mm focal length lens. Figure 100 shows the experimental set up.

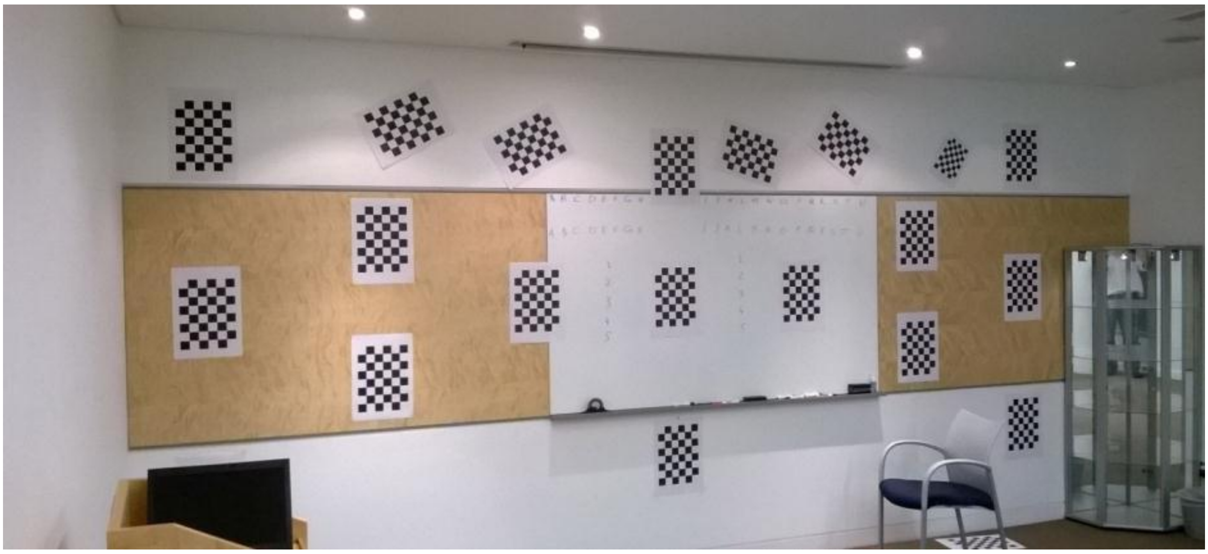


Figure 100: Experimental set up for demonstration of reprojection.

A plumb line was used to ensure that the targets were aligned as accurately as practically possible.

Images of the wall were taken at known camera orientations, with the bearings, elevations and distance measurements being used in the reprojection calculations.

To demonstrate the removal of perspective, lines were drawn on the images along the grids on the targets using Matlab. The equations of these lines were calculated before and after reprojection.

To demonstrate the uniformity of pixel size following reprojection the number of pixels in a block of squares was counted using images before and after reprojection.

The actual physical size of the squares was known by measurement to be 40mm x 40mm. The pixel size could then be determined.

9.2 Performance assessment of IBIS as GI method

Work described in Chapter 6 demonstrated under controlled conditions that by collecting images at 1 pixel per mm it was possible to detect more detail in a series of test targets than could be observed from a distance of 3m when viewing the same targets in a traditional manner. However, to validate that IBIS images would contain appropriate levels of detail the research has undertaken a comparison of traditional and IBIS based GIs.

9.2.1 Demonstration of potential for Image-Based Inspection

Initial work demonstrating the potential for using images to perform a GI has been reported previously by the author (McRobbie, et al., 2007). A summary of the findings of the assessment are presented here.

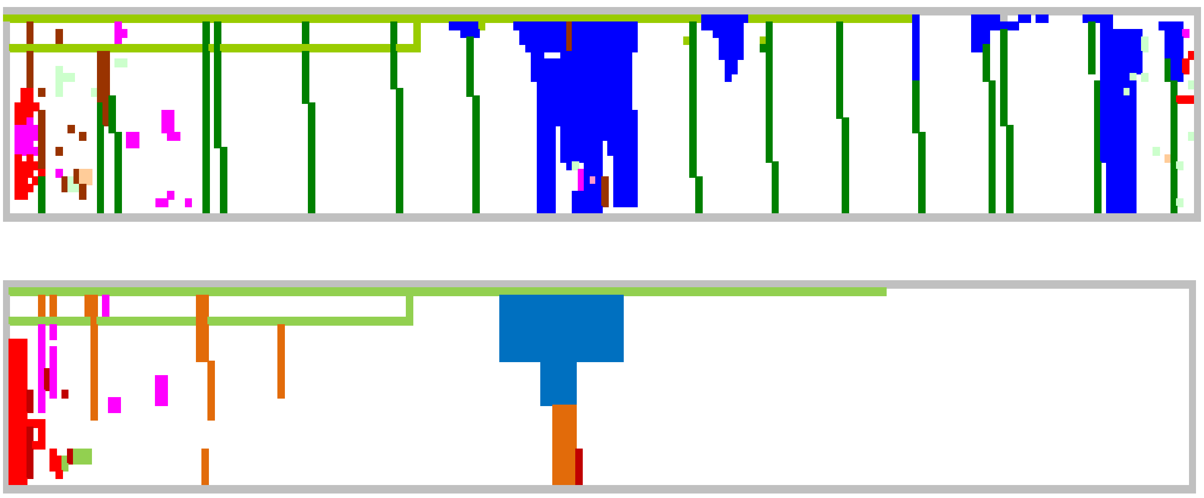


Figure 101: Defect maps produced by IBIS (top), and on-site inspection (bottom). Site (f), west abutment.

Figure 101 shows the defect maps produced during the image inspection and based on the on-site inspector's notes and drawings for the western abutment of bridge (f). The outline of the abutment is shown with the grey line; features which are supposed to be there are shown in green; defects are shown in reddish hues; blue indicates wet or damp areas. The image-based defect map includes more detail on the construction joints present, and there is more detail on the shape of the detected defects than in the defect map produced using the notes of the on-site inspector. For the creation of this defect map it had to be assumed that if something was not specifically mentioned in the report then it had been inspected, but was not defective.

The heavy concentration of defects at the south end of the west abutment (the left of the defect map) is apparent in both maps, as is the wet area in the middle of the abutment. The proportion of the bridge which was marked as being defective tended to be larger when the image-based methodology was used. This may be because every small defect was marked and recorded, whereas in a traditional inspection a representative sample of the defects would be noted and recorded, but not each and every individual defect. Also, the reported extent of large areas of defects tended to be larger with the image-based method.

Table 21 shows the results of the general condition assessment comparison on bridge (f).

Table 21: General condition assessment results

Element	On-site	IBIS	Difference
East abutment	5	5	0
West abutment	4 (2 at drainage)	4	0/-2
North external faces	5	5	0
South external faces	4	3	1
Overall	4	5	-1
Average	4.4	4.4	0

The differences between the condition ratings assigned on-site and looking at the images are generally small. Both inspection methods resulted in broadly similar results with, little difference. The on-site inspector assessed the west abutment in two parts, making a separate assessment for the drainage system at the south west end of the abutment (left hand edge of defect maps shown in Figure 101). This was deemed to be in 'very poor' condition and, in the opinion of the on-site inspector, should be replaced within 6 months of the inspection taking place. The rest of the abutment was deemed to be 'OK', an opinion shared by the Image-Based inspector, who did not provide a separate rating for this part of the abutment.

The inspector using the IBI approach felt that there was sufficient detail available in images provided by the prototype IBIS to enable an inspector to detect, and identify, a similar range of defect types and severities to those typically detected during a traditional on-site inspection. Comparison of the element condition ratings produced by the onsite and IBIS inspections (Table 21) indicated that inspectors came to similar conclusions on the overall condition of a bridge, or individual parts of a bridge, whether they visited it in person, or followed the IBI approach, provided the images were properly collected and presented.

9.2.2 Use of IBIS for performing General Inspection

To consider the use of IBIS data and tools specifically when completing a GI report experienced bridge inspectors were supplied with a set of IBIS images, the modified ChartCrack software, and were asked to undertake a GI using these. Figure 102 shows some examples of the IBIS images, overlaid with defect maps produced by the inspectors while undertaking this task. The complete set of defect maps is provided in Appendix D.

Figure 102: Example of defect maps created during IBI procedure.

9.3 Experience with IBIS

The experience of collecting, processing and using the images has provided understanding about the system usability and practicalities. This has identified strengths of the system, and areas which may require further development if the concept of routine IBI is to succeed.

9.3.1 Image collection

The Rodeon ST is robust and easy to work with following a short period of familiarisation. The process of assembling and connecting all the system components is straightforward and requires no specialist tools. The Rodeon ST motors are powerful enough to easily move and hold the payload steady throughout the data collection, meaning no image-blur due to platform motion was observed in the images.

The Rodeon ST is compatible with a wider range of DSLR cameras, and can cope with significantly heavier payloads than the GigaPan Epic used in the initial prototype (7 kg vs 0.68 kg). Using the Rodeon ST means that the system can use much heavier, longer lenses, meaning that it is possible to obtain the required resolution from longer distances (or get much higher resolution).

The GigaPan Epic system used six AA batteries which drained quickly, particularly when the system was being asked to carry payloads at the upper end of its capabilities. It was usually necessary to change the batteries after every 100 – 150 images, which involved interrupting the image collection procedure, and potentially disturbing the positioning of the system. The Rodeon ST system includes two 11.1V 5200mAh batteries, each of which can provide approximately 7 hours of working time, and can be recharged in 4 hours. Changing the batteries over when necessary does not involve removing the camera from the system, or the system from the tripod, reducing the risk of inadvertently altering the system position.

The Rodeon is controlled via a Bluetooth connection to the control PC, and can therefore operate wirelessly. The recorded images could be left on a memory card in the camera for later download and analysis, but downloading them via a USB cable as they are recorded makes it simple to check the image quality. This introduces a cable to the system, but it was decided that the benefits of being able to check the images outweighed the negative aspect of a slight mobility restriction for the operator. The RODEONmodular control software provides guidance which is useful in the lens selection process. This calculates and reports the maximum focal length which can be used with the selected scene FOV and number of images to be collected at each IP. The calculations described in Section 8.2.2 determine the minimum focal length necessary to produce images at the required resolution. If the lens used has a focal length long enough to provide adequate detail, and short enough to produce full coverage then the imaging should be successful.

Data provided by the distance measurement laser delivers measured values for parameters which were previously estimated. This means that the reprojection and alignment calculations can use more accurate data, making the need for accurate placement of the system prior to image collection less important. This relaxation of the need for accurate system placement means that much less time and care is required when positioning the system, which reduces the time spent on site.

9.3.2 Image coverage

If the image collection process is followed properly, the images provided by the core IBIS hardware (camera, Rodeon ST, tripod, etc.) provide full coverage of all parts of the bridge which are visible from the selected IPs, at the required resolution of 1 pixel per mm. It is important to ensure that the images collected have adequate overlap, and that they cover areas outside the scene of interest as the reprojection and scaling process results in portions of the edges of images being removed in order to produce rectangular orthoimages. An example of a full image set as recorded by the IBIS is provided in Appendix D.

Images of the upper deck surface, collected using HARRIS2, were felt to be beneficial by inspectors as it allowed them to see a part of the structure which was not visible using IBIS images alone. The inspectors also appreciated the provision of a few 'general view snapshots' of the bridge, allowing them to understand the environment the bridge was in, and put what they saw in the detailed images in context.

There are currently no methods in place to remove obstructions, or to routinely get cameras into parts of the bridge which are not visible from the IPs. However, no special access arrangements or equipment are used in traditional GIs, which are therefore affected by the same problems. Images could be collected in some of these situations, but it would be hard to do so systematically, controlling the image resolution and guaranteeing full coverage of affected areas.

9.3.3 Image alignment

The reprojection and alignment processing is done automatically following the creation of a file detailing the image names, camera bearings, elevations and distances from the bridge for each image. Producing this file requires little effort from the system operator and the subsequent processing requires no further input and can be done overnight.

The introduction of laser distance measurements makes the system more resilient to small errors in initial mis-location of the system IPs, as the calculations use measured, rather than estimated, values. The Rodeon ST also offers more accurate and more repeatable positioning of the camera, with the precision of the positioning data available being more than an order of magnitude more accurate than the GigaPan Epic.

Additionally, the image alignment is no longer solely reliant on the camera position information when calculating how images align relative to one another. The success of the image alignment processing was judged to be significantly better following the introduction of the hybrid camera-orientation/cross-correlation approach.

9.3.4 Software and interaction

In general, the inspectors were pleased with the functionality of the software, and found the interface 'simple and intuitive to use'. They liked the way in which defects or features could be selected from a customisable list, and that locations of detected defects could be marked. The generation of defect maps showing the position and type of defects was seen as useful, as was the ability to share inspections with others to discuss interpretations of what particular features might be, or might mean for the bridge condition and maintenance needs.

The current software is limited to recording one defect in any grid square. This could be overcome by outputting a separate defect map data file for all the possible defect types, and adjusting the way in which defects were displayed. The inspectors who used the system developed their own workaround solution by simply marking one square as containing one defect, and marking an adjacent square as containing the other defect. The fact that the inspectors managed to develop this solution unprompted, and with no guidance, reinforces the ease of use of the software, and suggests they felt very comfortable in using it.

The thumbnail facility and the lower resolution images were also appreciated by the inspectors. These mean that it is not necessary to continually switch between zoomed in views to see detail, and zoomed out views for context. With the thumbnail facility it is possible to keep the low resolution view open all the time, as well as a separate window containing the detailed view.

9.3.5 Summary of experience with IBIS

The inspectors found ChartCrack very easy to use and, although a detailed help manual is available (Appendix E), they reported that once familiar with the basic functionality and interface there is no need to spend a long time reading the manual. It was reported that the process of becoming familiar with the software could be achieved in no more than fifteen minutes. The inspectors who used the software found no issues with it regarding the speed of system response, or the ease of moving around within the imageset, or marking defects.

The inspectors found that the addition of general views of the bridge was helpful, and that this put the detailed views into context, and made it easier to mentally place themselves on-site and interpret the images. It was also found that the inclusion of images from HARRIS2 surveys over the top of the bridge was beneficial as these showed features and defects which were valuable in assessing the condition of the bridges.

There were some areas where it was felt the IBIS could still be further developed. For example it was reported that the combined image collection and interpretation processes still took significantly longer than traditional inspection approaches, and that the ability to change viewing angles and move obstructions while on-site were beneficial and were missing from the IBIS approach. Overall however, in the view of the inspectors, it was concluded that performing an image-based GI was possible, using images supplied, processed and aligned by the IBIS, with additional images from HARRIS2, with ChartCrack as the visualisation and interaction platform.

9.4 Assessment against defined IBIS requirements

Chapter 6 described the work undertaken to develop a set of requirements which a successful IBIS must meet. These requirements were used in the assessment of the usefulness and practicality of available systems for use as a routine IBIS in Chapter 7, which found that none of them met the requirements. The development of the IBIS (Chapter 8) was undertaken with this list of requirements in mind.

The following section presents an item by item discussion of the performance of the prototype IBIS against the draft requirements developed in Chapter 6.

9.4.1 Data collection

9.4.1.1 No special access or Traffic Management.

Meeting this requirement requires that the system can be operated from a footway or verge. On bridges with suitable footways and/or verges the IBIS has been seen to meet this requirement, as successful image collection surveys have been undertaken with no TM or special access in place.

Some bridges do not have suitable footways or verges, but these cannot be inspected easily using traditional GI methods. The IBIS may require special arrangements in order to collect data on such bridges, but so too would a traditional inspector.

9.4.1.2 No disruption or distraction to traffic.

The IBIS operates from the verges and footways and does not interfere with traffic. The operators only have to cross the carriageway to move the system from one side of the bridge to the other, and do not need to collect any images or data while on the carriageway. In a traditional GI the inspectors must also cross from one side of the carriageway to the other. During the development and testing of the IBIS it was noticed on a few occasions that drivers of passing vehicles were sometimes too interested in what the system operators were doing, or appeared to mistake the system for a speed camera and braked abruptly. The use of prominent 'Surveying' road signs reduced the instances of this happening.

9.4.1.3 System must be safe for operators and public.

Because the system operation does not need the operator to encroach on the carriageway there is no substantially increased risk to operators compared to just walking around the bridge undertaking a traditional inspection. The potential dangers to the operator are the same roadside dangers which would be faced by anyone inspecting or using the bridge. The tripod presents a minor, temporary obstacle to pedestrians, but the footprint of the tripod is comparatively small and it does not completely block a typical footway. Experience with the system found that it was rare that the system had to be moved to let pedestrians past, and that by marking the locations of the tripod feet it was simple to replace the system in the correct location and continue image collection.

9.4.1.4 Images must be recorded of all visible parts of bridge that would be normally included in a traditional General Inspection.

The core system can collect images of all surface parts of a bridge, apart from the surface of the pavement running over the top of the bridge. Images of this can be provided by pavement condition survey vehicles. The system cannot look into bearing shelves or behind fences or panels mounted close to the bridge. If it is easy to get a clear view of any part of the bridge from the existing footways or access arrangements then it is possible to collect images.

The systematic, automated image collection procedure helps to ensure that all parts of the bridge are imaged with no gaps.

9.4.1.5 The system must be able to facilitate the assessment of a range of different bridge types and designs.

The system has been used on the bridges shown in Figure 98. These include a double masonry arch bridge, a number of concrete beam and slab bridges, and a precast concrete bridge over a canal. Although not exhaustive, this shows that the system is versatile enough to work on more than one type of bridge, and that, if access is available, and the areas of interest are not obscured or hidden, then the method is applicable.

9.4.2 Data delivered

9.4.2.1 Must provide a full image record of whole surface of structure, excluding obstructed parts.

If IPs are correctly chosen, and the system is set up and operated correctly then this will provide image coverage over the whole bridge. If all parts of the bridge are successfully imaged, then the processing and alignment of images should result in a complete imageset for each imaging position with no gaps or duplication (see example imageset in Appendix D). The selection of appropriate IPs is not fully automatic, but spreadsheets have been developed to perform the calculations outlined in Section 8.2.2. These calculate the lenses required to collect images at the desired resolution given the bridge dimensions and the likely locations of the IPs. The additional images provided by traffic speed pavement condition surveys now fill the major gap in the image record supplied by the core IBIS. A permanent, high-resolution, image record is now supplied of all visible, non-obstructed or obscured parts of the bridge.

9.4.2.2 Images must provide clear views of all parts of bridge.

The orthoimages produced by the reprojection processing provide a 'face-on' view of all parts of the bridge, with perspective effects removed (Section 8.3.1). If the IPs have been correctly determined and the collection procedure is carried out correctly then all parts of the bridge (which have been imaged) are clearly visible in at least one image.

9.4.2.3 Images must be well lit.

As mentioned in Section 8.1 the IBIS has been designed to operate without artificial lighting. Consequently the system does not use a flash. If bridges (or tunnels) are particularly long, or the image collection takes place when there is insufficient natural light available then artificial light could be used, but only with appropriate traffic management measures in place.

The aperture closure necessary to produce a larger DOF and improve the image focus restricts the amount of light received at the sensor, but this can be countered by using a longer exposure time, provided the camera platform is stable enough. The important thing, and what this requirement is trying to ensure is not really that the images are 'well lit', as the lighting used when collecting the image is of no concern to the engineer looking at the images. Rather, what is important is that the images contain the important details and that features can be seen. Even if a digital image looks as if it has been over or under exposed (as discussed in Section 6.3.1.1) image processing methods can often be used to extract the information which has been recorded, producing useful images and data from seemingly useless input images.

Figure 103 shows an example of an underexposed image before and after application of image processing techniques to highlight and present details which were originally difficult to see.

Figure 103: Portion of underexposed image of top of a bridge abutment (top); same image following image processing (below).

A total of 317 images were collected to produce the imagesets shown in Appendix D: of these images, none were deemed to be inadequately lit, using a subjective assessment.

9.4.2.4 Images must have a minimum resolution of 1 pixel per mm.

The reprojection process produces images with a consistent pixel size, and it is this process which sets the output image resolution. This is achieved by a mathematical scaling of input images to achieve the desired resolution, and as long as the input image has sufficiently good resolution then the required output resolution can be achieved. The required input resolution varies with the desired output resolution, the camera-object distance, and the camera orientation (Section 8.3.1).

Qualitatively, the inspectors judged the images provided to be of 'good' quality, stating that the images presented sufficient detail for them to detect defects and zoom in for close views where required.

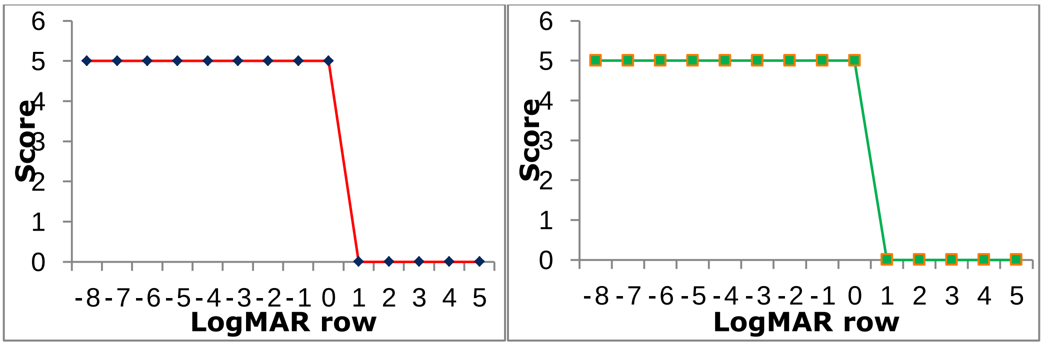


Figure 104: Results of inspector visual acuity testing on standard eye charts (L_A on left, L_B on right) using IBIS images shown in Figure 99.

The results shown in Figure 104 compare well with the results of the image acuity experiment (Figure 47). Using the supplied images the inspectors were able to correctly identify all letters up to and including the ninth row (labelled '0' on the chart). This is a better performance than was obtained in the resolution and acuity investigation by participants at 3m, and is similar to what was achieved in the investigation using images collected under controlled conditions at 1 pixel per mm.

It can be seen comparing Figure 105 (showing the inspectors recorded line orientations on target T_A) and Figure 106 (showing a zoomed in portion of the actual image containing T_A) that the inspector made one mistake in identifying the orientation of the lines in the visual acuity target. On the bottom row of the target they labelled a cell as containing a single diagonal line, when in fact it also contained a horizontal line, as can be seen in the zoomed in view of Figure 106, shown here as Figure 107.

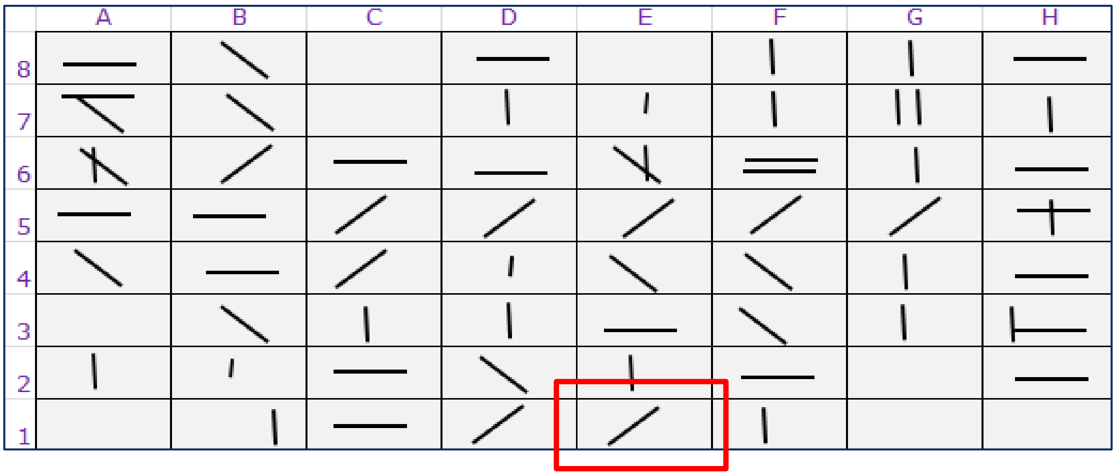


Figure 105: Inspector's recorded results identifying orientation of lines as seen in Figure 106.

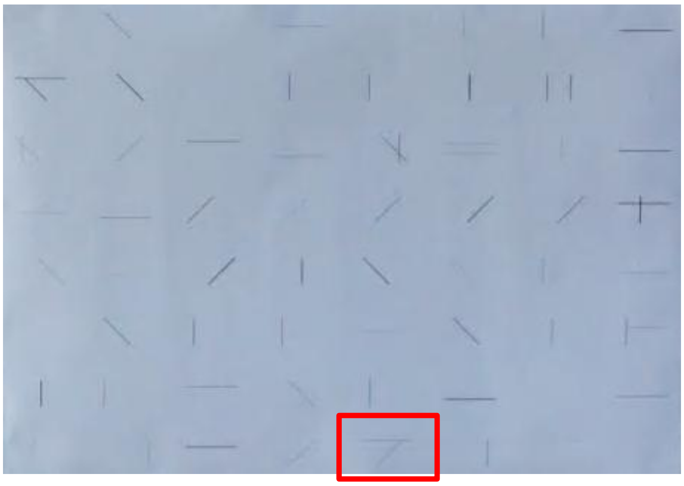


Figure 106: Image used to complete visual acuity tests (left), and close up view of test target.

Figure 107: Close up of location where inspector's answer was incorrect in image shown in Figure 105, showing presence of 2 lines in box.

It is unclear whether the inspector did not see the horizontal line, or simply failed to mark it on the results sheet. However, because of the image record being available it is possible to look again at the image and determine it was there. This would not be possible in a traditional inspection. The thickness of the missed line was 0.14mm. This is thinner than the minimum required crack width determined in the consultation of 0.4mm, so failure to detect this is acceptable. The results shown in Figure 108 compare well with those from the experimental work (Figure 49), which showed that inspectors sometimes failed to detect lines of this thickness even at 3m.

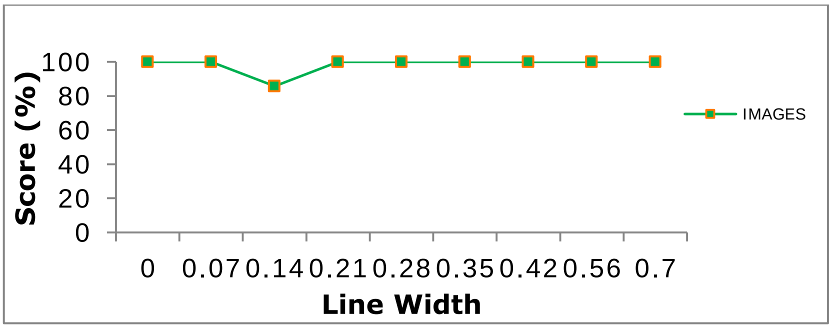


Figure 108: Results of LNEC visual acuity testing on line thickness target.

These images were collected on a real bridge as part of a standard IBIS image collection survey, using the same hardware and settings, and subjected to the same processing and reprojection. The results obtained on the test charts are similar to those obtained in the Chapter 6 investigation when looking at images at 1mm per pixel. It can be concluded from this assessment that the images supplied using the IBIS are comparable to those obtained under ideal test conditions, are at resolutions of 1 pixel per mm, and that the detail presented within them is adequate for inspection purposes. Therefore it can be stated with high levels of confidence that an inspection performed on such images can detect defects which would be expected to be detected in a traditional inspection.

9.4.2.5 Images must be properly focused.

This is vital for the images to be useful, and proved surprisingly difficult to achieve, even with use of camera autofocus capabilities. Changes to the camera settings and aperture have resulted in a wider depth of field for the images. This has produced better focussed images with no examples of unacceptably focussed images seen in the final imagesets collected using the IBIS and supplied to the inspectors for use in completing GI reports (Appendix D).

Feedback from the inspectors and engineers who used the system was that when the images are focussed they are good and fine detail can be seen.

9.4.2.6 Image pixels must represent areas of constant and consistent size over whole bridge (or over elements of bridge).

Images taken at different camera orientations from a common IP will have different distances from the sensor to the bridge. This results in the area of the real world represented by individual pixels changing depending on the orientation of the camera and the distance to the bridge.

Figure 109 shows examples of the target areas of images taken at different camera orientations using the experimental setup described in Section 9.1.2. The images shown were taken from the upper left corner of the scene (left), the centre of the scene (centre) and the upper right corner of the scene (right). The upper row of images shows the targets in the collected images, the lower row shows the targets following reprojection and scaling. The dots on the images show the locations of vertices which were used in the calculation of straight lines to demonstrate the effect of reprojection.

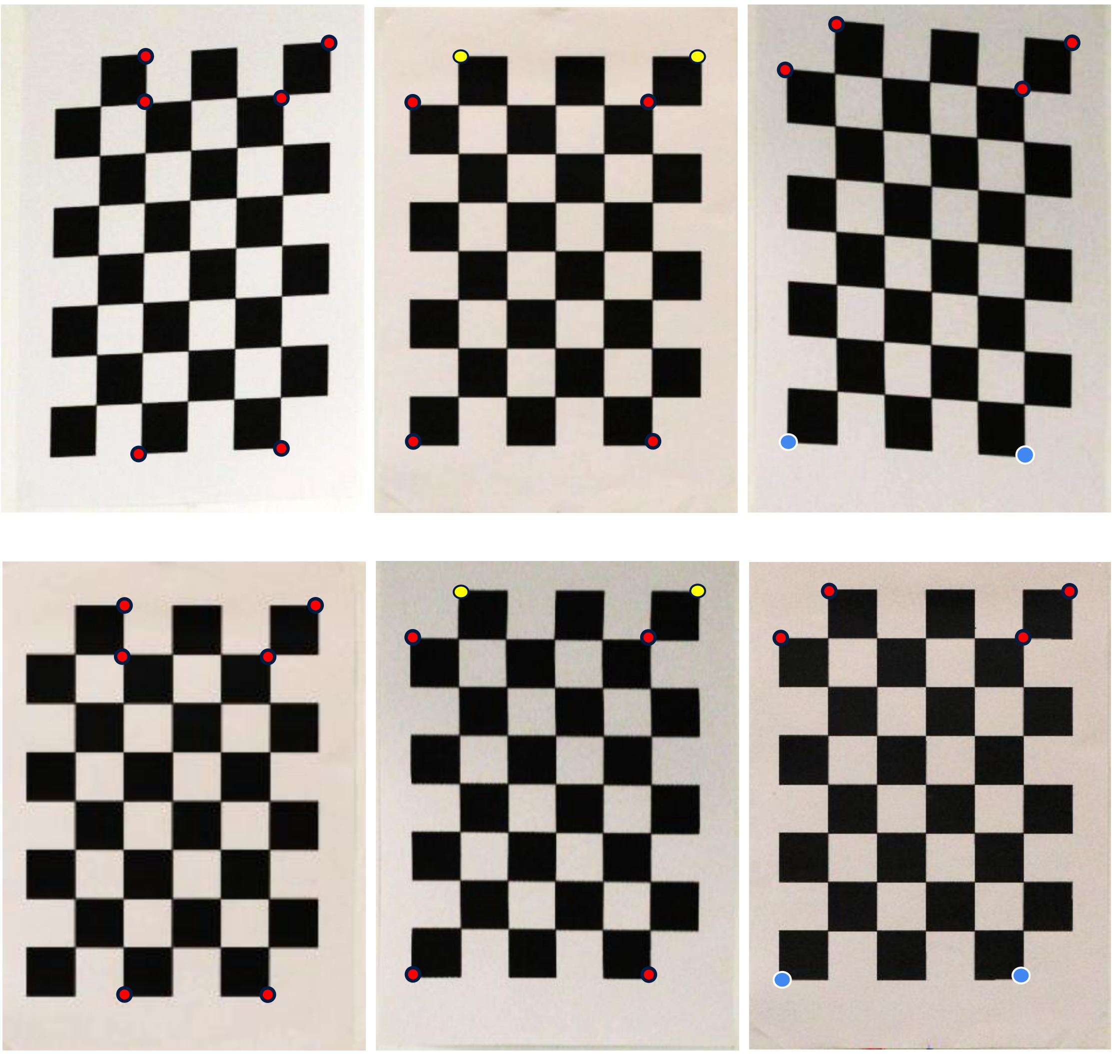


Figure 109: Examples of images before (top) and after (bottom) reprojection to remove perspective effects.

Table 22: Examples of gradients of lines used in demonstration of image reprojection as a method to remove perspective in images

		(x, y) point 1	(x, y) point 2	Gradient
Central image (yellow dots)	Collected	(1558, 435)	(2512, 436)	0.00105
	Reprojected	(337, 97)	(541, 97)	0
Upper right image (blue dots)	Collected	(1458, 3188)	(2206, 3234)	0.0615
	Reprojected	(302, 708)	(502, 708)	0

The lines calculated using pixel coordinates in the reprojected images have gradients of zero (shown in Table 22). This demonstrates that the reprojection has correctly adjusted the positions of image pixels to represent horizontal features correctly, demonstrating that the reprojection is correctly removing the effects of perspective.

Figure 110 shows three images before (top) and after (bottom) reprojection, and has three areas highlighted within each image. These three areas were the squares which were measured in the pixel size calculations, the results of which are shown in Table 23.

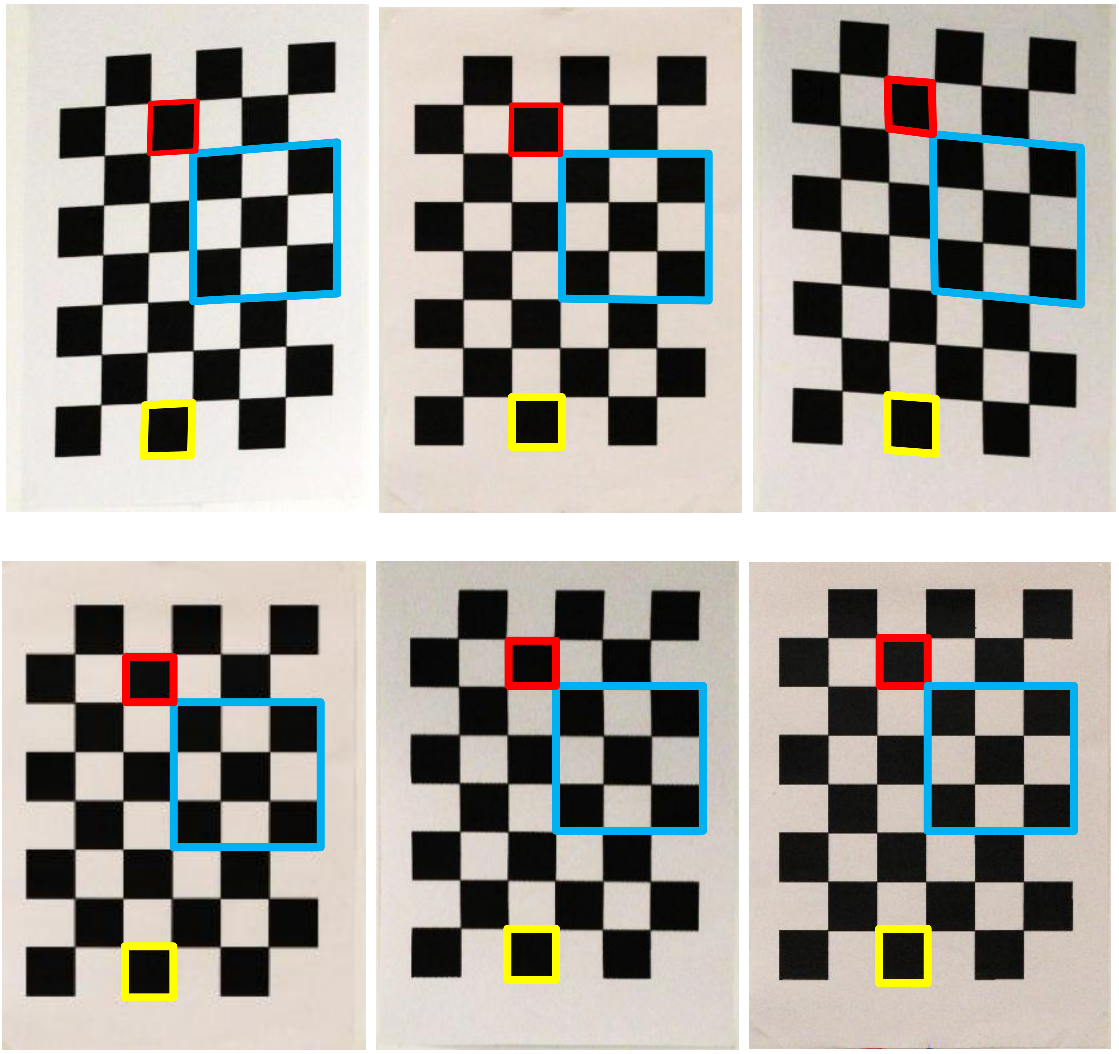


Figure 110: Examples of images before (top) and after (bottom) reprojection showing squares used in measurement of pixel size.

The mean sizes of pixels in the reprojected images are not exactly 1.00, but they are very close. The reprojection does reduce the image resolution (in this case from between 4 and 5 pixels per mm to 1 pixel per mm), but the consistency of pixel size over all parts of all images is vital in providing the ability to accurately align images and measure defects therein.

Table 23: Mean pixel size before and after reprojection of images

Image position		Mean pixel width (mm)	Mean pixel height (mm)	Mean pixel size (mm)
Top left	Collected	0.26	0.24	0.25
	Reprojected	0.97	0.98	0.97
Central	Collected	0.21	0.21	0.21
	Reprojected	1.00	1.00	1.00
Top right	Collected	0.27	0.24	0.25
	Reprojected	1.01	1.00	1.00

9.4.2.7 Image display system used by inspectors to complete inspection must display aligned images with no gaps between images, or duplications of imaged features.

The image reprojection process calculates the alignment coordinates of each image on the plane of the imaged surface. The hybrid image alignment approach has improved the accuracy of image alignment meaning the images are now automatically aligned to within a few mm. If the image collection process is carried out correctly and there is sufficient overlap between images then there are no gaps in the image record, and the accurate hybrid alignment means there are very few duplicate features in the display. The overlap in the images means that some features will be duplicated within the imageset, but the way in which the images are displayed, with only one image of any location being visible at a time means that the display does not show these.

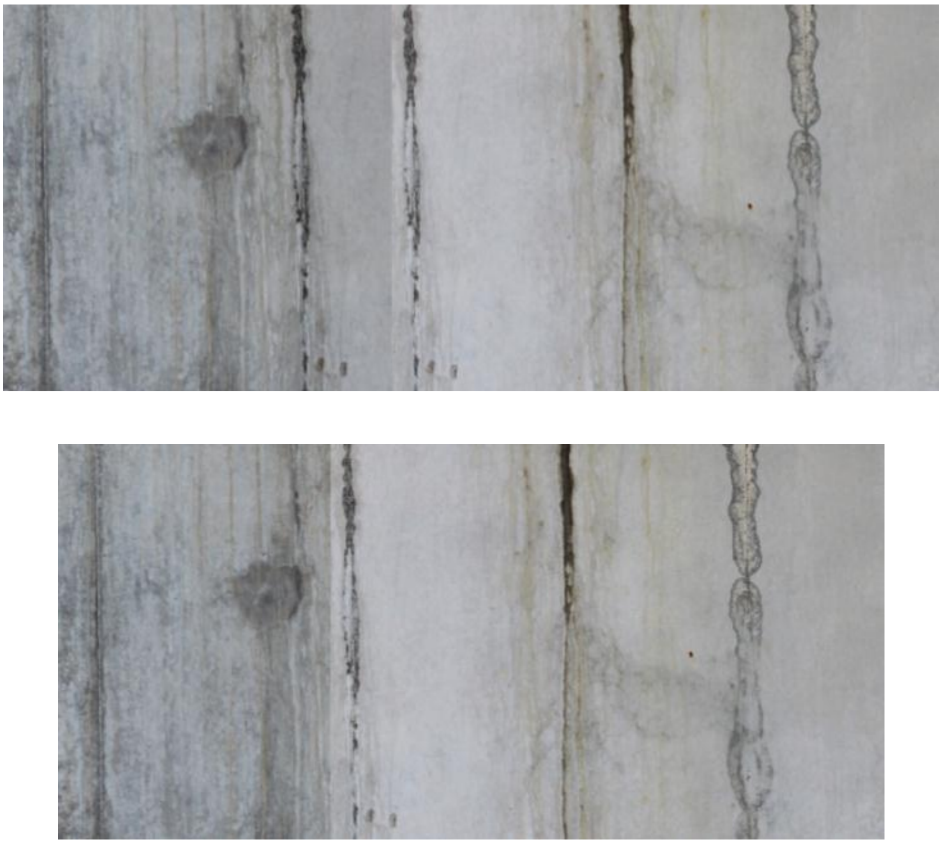


Figure 111: Images aligned using bearing and elevation data only (top) and with image cross-correlation information (bottom).

Figure 111 shows images which have been aligned using only camera orientation information (top), and with the hybrid camera-orientation/cross-correlation approach (bottom). The duplication of features in the top image can be clearly seen. This has been removed in the lower image, which has been produced using the hybrid alignment method. In the top image, the horizontal misalignment shown is approximately 220 mm, in the lower image the misalignment is now less than 10mm.

9.4.2.8 The image inspection system must allow the inspector to identify and record the location, type and severity of any defects, within the individual image, and within the context of the bridge as a whole, to within 0.5m of actual position on bridge.

The modified ChartCrack system used to facilitate the Image-based Inspections can use grid squares of any size from 20mm to over 1000mm. This means that the location information available can also be at these levels of detail, although errors in the reprojection process caused by measurement error may cause small location errors.

The accurate measurements provided by the distance measurement laser, and used in the reprojection and alignment calculations, combined with the hybrid image alignment approach described in Section 8.3.2 mean that each individual image is aligned to within 10mm of its true position relative to its neighbouring images. It would be possible for these minor mis-alignments to build up and compound one another. For example if image column 1 is correctly located, image column 2 may be shifted 10mm to the left of its correct location, and image column 3 may be shifted 10mm left of its correct position, relative to image column 2. This would be 20mm left of its correct position relative to image column 1. Typically somewhere between 7 and 15 image columns are required from each IP, meaning that the maximum expected error in pixel position would be closer to 150mm, which is significantly less than the 500mm requirement.

The measured length of abutment on bridge (e) for example was 11.01m. The inferred length of this same abutment using calculated pixel positions was 11.10m, a difference of 90mm. Similar results were found on other bridges.

9.4.2.9 Image views must be consistent enough that year on year comparisons can be made in the certainty that any apparent changes are genuine and not merely a result of different imaging conditions.

Figure 112 shows images of part of a bridge, taken with the IBIS during three different inspections. Figure 113 shows images provided as part of traditional General Inspection reports undertaken in different years.

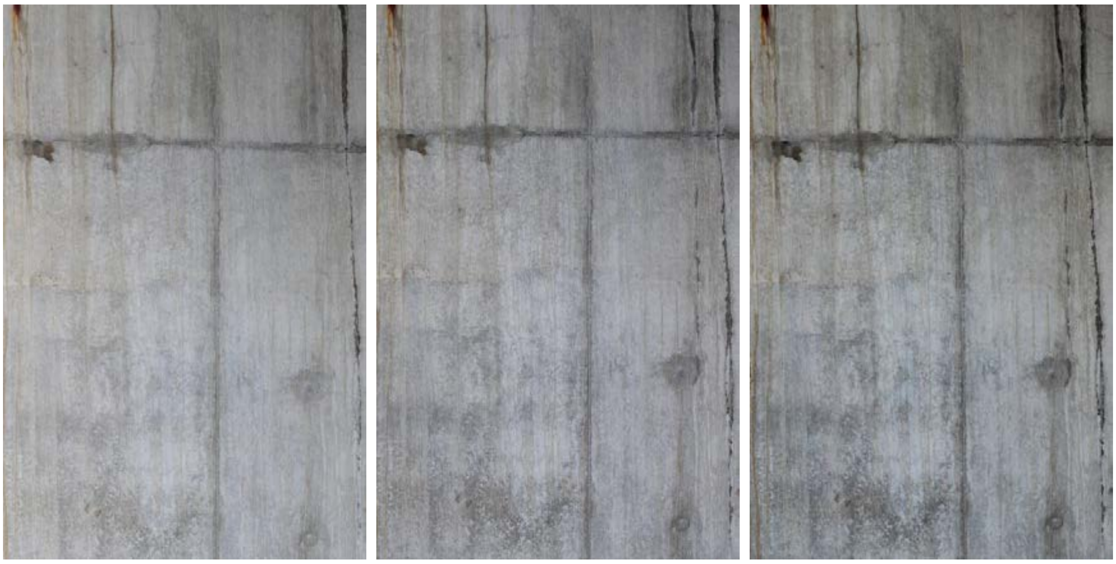


Figure 112: Images of same part of bridge collected during different survey visits using IBIS.

Figure 113: Images of same part of bridge collected during different survey visits using traditional GI methods.

Although both images in Figure 113 show the same part of the bridge, and are illustrating the same defects, the way in which the images have been taken and presented makes it difficult to judge the progression of the defect. The way in which the IBIS images in Figure 112 are presented makes it much easier to judge and assess changes in the bridge condition.

Figure 114 shows images from successive sweeps of the bridge surface. The laser measurement device was swapped in and out between the collection of image 1 and image 2. Specific, matching points in each image have been identified by close inspection, and the pixel coordinates of these positions in each image recorded.

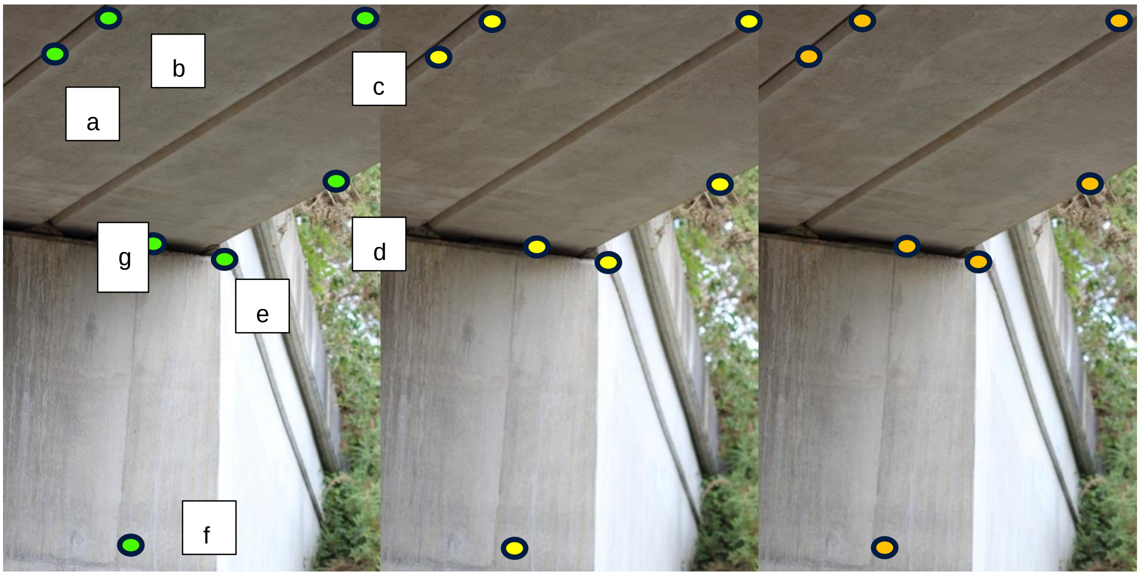


Figure 114: Three images taken in successive sweeps of bridge surface showing repeatability of positioning.

Table 24 shows the mean position of each of these points, and the deviation from this mean for each point in each image.

Table 24: Differences in observed pixel position of features in images shown in Figure 114

Image	a	b	c	d	e	f	g
Mean Position of point	(312, 631)	(819, 259)	(3279, 198)	(3016, 1648)	(1983, 2418)	(1038, 5165)	(1248, 2283)
Difference between mean position of point and individual position of point							
1	(1.6,15.3)	(0.6, 17)	(0.3, 15)	(3.6, 12.6)	(3, 11.6)	(4.3, 15.6)	(2, 15.6)
2	(0.3, 9.6)	(0.6, 11)	(0.6, 10)	(0.6, 9.3)	(2, 4.3)	(2.6, 10.3)	(0, 11.3)
3	(1.3, 5.6)	(1.3, 6)	(0.3, 5)	(4.3, 3.3)	(1, 7.3)	(1.6, 5.3)	(2, 4.3)

It can be seen that the largest differences in measured position are between image 1 and the calculated mean of the positions. This is likely to be due to the system being nudged slightly while exchanging the camera and the laser. However, even with this happening, the difference in the pixel location of the seven measured points is, on average, 1.65 pixels in the x direction, and 9.8 pixels in the y direction. This is an average difference of less than 2mm in x, and 10mm in y.

9.4.3 System Practicalities

9.4.3.1 Time on site should be minimised

The actual process of image collection is automated and fast, allowing images of a 15m x 5m abutment to be collected in under 5 minutes, however the process of moving the image collection system from IP to IP, positioning the system, and ensuring it is correctly set-up takes 15-20 minutes per IP. A simple bridge with 2 wingwalls and a parapet at each end, abutments and a soffit therefore requires about 12 IPs. This will take about 1 hour of actual image collection, interspersed with about 4 hours of setting up and measuring. Collecting images with the IBIS therefore takes significantly longer than a traditional GI (see Section 2.3.7).

GPS cannot be used to locate the IPs as signals in the environment in which the system will be used (under bridges) are poor. If the image collection positions could be permanently marked somehow this would reduce the time considerably, meaning that approximately 10 minutes per station would be needed. This would possibly allow all images to be recorded in about 2 hours.

The battery life of the Rodeon ST is much improved from the GigaPan Epic which required frequent changes of the AA batteries used to power it. The procedure for changing the batteries in the enhanced system is also much simpler and faster, and does not require the system to be disassembled.

9.4.3.2 Time to process data ready for inspection should be minimised.

The processing is currently very slow. The current approach, (as outlined in Figure 97) uses code written in Matlab which has not been optimised for speed, but to be robust and provide detailed debug information. The processing is however largely automated, and can run unsupervised following the creation of a short batch file containing details of files and camera orientations. The processed images are not available on-site, but the collected images are. These can be used to ensure the basic image quality is adequate, and that images are suitable for further processing.

9.4.3.3 Ease of use / required expertise

There are two possible approaches to the complexity of the system and the required expertise of the operator:

- One way would be to outsource the collection of inspection data to specialised contractors who collect and process data and supply results, which could be either images and data ready for an inspection, or a full inspection report. This approach would allow the system to be quite complex and require a high degree of training for the operators.
- The alternative approach would be for a system which was much more simple and straightforward to operate, which would reduce the required expertise of the system operator, and hence reduce the cost of the survey. Such a system may require no more than a couple of days training.

Experience with the IBIS suggests that the ease of use and user friendliness of the system is good, and the system could be operated by inspectors or surveyors following a couple of hours training.

9.4.3.4 Data processing and alignment should be as automated as possible and require a minimum of human intervention at any stage.

It currently takes approximately 5 minutes for the Matlab code to reproject each image and calculate accurate alignment coordinates. However, this process requires no manual input. The system requires a batchfile containing the image name, bearing and elevation, and a separate file giving details of the camera, the lens and the camera position relative to the bridge; all subsequent processing is fully automated.

9.4.3.5 *Data processing should be done in such a way that 'corrections' can be made to the output if any are needed.*

Image alignments are provided as a simple text file with (x,y) coordinates of each image. These can be overruled and adjusted if necessary. Changes to the image coordinates within the text file will change the alignments of the images within the display and inspection software. It is therefore possible to adjust the position of any individual image if this is required due to errors in the alignment process.

9.4.3.6 *System must not be significantly more expensive than a standard inspection and any increase in cost must be justifiable.*

The total cost of hardware in the enhanced system was just under £7.5k. However, the major cost of adopting an IBI approach is the time needed to collect and process the images. The system provides data beyond that provided by a traditional GI, which can be used for a range of purposes, such as training, consultation, tracking defect evolution, or record keeping to demonstrate that a particular feature was or was not visible at a particular time.

9.4.3.7 *The images must be suitable for use in an image-processing based automated inspection system.*

The investigation and development of methods for automatically analysing and interpreting the image data to detect and characterise features and defects on the bridge has not been a major focus of this work, but related work by the author (McRobbie, 2008), together with the use of IBIS images (Mehrabi, 2012) has demonstrated that IBIS images are suitable for such processing. Figure 115 shows some examples of IBIS images following the application of different image processing techniques, demonstrating that the images should be suitable for use in such a system.

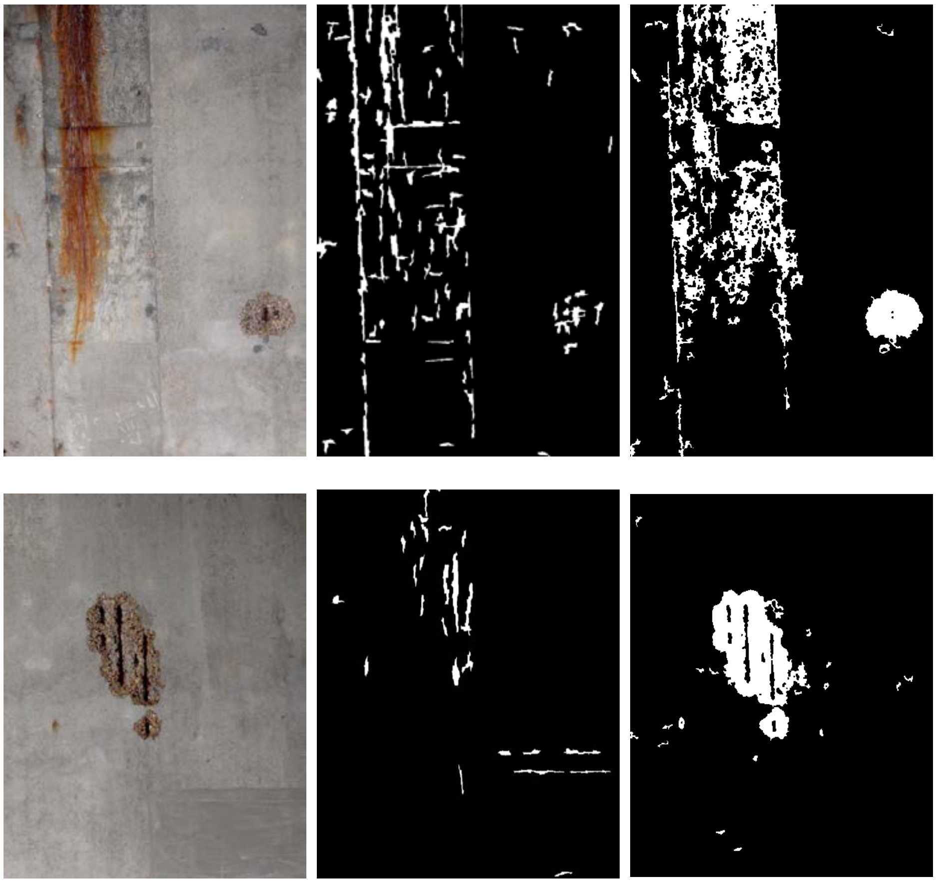


Figure 115: Example IBIS images following different image processing techniques.

9.5 Summary of IBIS suitability for use in routine visual inspections

Table 25 summarises the findings of the assessment of the IBIS in terms of the strengths and weaknesses of the system.

Table 25: Summary of strengths and weaknesses of prototype IBIS

Strengths of prototype IBIS
Following set up and location of system at imaging position, process is largely automated from collection, through processing, alignment and display.
Produces image record of surveyed parts of bridge.
Image quality (when collected properly) good enough to detect defects of interest.
Consistency of view from inspection to inspection and inspector to inspector reduces some of the inherent variability of visual inspections.
Provides consistent levels of detail over all imaged parts of bridge, so that all parts can be inspected at consistent detail, unlike traditional inspection where some parts are far from the inspector and cannot be well inspected.
Weaknesses and issues requiring refinement (or further research)
Initial set up and measurement to locate imaging positions takes a long time.
Images must be reprojected and aligned prior to inspection.
Image illumination is sometimes uneven between images, leading to large changes in colour balance in final imageset.
Obscured or hidden parts of the bridge cannot be inspected.
Alternative viewing angles are not available.

10 SUMMARY OF PART 2 - IMAGE-BASED INSPECTION SYSTEMS: REVIEW, DEVELOPMENT AND TESTING

A draft specification has been produced detailing the requirements of a viable Image-Based Inspection System if it is to operate and provide data at a level comparable to that provided in a traditional UK General Inspection. This considered the levels of detail which are reported during a GI and involved an experiment to determine whether such levels of detail could be discerned at various typical inspection distances and within images at different resolutions. The experiment found that more detail could be resolved in images at 1 pixel per mm than was resolvable from a viewing distance of 3m in a traditional inspection. It was therefore concluded that if the IBIS could provide and present images at this resolution then they would contain sufficient detail to enable inspections to be performed.

Existing systems which appeared to be suitable candidates for use in an IBIS approach were identified and assessed against the draft requirements. Where possible the systems, or data from the systems, were assessed first hand, but due to budgetary restrictions it was impossible to do this for all systems, and some were assessed as desk studies.

It was concluded that none of the available systems were ready for use as a method for undertaking routine visual inspections of bridges. However, a number of the systems investigated had aspects which could be adapted and developed into an IBIS, either in hardware, or methodology.

Bearing in mind the requirements for an IBIS, and the lessons learnt in the assessment of existing systems, a prototype IBIS was developed. This was based on the use of a camera mounted on an automated pan-tilt unit, which could be positioned around the bridge and which would control the collection of the images. Methods to process and align the images, and present them to an inspector for analysis were developed, along with software to implement the methods. Using this it was possible to mark the type and location of defects or features within the images.

Assessment, including some by independent expert inspectors, of the use and usefulness of the IBIS found that the images were of high enough resolution to be useful, and the software provided for viewing and inspecting the images worked well in terms of its capability and functionality. It was found that it was possible to undertake a GI and detect defects of interest using images alone, without having visited the bridge in person. It was also demonstrated that the results of an IBI were comparable to those obtained during a traditional inspection. The capabilities of the reprojection and alignment methods developed during this research were assessed and it was demonstrated experimentally that the images presented for inspection have pixels of a uniform consistent size, and the effects of perspective are reduced considerably, if not removed entirely. The capabilities and functionality of the IBIS were assessed against the draft requirements developed in Chapter 6, and it was found that it met most of the requirements, although it was noted that the on-site setup required to ensure that the system was correctly located at the calculated imaging positions was time-consuming.

An overall summary of the findings and conclusions of the research (Parts 1 and 2) is presented in Chapter 11, followed by ideas for future research in Chapter 12.

11 FINDINGS AND CONCLUSIONS

11.1 Findings of research

Visual inspections play a key role in the condition monitoring and maintenance process for bridges. These are currently primarily undertaken on UK highways using the General Inspection procedure. Consultation with engineers has found that the information they receive from GIs is the primary source of information when planning the maintenance needs of a bridge. However, evidence has been presented demonstrating large amounts of variability in visual inspection results. This variability is not unique to visual inspections of bridge condition. Technological solutions have been developed and adopted in many sectors to improve the reliability and objectivity of visual inspection data, including in many civil engineering condition monitoring applications.

The levels of detail which could be detected at a range of typical inspection distances, and in images at different resolutions, were established, and these were used to help develop a list of requirements for any system to be successfully used as a source of routine visual inspection data. Practical and desk-based reviews of existing systems which could potentially be used to provide Image Based Inspection data found none which fully meet the requirements and are ready for use as a routine visual inspection tool. It was concluded that development of an Image Based Inspection System (IBIS) would be worthwhile. The development, testing and assessment of a prototype system has been described.

It has been found that the IBIS methodology described within this research (consisting of a camera mounted on a tripod with an automated pan-tilt unit) can systematically collect images and data on-site, without requiring traffic management or road closures, and without causing disruption or delay to traffic. Methods of successfully processing and reprojecting these images to produce aligned orthoimages in which all pixels are consistently sized, and the effects of perspective are removed, have been established. This enables the system to deliver a full image record of all visible parts of a bridge at a consistent resolution of 1mm per pixel.

The IBIS assessment produced a number of findings. The initial testing of the detail present within images found that defects of interest could be seen, and that inspections undertaken using images produced similar results to those obtained on-site. This similarity was apparent in both the assessment of individual bridge element condition, and the overall bridge condition assessment. The presence, location and classification of individual defects were also similar, although the image-based approach provides more detail about the locations and extents of individual defects, whereas the traditional approach just noted the general positions and severities of defects seen.

Experience in operating the system on a number of different bridges found that the system could cope with some variations in bridge design and construction, but bridges with hidden, obscured, or hard to see elements may not be suitable candidates for using the IBIS. The system has been designed primarily for use on concrete bridges and is not suitable for all types of bridges, as some have too many elements and need too many imaging positions. However, the IBIS approach could still form a useful part of an inspection regime on suitable bridges.

The image display and interaction software was found to provide a functional and intuitive working environment, enabling defects to be detected, identified, and recorded. The automatic generation of defect maps was found to be very useful, and the completion of an inspection report was found to be possible with the IBI approach.

The prototype IBIS was found to perform very well onsite, deliver excellent images and provide an intuitive and user-friendly inspection interface. Additionally it was seen to satisfy almost all the requirements of the draft specification, with the exception of requirements relating to the time spent collecting or processing images. However, these are issues affecting the particular hardware and software used in the prototype IBIS and are in no way insurmountable. The prototype system was developed in order to demonstrate the potential for IBI – the issues are not related to the concept of IBI, but the implementation. It is anticipated that with additional development the time required onsite, and to process images for inspection, will decrease substantially. The development of more sophisticated data collection systems and methodologies will also lead to improvements in the consistency of lighting and appearance of the images.

Table 26 summarises the findings of the research and the section of the thesis where the finding is discussed.

Table 26: Findings from research undertaken

Finding	Section discussed
Routine visual inspection still a key part of inspection regime	2.2
GI data is primary source of information about visual condition of bridge	2.3
Visual inspections sometimes fail to spot defects	2.3
Visual inspections should record all defects larger than 0.4mm in size	2.3
Inspectors already take and use images to prepare inspection reports	2.3
These images don’t follow any guidelines on how and what to photograph	2.3
There are many problems with reliability and repeatability of visual inspection data, and many factors which influence these	3.1
Such problems specifically affect, but are not unique to, bridge inspections	3.1

Finding	Section discussed
and civil engineering	
Training and QC approaches are used to improve visual inspection outputs in other applications, and have been implemented within bridge inspection, however these are unlikely to solve all problems	4.1 4.2
Technological approaches are adopted in other applications to improve results of visual inspection	4.3
Inspectors can see more detail in images presented at 1mm per pixel than at 3m viewing in traditional manner	6.3
No existing systems are suitable and ready for use as part of routine visual inspection system	7.3
Automated image collection, processing, alignment and presentation for inspection is useful	9.2 and 9.3
Production of full image record is good	9.3 and 9.4
Consistent levels of detail over all of bridge are available	9.4
System much slower than traditional methods	9.4
System outputs benefit from use of image cross correlation data to assist image alignment and tessellation	9.4
System much more useful with images of upper bridge deck included	9.3
Increasing depth of field and system stability results in better images which show more detail.	8.2
Software for display, interaction and inspection is useful and useable.	9.2 and 9.3
Data from system can be used to complete general inspection report forms at	9.2, 9.3

Finding	Section discussed
similar levels of detail to traditional.	and 9.4
Images can be compared year on year	9.4

11.2 Conclusions

The research concludes that the use of systematic imaging technologies can be used to improve the consistency of visual inspections of bridges. It has been found that inspectors looking at high resolution images of features are able to correctly resolve and detect features to a level of detail that exceeds that achievable from an inspection carried out from 3m. Images at a resolution of 1 pixel per mm at the surface of the bridge will allow inspections to be carried out and detect details comparable to those detected during traditional inspections. No evidence was found of suitable systems already available, and it was concluded that the development of such a system would be beneficial.

Visual inspections, particularly GIs, are a critical source of information in the bridge management process. Although the adoption of an IBI approach will not provide any new information to inspectors and engineers, as it will still be operating at the GI level, it will provide a breakthrough in the consistency of detail available to the inspectors carrying out the inspections, and in the condition records available for subsequent review. The IBI approach will provide a less subjective, more repeatable, standardised method of producing the data needed in the maintenance and management of structures. The full image record produced assists with record keeping and provides a means of tracking condition changes from successive surveys. The image record is comprehensive and can be used for training purposes as all trainees and trainers can view the same images, showing the same bridge in the same conditions.

Images collected using an IBIS are suitable for use in computer based inspection systems, in which image processing techniques can be used to automatically detect and classify defects. The collection of a complete high resolution image set for an entire bridge is a necessary first-step towards any automation of the inspection process. Such approaches have been successfully used in many other aspects of civil engineering asset monitoring, but any automatic neural or image processing techniques to detect defects can only be developed and implemented if images are routinely available.

Regardless of the strengths and weaknesses of the particular IBIS developed and presented in this research, the need for, and requirements of a system which could provide routine visual inspection data has been demonstrated. It has also been demonstrated that it is possible to use data from such a system to undertake a GI.

It is concluded that systematically collected, high-resolution image data can be used to enable General inspections to be performed with no loss of detail compared to that provided by traditional General inspections. A prototype system has been developed and tested which demonstrates a potential methodology for successfully collecting, delivering and interpreting such data. Advantages of such an approach will include the improved consistency of detail used in inspecting bridges, better inspection records, and direct measurement of condition change.

11.2.1 Objectives of this research

The research objectives set out in the introduction of this thesis have been addressed as follows:

- Establish the role of routine visual inspection data in the UK highway bridge inspection regime.

This has been addressed in Chapter 2, specifically in Sections 2.2.2 and 2.3.9.

- Establish the potential for adoption of an Image-Based Inspection approach.

Chapter 3 presents some of the known issues with visual inspection, leading to the investigation in Chapter 4 into methods of improving the quality of visual inspection data. The discussion in Section 4.3.6 concludes that there is the potential for using such an approach. This is confirmed by the results presented in Chapters 8.5 and 9.

- Establish the levels of detail which such a system would have to provide.

One of the major successes of the research is the experimental work described in Section 6.3, which built on the results of the consultation presented in 2.3.4 to establish that images at 1 pixel per mm showed more detail than could be seen in a traditional inspection at 3m.

- Establish how such data could be collected.

Chapter 8 discusses in detail methods which have been developed and demonstrated to successfully collect images at resolutions meeting the requirements established in Chapter 6.

- Understand how such data could be processed.

Chapter 8 also discusses the processing methods which have been developed to successfully align and reproject the images collected in such a way as to provide consistent views and consistently scaled images in which the views are not distorted by perspective effects. The discussion also includes the need for methods of aligning the images, and the hybrid method developed for this, combining image and orientation data.

- Understand how such data could be presented and used.

This is addressed in Chapter 9.

11.2.2 Novelty and contribution to knowledge

Specific new contributions resulting from this work include:

- the results of the consultation which quantified the requirements of GI data. This demonstrated that visual inspection data was important, was largely trusted and determined that an acceptable routine visual inspection should not fail to detect features larger than 0.4mm in width;
- development of the draft requirements specification for what an IBIS should do. This provides a framework for the assessment or development of potential systems;
- experimental work to determine the levels of detail required, and the image resolution levels necessary. This establishes that images at 1mm per pixel show more fine detail than can be seen at a 3m viewing distance, providing a base standard for image quality in an IBIS;
- experimental work to demonstrate that the prototype IBIS could deliver acceptable images at the required resolution. This proves that it is possible to collect images in a practical way, without requiring traffic management or closures;
- demonstration that the use of IBIS could produce acceptable GI results. This shows that the images collected by the IBIS can be processed, aligned, displayed and inspected using a pragmatic, practical system and that it is possible to detect defects of interest in the images;
- production of a novel prototype IBIS incorporating the following aspects:
    - spreadsheets providing interactive assistance to system operator in determining appropriate Imaging Positions and lenses for use onsite. These were developed specifically for this research.;
    - automated pan-tilt unit controlling camera orientation and image acquisition. The system design and image collection approach was

based on the use of existing hardware, which was successfully incorporated into the IBIS;

- o distance measurement laser providing accurate information regarding the position of the IBIS relative to the imaged surface. Including an off-the-shelf measurement laser and adapting the data collection methodology to measure the camera-bridge distance at each imaging position and orientation allows more accurate reprojection and alignment to take place;
- o processing software which automatically reprojects, resizes and aligns the images for inspection. This software was developed for this research specifically to produce image displays suitable for inspection;
- o inspection software allowing the inspector to view the bridge as a series of discrete surfaces, and zoom in and out of images to look at details as they see fit. This software was adapted from existing software used for pavement condition assessment and was modified to display context thumbnails for the surface being inspected, and to enable a range of different defects and comments to be recorded;
- o software functionality to mark the position and type of any observed defect, and automatically produce output defect maps. This functionality was also adapted from existing pavement inspection software.

A list of publications resulting from the research described in this thesis is provided in Appendix G.

12 RECOMMENDATIONS FOR FUTURE RESEARCH

12.1 Other data sources

Data from the IBIS could be combined with data from other sources to provide a comprehensive visualisation of all available information about the condition of the bridge. The display and inspection software could be adapted to also include information from other sources, enabling the inspector to view overlays on the images showing data from design drawings, GPR surveys, thermal images half-cell potential testing, or other inspection and/or testing techniques. As part of this research a thermal camera was used to record images of defects on a bridge, Figure 116. However it was not possible to undertake in-depth analysis of these beyond noting that certain defects were highly visible in the thermal images.

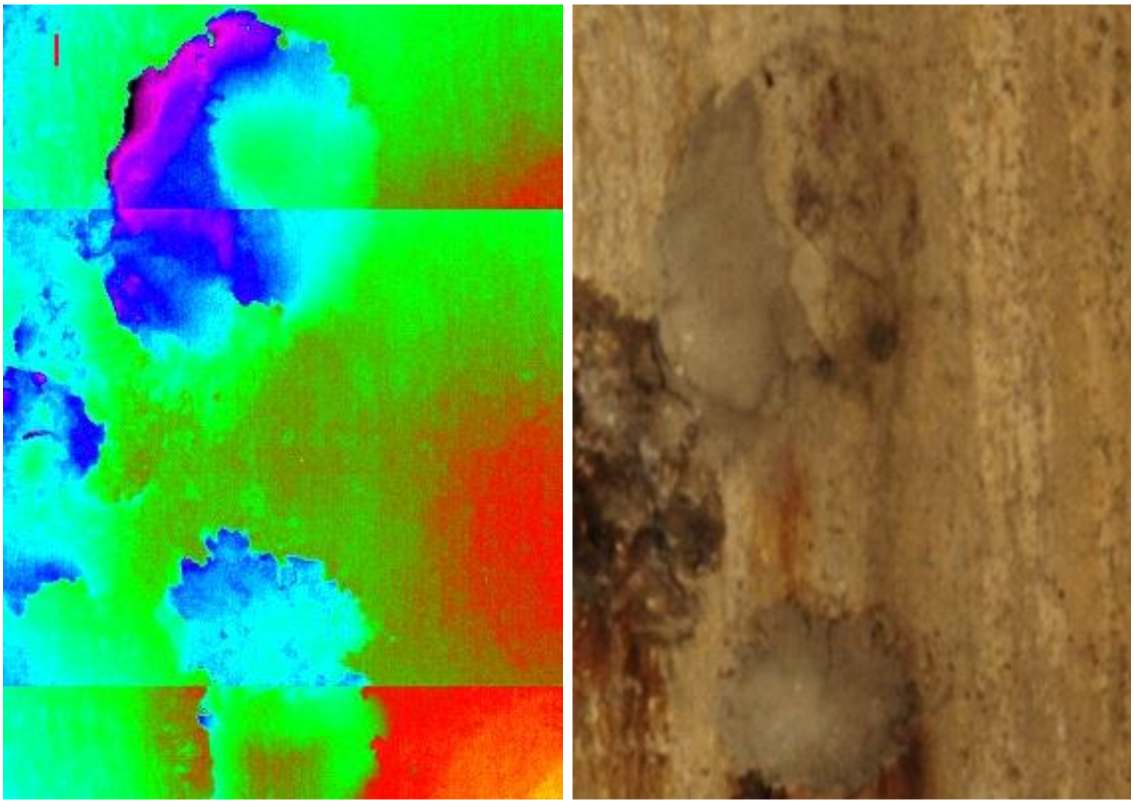


Figure 116: Example of thermal and visible images of part of a bridge showing different temperatures on defective and repaired areas.

By including data obtained using these techniques the inspector would be able to make use of all available data sources and see how visible defects relate to the underlying bridge design. For example knowing the relative positions of cracks and reinforcement bars could help the inspector interpret what is seen more fully.

12.2 Automated processing and defect detection

Automated image inspection and analysis is widely used in many applications and industries to reduce or remove problems related to human inspector subjectivity, (Chang & Abdelrazig, 1999), (Demant, et al., 1999) (Brosnan & Sun, 2004), (Elbehiery, et al., April, 2005), (Furness, et al., 2007), (Sharpe, et al., 2008). There is no reason to suspect that such approaches cannot also be applied to bridge inspection and the analysis of IBIS imagery.

In fact, a number of researchers are already actively developing methods specifically for detecting and identifying cracks and other defects in concrete structures, ((Abdel-Qader, et al., 2003), (Abdel-Qader, et al., 2006), (Jahanshahi, et al., 2009), (Uhl, et al., 2011), (Moon & Kim, 2011), (Li, et al., 2013), (Adhikari, et al., 2014), (Matsumoto, et al., 2014), (Yamamoto, et al., 2014)). Without high-quality, high-resolution, systematically collected images these approaches may succeed in detecting test defects and cracks in laboratory or controlled samples, but will not be able to routinely inspect an entire structure.

Work was undertaken in the early stages of this research to investigate the use of image processing techniques in an attempt to develop a fully or semi-automated bridge inspection system ((McRobbie & Lodge, 2006), (McRobbie, et al., 2007), (McRobbie, 2008), (McRobbie, 2009)). This work attempted to split each image into a series of cells, and use common image processing techniques to detect whether or not each cell contained any features or defects of interest, and attempted to classify these. Figure 117 shows some of this initial work on automated defect detection.

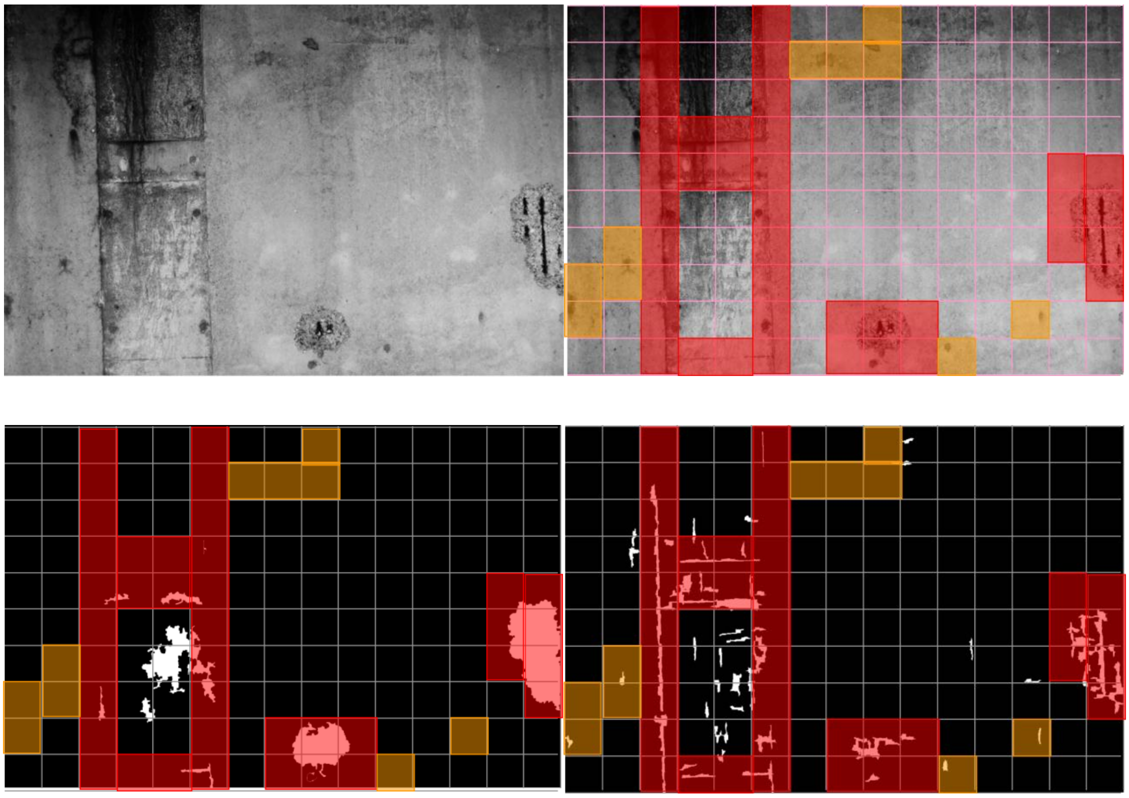


Figure 117: Examples of IBIS images following application of various image processing techniques (segmentations based on image entropy and on concentration of detected edges) compared against manually generated reference data showing which cells contain features or defects.

Although the work undertaken in this research did not progress beyond the use of relatively simple approaches, such as the use of image entropy, edge detection, or considering the relative intensities of the three colour channels, it showed that the images produced by the IBIS could be used in conjunction with image-processing and analysis techniques to automate, or semi-automate the inspection process itself. Such approaches might be used as a first-pass on the images to highlight areas which an inspector should look at in more detail, or could be allowed to automatically generate an inspection report with no human interaction needed.

These techniques could be used either to identify features which were not present in previous inspections, identify the presence of a defect, or categorise the type, severity and extent of the defects present in the images.

Images taken using the prototype IBIS have already been used in PhD research undertaken at the University of Surrey (Mehrabi, 2012) looking at the use of Restricted Boltzmann Machines (a form of neural network) for detecting cracks in concrete surfaces.

12.3 Potential use of 3-D data in IBI process

The IBI system developed for this research displays the images as a series of two-dimensional (2-D) surfaces, each of which is inspected and assessed in isolation. The consultation with engineers and inspectors discussed previously (Section 2.3) included a question about the possible usefulness of three-dimensional (3-D) data. Over 78% of consulted inspectors and engineers reported that they would find a 3-D model to be either 'very useful', or 'useful' in their interactions with the data (Figure 118).

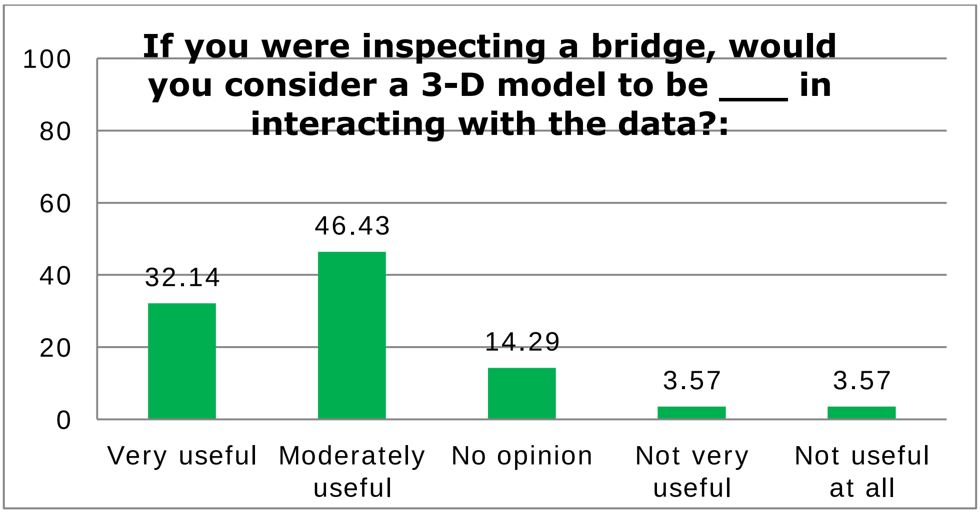


Figure 118: Responses to consultation question about usefulness of 3-D model of bridge when undertaking Image-Based Inspection.

Although the assessment of the Riegl laser scanning system discussed in Chapter 7 found that the system was unsuitable for use as a routine inspection tool, the models produced using the recorded data were impressive visualisations. Combining the high resolution IBIS images with these models could produce highly visually detailed 3-D models enabling fine detail and defects to be detected, while replacing some of the contextual information lost when viewing the images in 2-D.

Correctly rendering an entire bridge in 3-D, at 1 pixel per mm, requires a massive amount of data. A 1m x 1m section of the bridge requires 1 million pixels. To render this in full colour requires pixel intensity values (0-255) for the red, green and blue channels, and x, y and z coordinate information for each of the million pixels in the $1m^2$ area.

Figure 119 shows 3-D models produced using simulated depth data, at greater resolution than would be possible using the current IBIS with the Acuity AR1000 distance measurement laser. The size of the area represented in the figures below is 3.872m x 2.592m. The 3-D data file, for this one image alone, not including the information required to enable it to be aligned with other images (i.e. x, y, z, R, G, B only), is 124MB.

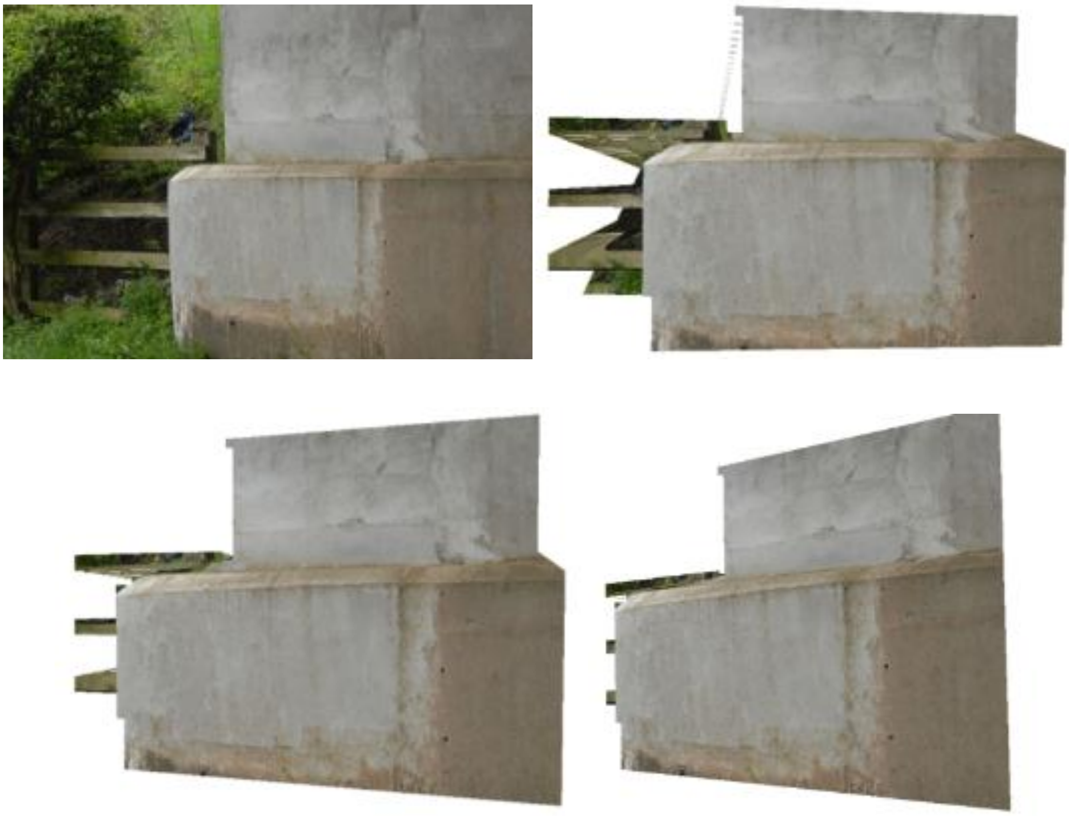


Figure 119: Original 2-D image data (top left) and three views of 3-D representations created from this image data and artificial LiDAR shape measurement data.

As computer processing and memory becomes cheaper and faster, and as improved methods for handling large 3-D datasets and models are developed it may be the case that technology reaches a point where it becomes relatively simple and practical to use 3-D models in the inspection process.

Appendix A Consultation documents

<u>Section 1</u>

Role and importance of General Inspections

1.1. General Inspections are the primary source of information about the visual condition of a bridge.

Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly Agree	Agree	Strongly agree

1.2. General Inspections produce an accurate picture of the visual state of the bridge at the time of inspection.

Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly Agree	Agree	Strongly agree

1.3. General Inspections record all visual defects which may be of interest to an engineer.

Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly Agree	Agree	Strongly agree

1.4. General Inspections sometimes fail to spot small defects which are not close to the inspector (for example fine cracks on the soffit).

Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly Agree	Agree	Strongly agree

1.5. What is the largest crack width which it might be acceptable to fail to detect in a General Inspection?

0.2mm	0.4mm	0.6mm	0.8mm	1mm	2mm	4mm	>4mm

Please provide some information on what types of defect are generally well detected in General Inspections, and which, if any, are not. I would be particularly interested in your opinions on how the severity, extent and location of a defect affect how well it may be seen and recorded:

1.6. General Inspection results are used to plan maintenance.

Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly Agree	Agree	Strongly agree

1.7. General Inspection results are used to plan other inspections before planning maintenance.

Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly Agree	Agree	Strongly agree

1.8. General Inspections provide information which is useful for efficient management of bridge stock within a network.

Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly Agree	Agree	Strongly agree

1.9. General Inspections provide consistent data (you would expect separate inspections of the same bridge, by separate inspectors to produce similar inspection reports).

Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly Agree	Agree	Strongly agree

1.10. General Inspections provide objective data (the findings in the inspection report would be statements of fact, not opinion).

Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly Agree	Agree	Strongly agree

1.11. General Inspections provide quantitative data.

Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly Agree	Agree	Strongly agree

1.12. Please feel free to give any further information regarding the usefulness of General Inspections. I would be particularly interested in your opinion on the strengths and weaknesses of the inspection method, data produced, or ease of interpretation of the results.

Section 2

Questions about General Inspection procedure

2.1. What proportion of the total time involved in a General Inspection is spent on each phase?

Preparation	On-site	Post-inspection	Total
			100%

Preparation

2.2. Before going on site to perform a General Inspection, results of previous inspections on that site are studied.

Never	Less than 20% of the time	20% to 40% of the time	40% to 60% of the time	60% to 80% of the time	80% to 100% of the time	Always

2.3. Before going on site to perform a General Inspection, systems such as Google StreetView are used to familiarise the inspectors with the site and surroundings, and the conditions expected on site.

Never	Less than 20% of the time	20% to 40% of the time	40% to 60% of the time	60% to 80% of the time	80% to 100% of the time	Always

2.4. Before going on site to perform a General Inspection, a pre-inspection visit is undertaken to familiarise the inspectors with the site and surroundings, and the conditions expected on site.

Never	Less than 20% of the time	20% to 40% of the time	40% to 60% of the time	60% to 80% of the time	80% to 100% of the time	Always

On-site

2.5. Would you use any equipment to get a better view of part of the structure during a General Inspection? (e.g. ladders, binoculars, …)

Never	Less than 20% of the time	20% to 40% of the time	40% to 60% of the time	60% to 80% of the time	80% to 100% of the time	Always

2.6. If you would/do use equipment to get a better view of the bridge, which of the following would you use, and how often?

	Rarely	Often	Usually	Always	In what circumstances?
Ladder					
Binoculars					
Camera with zoom lens					
Torch					
Other (please specify below)					

2.7. Obviously all bridges are different, and this is very much dependent on the size and construction of the bridge, but approximately how long would you expect to spend on-site actually inspecting a typical bridge?

<15 minutes	15 – 30 minutes	30 – 60 minutes	60 – 90 minutes	90 – 180 minutes	180 – 240 minutes	>240 minutes

2.8. In how many of your General Inspections would you expect to take some photographs?

Never	Less than 20% of the time	20% to 40% of the time	40% to 60% of the time	60% to 80% of the time	80% to 100% of the time	Always

2.9. Do you have a systematic approach to recording images of a structure?

Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly Agree	Agree	Strongly agree

2.10. How many photographs would you expect to take while performing a General Inspection?

None	1 – 20	21 – 40	41 – 60	61 – 80	81 – 100	Over 100

What would you expect to take photographs of:

Post inspection

2.11. How likely is it that there would be photographs from a previous inspection of the defects photographed and of interest in the current inspection?

Never	Less than 20% of the time	20% to 40% of the time	40% to 60% of the time	60% to 80% of the time	80% to 100% of the time	Always

2.12. When preparing a General Inspection report, and where photographs from a previous inspection exist, how often would you compare photographs taken during a General Inspection with those taken in a previous inspection?

Never	Less than 20% of the time	20% to 40% of the time	40% to 60% of the time	60% to 80% of the time	80% to 100% of the time	Always

2.13. How confident would you be that any differences in the defect shown in the images would be a genuine change in the defect, and not a result of changes in the image taking methodology (lighting, camera, position,…)?

No confidence	< 20%	20 – 40%	40 – 60%	60 – 80%	80 – 100%	Complete confidence

If you have low confidence in this, what are your reasons?

2.14. When the results of a General Inspection are presented to, or discussed with the engineer responsible for its maintenance, how often does the engineer request additional information?

Never	Less than 20% of the time	20% to 40% of the time	40% to 60% of the time	60% to 80% of the time	80% to 100% of the time	Always

2.15. When the results of a General Inspection are presented to, or discussed with the engineer responsible for its maintenance, do all interpretations of the bridge condition agree?

Never	Less than 20% of the time	20% to 40% of the time	40% to 60% of the time	60% to 80% of the time	80% to 100% of the time	Always

If there are different interpretations, or disagreements, what are the reasons for this?

2.16. Please feel free to give any further information regarding the process and practicalities of preparing, performing and presenting General Inspections and inspection reports.

Section 3

In my PhD I am proposing that an inspection system could be developed which will systematically and methodically collect images of the entire accessible surface of a bridge. After the completion of the survey the images (having a minimum resolution of 1 pixel per mm) would be viewed in a software viewer that allows the inspector (in the office) to inspect the bridge by moving around the images to inspect all parts in detail (zooming in if desired). The inspector would mark (using the software) the location, type and extent of any defect seen. Maps and statistics of the defects could be generated and exported for quantitative analysis.

Questions relating to an image-based inspection system

3.1. I am very interested in opinions from practitioners on this proposed image-based inspection system. Based on the capability outlined above, please give your opinions on the potential for the system in comparison with the existing inspection method in the following areas (please tick all that apply):

	No use and/or would inhibit the performance of the inspection.	Could be combined with a current inspection, to enhance the performance of the inspection.	Could be used to replace current inspection method with no loss of quality.	Could be used to enhance the performance of current inspections.	Could be exceptionally useful and/or improve the usefulness of the inspection data.
Identify areas of concern on a bridge					
Identify individual defects					
Monitor the evolution of defects over time					
Discuss aspects of the inspection or condition with others					
Plan supplementary inspections					
Plan maintenance work					
Perform a complete General Inspection					

3.2. The current display system has focussed on the assessment of the bridge as "faces" in 2 dimensions, with the inspector viewing each face to build up an inspection of the bridge. I am considering the development of a 3D environment to show the whole bridge. If you were assessing a bridge would you consider this way of interacting with the data to be:

Very useful	Moderately useful	No opinion	Not very useful	Not useful at all

3.3. Please feel free to give any further information about what you would want/need from an image-based, or other automated, inspection system, in particular if you have any views on capability required to meet your requirements in the areas given in question 3.1.

Section 4

The following questions will provide information which will help me in the analysis and interpretation of your responses.

Name:				
Role:	**Inspector**	**Engineer**	**Both**	
How long have you been involved in bridge inspections (inspecting or using inspection data)?				
Network type:	**Local Authority**	**Highways Agency**	**TfL**	**Other**
Types of structure inspected:	**Concrete**	**Masonry**	**Metal**	**Other**
Estimated number of inspections performed in past 2 years:				
Estimated number of inspections performed in career:				

Many thanks for your time and attention in completing this survey.

If you have any questions, or wish to return your completed questionnaire, please contact me at [redacted]

Appendix B Currently delivered by a General Inspection

The consultation discussed in Chapter 2 found that engineers consider the information provided by General inspections to be their primary source of data on the visual condition of a bridge, and that they record all the visual defects which are of interest to the engineers, even though they acknowledge that they do sometimes miss small cracks. Generally the engineers are happy with the outputs of GI inspections and expect that all cracks wider than 0.4mm will be detected. The results of GIs are used in the maintenance planning process.

A General Inspection report provides information on the visual condition of the bridge at the time of inspection, including the overall appearance of the bridge, the presence of any defects, and the inspectors' interpretation of the importance of the defect, and recommended maintenance approach, and sometimes an estimate of the cost of the action. The action may be maintenance, or may be further investigation or monitoring. The report also includes an assessment of the success and quality of any repairs carried out since the last inspection.

General Inspections try to detect and report all visible defects which may be likely to cause concerns for engineers. Such defects include cracking, spalling, signs of rust staining or damp areas, problems with drainage or fire or impact damage. The inspectors do not usually use any tools such as binoculars or ladders, but merely report what they can see from the footway. Typically, digital cameras are used to record a few images at each inspection, some of which are used to show the overall condition of the structure and some to illustrate reports of defects. Not all defects will be pictured, and there are no controls over how any of the images are taken. For this reason the images taken in one inspection may be hard to compare with those from a different inspection.

Consultation showed that General Inspections typically take 30 minutes to an hour to perform, and that the information is used by engineers in the identification of bridges which may require further investigation or work, and in determining what the appropriate forms of investigation or work may be.

The results of the inspection are delivered to the engineer in the form of an inspection report. These are prepared by the inspector using an inspection pro-forma as shown below, and provide room for the inspector to consider each element of the bridge in turn, and report whether or not it is affected by any defects, what the extent and severity are of any defect, and the recommended work and priority for this are. There is also space for any comments. The reports are usually supplemented with the images taken during the inspection.

Bridge Inspection Pro Forma - [redacted] ***M4 over Brocks Lane Bridge***

Inspection type: General	[redacted]	Form 1 of 1	for this brid[redacted]
Inspector:	Next Inspection		
Bridge Name: M4 over Brocks Lane	Bridge Ref/No: N/A		Road Ref/No: Brocks Lane
O.S. Map Ref: SU	O.S. Eastings: 53898	O.S. Northings: 74108	Bridge Code – Primary deck form (Table 2): **04**
Span: 1 of: 1	Span Width (m): 36.0m	Span Length (m): 12.1m	Bridge Code – Primary deck material (Table 4): **D**
All above ground elements inspected? NO		Photographs? YES	Bridge Code – Secondary deck form (Table 3): **24**
Number of construction forms in bridge/span: 1			Bridge Code – Secondary deck material (Table 4): **A**

Set	No	Element Description	S	Ex	Def	W	P	Cost	Comments/Remarks
Deck Elements	1	Primary deck element (Table 2)	2	B	2.2	a,c			Comment 1. Photos 5,22,23,24, 25, 26
	2	Secondary deck elements: ~~Transverse beams~~	N/A						N/A
	3	Secondary deck elements: Element from Table 3	NI						No access to deck slab
	4	~~Half joints~~	N/A						N/A
	5	~~Tie beam/rod~~	N/A						N/A
	6	Parapet beam or cantilever	2	B	M	a	L		See Multiple defects. Photos 30,32,33
	7	~~Deck bracing~~	N/A						N/A
Load-bearing Substructure	8	Foundations	1	A	6.1				No visible signs of settlement on bridge
	9	Abutments	2	C	M	a,d,e	L		See Multiple defects. Photos 3,47,8-21
	10	~~Spandrel wall/head wall~~	N/A						N/A
	11	~~Pier/Column~~	N/A						N/A
	12	~~Cross-head/capping beam~~	N/A						N/A
	13	Bearings	NI						No access
	14	Bearing plinth/shelf	NI						No access
Durability Elements	15	Superstructure drainage	3	B	8.1	b	M		Comment 2. Photos19,20, 26
	16	Substructure drainage	1	A	8.1				Weep holes buried if present
	17	Waterproofing	1	A	14.1				No evidence of any defects
	18	Movement/expansion joints	2	C	M	d	L		See Multiple defects. Photos 32
	19	Finishes: deck elements	2	C	4.1	e	L		Comment 3. Photos 5,23
	20	Finishes: substructure elements	2	D	4.1	e	L		Comment 4. Photos 3,4,27,29,31,34
	21	Finishes: parapets/safety fences	NI						No access
Safety Elements	22	~~Access/walkways/gantries~~	N/A						N/A
	23	Handrail/parapets/safety fences	NI						No access
	24	Carriageway surfacing	NI						No access to M4
	25	Footway/verge/footbridge surfacing	2	E	9.1	e	L		Comment 5. Photos 36
Other Bridge Elements	26	~~Invert/river bed~~	N/A						N/A
	27	~~Aprons~~	N/A						N/A
	28	~~Fenders/cutwaters/collision prot.~~	N/A						N/A
	29	~~River training works~~	N/A						N/A
	30	~~Revetment/batter paving~~	N/A						N/A
	31	Wing walls	2	B	M	a	L		See Multiple defects. Photos 27,29,31,34
	32	~~Retaining walls~~	N/A						N/A
	33	Embankments	1	A	11.1				No evidence of any defects
	34	~~Machinery~~	N/A						N/A
Ancillary Elements	35	Approach rails/barriers/walls	2	B	16.1	e	L		Comment 6.
	36	~~Signs~~	N/A						N/A
	37	~~Lighting~~	N/A						N/A
	38	Services	2	B	13.1	c,e	L		Comment 7. Photos 30,37
Spare Rows	39	Graffiti	2	B	0	e	L		Comment 8. Photos 13,14
	40								
	41								
	42								

S - Severity, **Ex** - extent, **Def** - Defect, **W** - Work Required, **P** - Work Priority, **Cost** - Cost of Work

Figure 120: Example of a completed General Inspection report.

The General Inspection form does not have a lot of room for detail, but covers everything which the engineer typically needs to know about, and allows supplementary notes and photographs to be attached and referenced to support the inspectors' findings. The General Inspection form enables a summary of the condition of every part of the bridge to be presented in a single sheet.

However, the summary of the condition is presented at quite a low level of detail or resolution. Each element of the bridge is assigned a single value to represent the severity of any defects present, another to indicate the extent of the defects present, a code to identify the type of defect present, and is also assigned codes to indicate what work is required (in the inspectors opinion) and what priority this work should be given (again in the opinion of the inspector). The form also has space for an estimate of the cost of any recommended work or further investigation to be entered, and for any comments or remarks to be made. These comments often describe access or viewing issues which may affect the inspection report, or refer to supplementary notes and photographs showing defects in more detail. As was reported in the consultation, a typical inspection report usually includes about 20 photographs, and while the consultees responded that, in general, they feel they have a systematic approach to recording the images of a structure, the comments which accompanied the consultation tended to show that this meant that they had a certain order in which they would take photographs (general views of bridge, then views of specific elements, then views of any defects seen, etc.) and that they would record which image number showed which view, they were not systematic in terms of recording details of where the images were taken from, precisely which part of the structure was shown, or the angles (bearing and elevation) at which the camera was pointing. Consequently, although successive inspections may include images of the same feature or defect, there is no guarantee that the images will be easily comparable.

The following photographs (shown in Figure 121 to Figure 125) were taken during 2 General Inspections performed 2 years apart on the same bridge carrying the M4 over a local road. One was the normal General Inspection performed for the Highways Agency in 2008; the other was performed as part of this research in 2010.

The first three images show a portion of the southern end of the west abutment. Figure 121 shows the image taken in 2008 as part of the scheduled General Inspection on behalf of the Highways Agency, Figure 122 and Figure 123 show the images taken in 2010 by the inspector undertaking the General Inspection commissioned specifically for this research. Although there are sufficient features within the images to be confident that the images show the same general part of the structure the way that they have been taken, with no control over exactly what is imaged makes it very difficult to determine whether any of the defects shown have grown or changed over time.

Figure 121: Image of south end of west abutment taken in 2008 as part of scheduled General Inspection.

Figure 122: Image of south end of west abutment taken in 2010 as part of research General Inspection.

Figure 123: Image of south end of west abutment taken in 2010 as part of research General Inspection.

Figure 124 and Figure 125 show images of part of the soffit taken during successive General Inspection visits. Because of the different angles at which the photographs were taken, the regular beam pattern in the images, and the appearance of a wet area in Figure 125 it is not immediately obvious that the images do show the same part of the bridge. Both images obviously show soffit beams, but the images must be looked at quite closely to pick out features that are definitely the same in the two images, before any comparison or trending of defects can take place.

Figure 124: Image of central portion of west end of soffit beams taken in 2008 as part of scheduled General Inspection.

Figure 125: Image of central portion of west end of soffit beams taken in 2010 as part of research General Inspection.

Figure 126 is an attempt to illustrate which part of Figure 124 is visible in Figure 125, and how the viewing angles have changed.

Figure 126: Highlighted areas show part of bridge common to both Figure 124 and Figure 125.

These examples show that individually the images typically taken as part of a General Inspection provide good illustrations of the visual condition of the elements, or parts of elements, photographed, but that they do not show fine details, and are hard to compare with other images showing the same, or similar, parts of the bridge from other inspections. The choice of inspection location for the on-site inspector affects the consistency of the inspection results from inspection to inspection.

Appendix C IBIS completed GI form

Bridge Inspection Pro Forma -

Inspection type: General Inspection		Date:	Form of for this bridge		
Inspector: [redacted]		Next Inspection Type/Date:			
Bridge Name: Frilsham			Bridge Ref/No: N/A	Road Ref/No:	
O.S. Map Ref:	O.S. Eastings:		O.S. Northings:	Bridge Code	Primary deck form / Table 2
Span: of:	Span Width (m):		Span Length (m):		Primary deck material / Table 4
All above ground elements inspected? YES			Photographs? YES		Secondary deck form / Table 3
Number of construction forms in bridge/span:					Secondary deck material / Table 4

Set	No	Element Description		S	Ex	Def	W	P	Cost	Comments/Remarks
Deck Elements	1	Primary deck element (Table 2)		**3**	**C**	**1;2;4**				The I beams are in good condition but there is a considerable water infiltration between the central beams (IMG_1952; IMG_1958; IMG_1964; IMG_1970;) Insignificant concrete spalling of I beams edges (probably during transport or assembly)
	2	Secondary deck element/s	Transverse beams	N/A	-					-
	3		Element from Table 3	N/A	-					-
	4	Half joints		N/A	-					-
	5	Tie beam/rod		N/A	-					-
	6	Parapet beam or cantilever		N/A	-					-
	7	Deck bracing		N/A	-					-
Load-bearing Substructure	8	Foundations		N/A	-					-
	9	Abutments (incl. arch springing)		**2**	**B**	**1; 2;3; 5; 7**				North Abutment: Defects 1 and 5 mainly under the first two or three external I beams. Defects 2 and 3 were detected in small areas. Cracks (def. 7) with small apertures and irregular pattern (IMG_1198_3) can be found essentially in the south half of the spandrel wall, possible causes are expansive reactions or deficient concrete curing. One vertical crack (IMG_1182_3) possibly due to temperature or earth pressure was found. South Abutment: Defects 1 and 5 mainly under the first three external I beams. Defect 3 was detected in small areas but mainly in the lower south part of the wall (IMG_1580_7). Defect 2 is common in the lower part of the wall.
	10	Spandrel wall/head wall		N/A	-					-
	11	Pier/column		N/A	-					-

	12	Cross-head/capping beam	N/A	-					-
	13	Bearings	N/A	-					No images about
	14	Bearing plinth/shelf	N/A	-					No images about
Durability Elements	15	Superstructure drainage	N/A	-					No images about
	16	Substructure drainage	N/A	-					No images about
	17	Waterproofing	N/A	-					No images about
	18	Movement/expansion joints	N/A	-					No images about
	19	Finishes: deck elements	N/A						
	20	Finishes: substructure elements	N/A						
	21	Finishes: parapets/safety fences	N/A						
Safety Elements	22	Access/walkways/gantries	N/A						No images about
	23	Handrail/parapets/safety fences	**1**	**A**					Only images from the ground
	24	Carriageway surfacing	N/A						No images about
	25	Footway/verge/footbridge surfacing	N/A						No images about
Other Bridge Elements	26	Invert/river bed	N/A	-					-
	27	Aprons	N/A	-					-
	28	Fenders/cutwaters/collision prot.	N/A	-					-
	29	River training works	N/A	-					-
	30	Revetment/batter paving	N/A	-					-
	31	Wing walls	(Def. 2;3;7) **2** (Def. 6) **3**	(Def. 2;3;7) **B** (Def. 6) **D**	**2; 3; 6; 7**				Northwest wing wall: Small cracks or voids and generalized vegetation intrusion Northeast wing wall: Small cracks or voids and generalized vegetation intrusion Southwest wing wall: Small cracks or voids and generalized vegetation intrusion Southeast wing wall: Small cracks or voids and generalized vegetation intrusion
	32	Retaining walls	N/A	-					-
	33	Embankments	N/A	-					-
	34	Machinery	N/A	-					-
Ancillary Elements	35	Approach rails/barriers/walls	N/A	-					-
	36	Signs	**1**	**A**					Only images from the ground
	37	Lighting	N/A	-					-
	38	Services	N/A	-					-

Spare Rows	39								
	40								
	41								
	42								

S - Severity, **Ex** - extent, **Def** - Defect, **W** - Work Required, **P** - Work Priority, **Cost** - Cost of Work

MULTIPLE DEFECTS										
Element No.	**Defect 1**			**Defect 2**			**Defect 3**			**Comments**
	S	**Ex**	**Def**	**S**	**Ex**	**Def**	**S**	**Ex**	**Def**	

INSPECTOR'S COMMENTS	
Def. 1	Calcium carbonate deposition as a result of concrete's calcium hydroxide leaching
Def. 2	Rust stain due to insufficient rebar cover
Def. 3	Concrete voids due to air bubbles retained against the formwork (insufficient vibration) or to misalignment of formwork panels
Def. 4	Concrete spalling
Def. 5	Algae formation due to water infiltration
Def. 6	Vegetation intrusion
Def. 7	Concrete crack

Name: Paulo Silveira	Signed:		Date:	2014-07-09

ENGINEER'S COMMENTS

Name:	Signed:		Date:	

WORK REQUIRED

Ref. No.	Suggested Remedial Work	Priority	Estimated Cost	Action/Work Ordered?
1	Seal the pavement cracks	Next maintenance programme		
9	Seal bridge expansion joints			
31	Remove the vegetation from the wing walls in a 2m band			
Name:	Signed:		Date:	

Appendix D IBIS defect maps

The following images show the complete set of tessellated images supplied to inspectors for inspection, marked up with the detected defects, similar to those shown in the main body of the thesis in Section 9.2.2. The defect marking was done using the modified ChartCrack software.

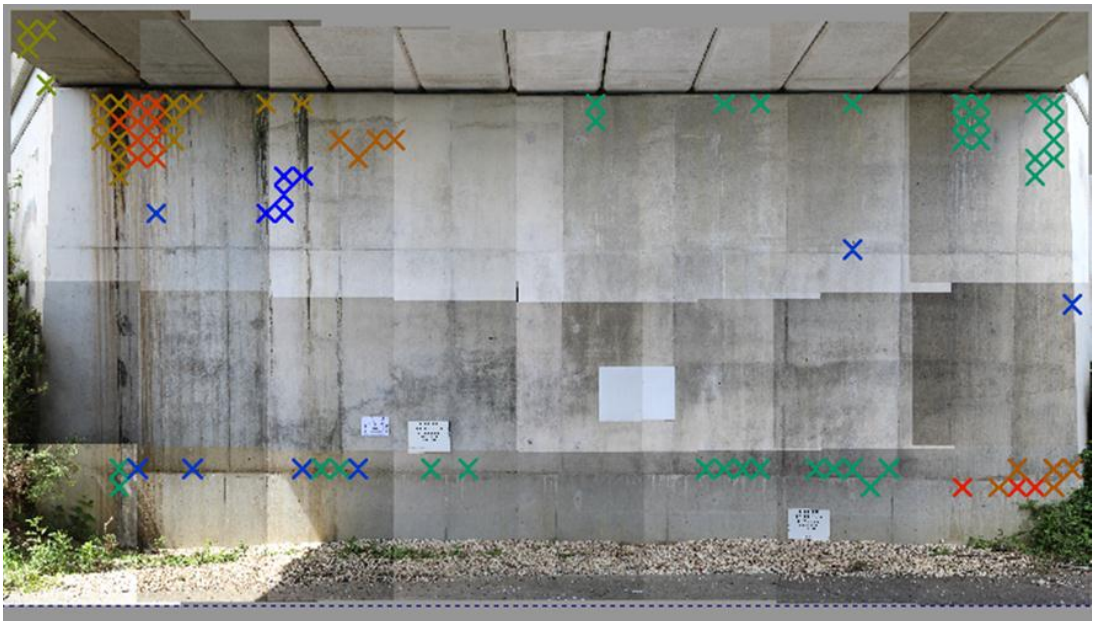


Figure 127: Defect map overlaid on tessellated imageset from IP1.

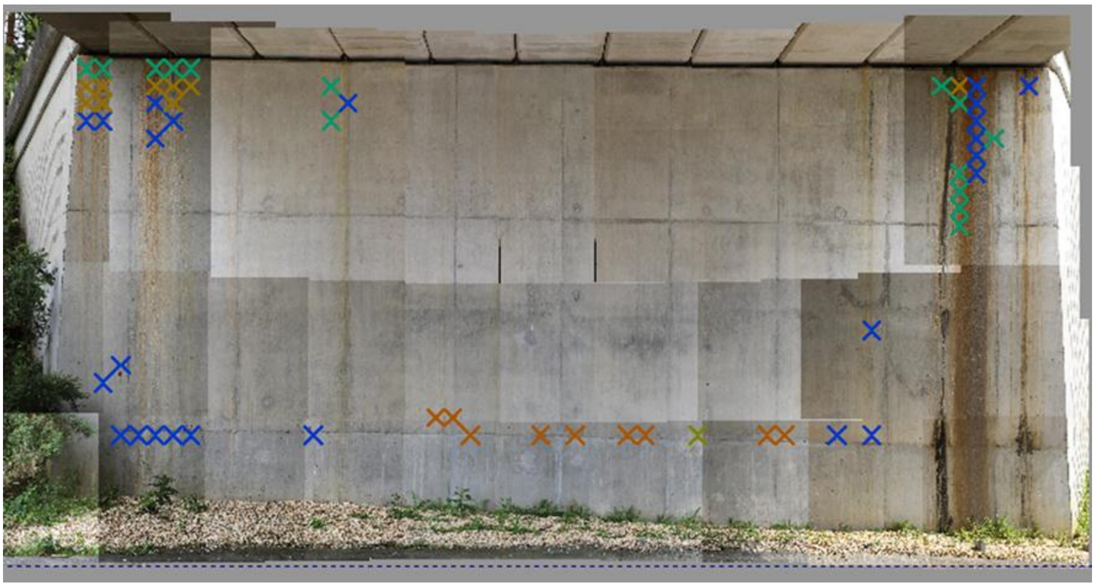


Figure 128: Defect map overlaid on tessellated imageset from IP2.

Figure 129: Defect map overlaid on tessellated imageset from IP3.

Figure 130: Defect map overlaid on tessellated imageset from IP4.

Figure 131: Defect map overlaid on tessellated imageset from IP5.

Figure 132: Defect map overlaid on tessellated imageset from IP6.

Figure 133: Defect map overlaid on tessellated imageset from IP7.

Figure 134: Defect map overlaid on tessellated imageset from IP8.

Figure 135: Defect map overlaid on tessellated imageset from IP9.

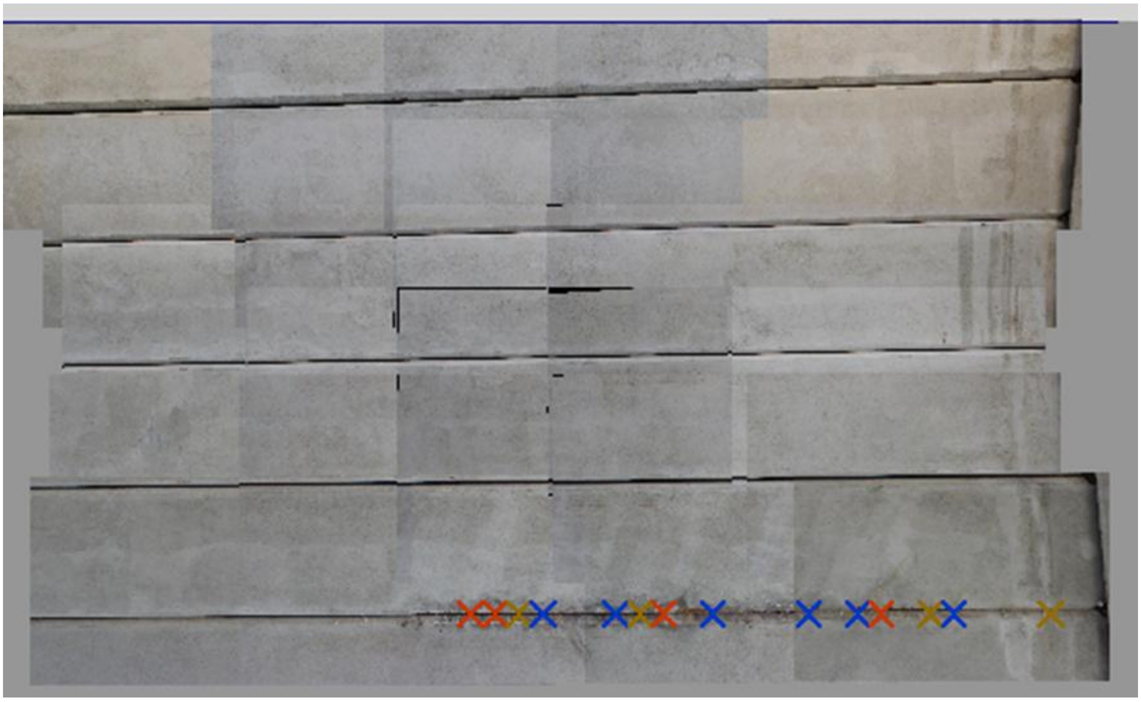


Figure 136: Defect map overlaid on tessellated imageset from IP11.

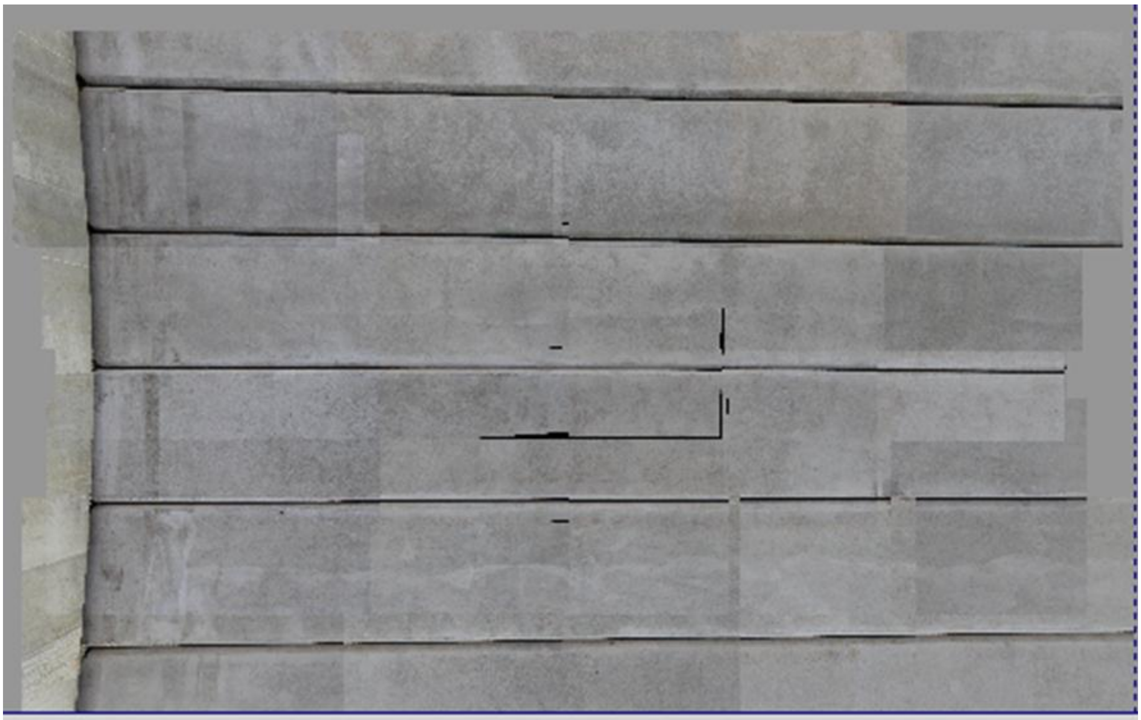


Figure 137: Defect map overlaid on tessellated imageset from IP12.

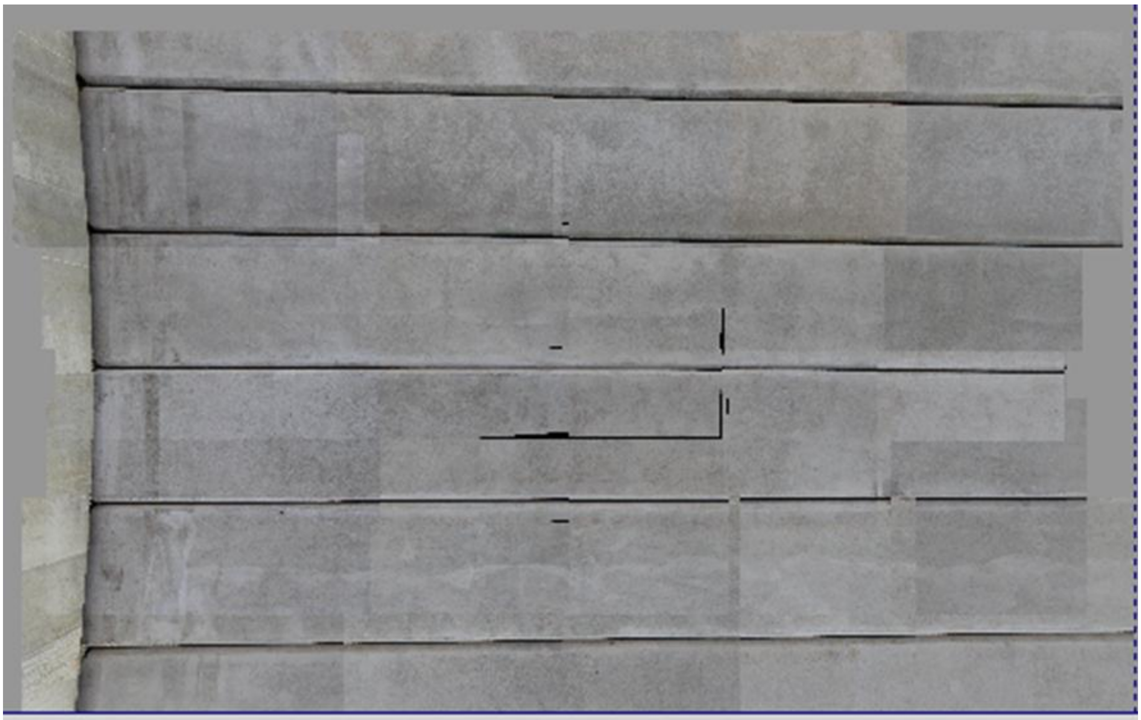


Figure 138: Defect map overlaid on tessellated imageset from IP14.

Appendix E ChartCrack help files for performing an IBI

Performing image based bridge inspections with ChartCrack – introduction and general operation

Basic outline of image-based inspection procedure: from collection to interpretation.

The ChartCrack software can be used to undertake manual inspections of the images of structures. The process can be summarised as follows:

- High resolution images are systematically collected covering all visible surfaces of a structure.
    - This involves moving the camera to a number of pre-determined imaging positions
    - Multiple imaging positions may be required for individual surfaces, for example it may be necessary to move the camera to 2 or 3, or more positions to capture images of a single abutment.
- The images are pre-processed to reduce the effects of parallax and perspective, and to calculate the relative positions of each image within an imageset.
    - An imageset is the set of images recorded at a single imaging position.
- The images are stored in a set of directories, along with a .txt file giving details of the file alignment, and an .nbp file containing details needed for displaying the images correctly.
- The images are transferred to a computer running ChartCrack.
    - Ideally this will be a powerful PC, with a large dual-screen display.
- The list of defect types of interest in the survey will be decided and an .ini file edited to ensure that all relevant defects can be selected.
- ChartCrack is opened.
- The .nbp file for the imageset you wish to inspect is selected. This will open the images.
- Set up the view so that it is optimised for how you want to carry out the assessment
- Undertake manual analysis of the images by selecting defects from a list and clicking on the screen at their locations.
    - Comments can be added to the inspection if desired/appropriate.
    - Individual images can be opened for detailed inspection or sharing
- Save the results to a data file

---

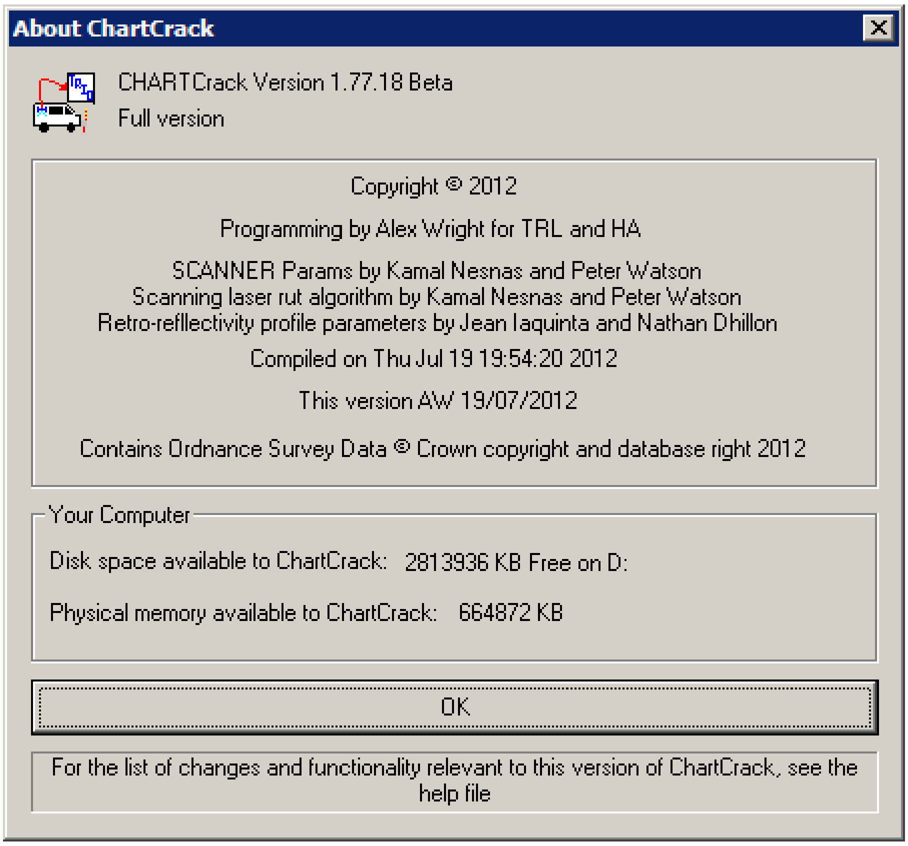
introduction_structures_inspection

- Exit the program.
- The results can be revisited and interpreted at a later time either using ChartCrack to display the images and the overlaid defect locations, or using Excel, to display the defect maps.

[#] Which version of ChartCrack can be used to undertake inspections of structures?

Use ChartCrack **V1.77.18 Beta** to carry out surveys of structures.

If in doubt check “**Help / About ChartCrack…**” – it should be the same as shown below.



[#] version_structures_inspection

[#] *Setting up a PC to carry out inspections of structures*

Recommendations for PC

Performing an image based bridge inspection requires the use of high-resolution images. When there are a lot of images in an imageset this can be a test for a computer, resulting in lag and display difficulties. In order to overcome this, it is recommended that the inspections are done on as powerful a computer as is available.

The inspection process is tolerably fast when using the following specifications:

- Intel® Core™2 Duo CPU
- T8300 @ 2400GHz
- 2.39GHz, 2.00GB of RAM

Anything at or above this level should be fine.

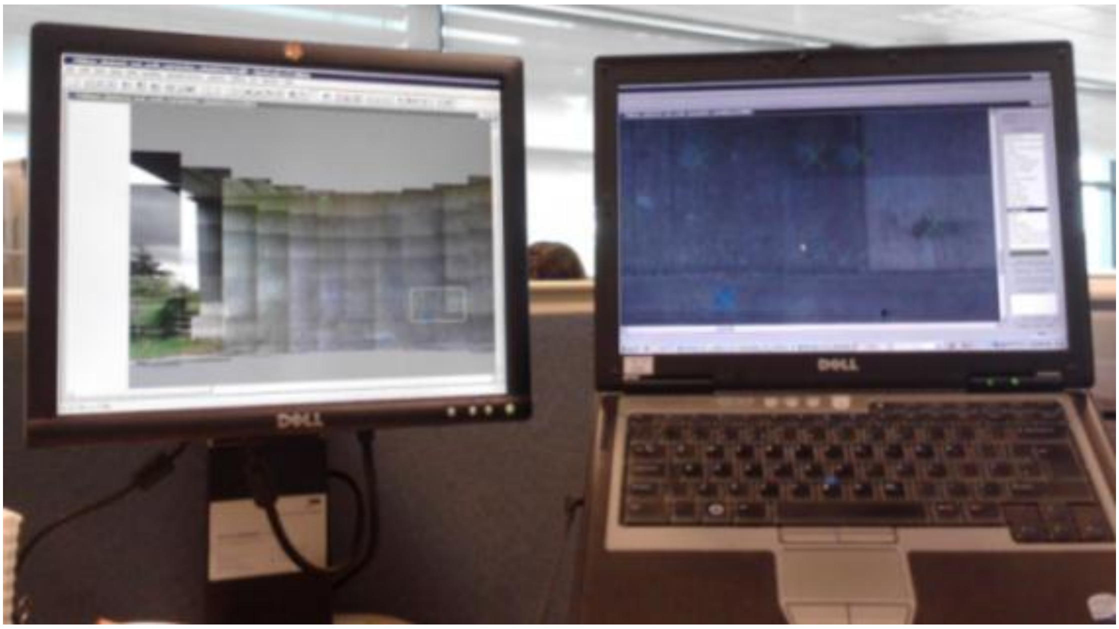
Additionally, the loading and manipulation of images is faster, and hence the inspection process is faster, if the images are stored on either a USB hard disc, or from the PC hard disk itself, rather than over a network connection.

As with all computationally intensive applications, it may also be a good idea to turn off any non-essential applications on the PC while performing the inspections.

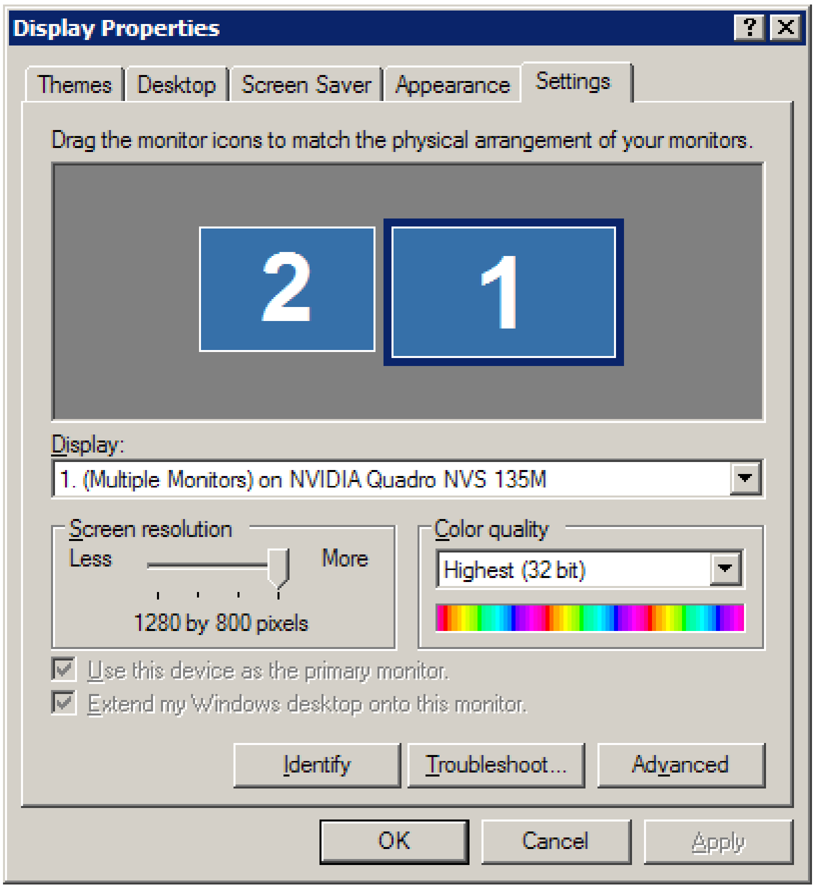
Recommended display screen set up

The inspections will be easiest if performed on a large dual screen setup.

This will enable you to use one screen to display the thumbail images showing your location on the bridge, and the other to display the close up detailed images to be used for performing the inspection.



[#] PC_setup_structures_inspection


Display Properties
Themes
Desktop
Screen Saver
Appearance
Settings
Drag the monitor icons to match the physical arrangement of your monitors.
2
1
Display:
1. (Multiple Monitors) on NVIDIA Quadro NVS 135M
Screen resolution
Less
More
1280 by 800 pixels
Color quality
Highest (32 bit)
Use this device as the primary monitor.
Extend my Windows desktop onto this monitor.
Identify
Troubleshoot...
Advanced
OK
Cancel
Apply

[#] Files used in carrying out inspections of structures

Directory structure

In order to open, display and inspect the images you will need the following files and directory structure (directories are shown in **bold**, files are shown in *italics*):

Structure name
|-------**Structure element/surface**
|--------------**Viewing position**
|---------------------*Name_surface_position_reprojection_calculations.txt*
|---------------------*Name_surface_position_reprojection_calculations.txt.cam*
|---------------------*Name_surface_position_reprojection_calculations.txt.NBP*
|---------------------**full**
|----------------------------*Name_surface_position_reprojection_…_reordered.txt*
|----------------------------*TRL_xxxx_0_reproj.bmp*
|---------------------**half**
|----------------------------*TRL_xxxx_0_reproj.bmp*
|---------------------**quarter**
|----------------------------*TRL_xxxx_0_reproj.bmp*
|---------------------**eighth**
|----------------------------*TRL_xxxx_0_reproj.bmp*
|---------------------**sixteenth**
|----------------------------*TRL_xxxx_0_reproj.bmp*
|---------------------**thirtysecond**
|----------------------------*TRL_xxxx_0_reproj.bmp*

What each directory contains

.nbp file– Contains information about the images and file structure. ChartCrack needs this to know where to look for information, and how to display the images.

.txt file – Contains details of where each image was collected on the face of the structure (x,y coordinates in own local co-ordinate system)

.cam file – information about the camera and viewing position for each image collection spot. Needed for pre-processing of images, but not needed by ChartCrack.

[#]files_structures_inspection

[#] The txt file use for locating the images of structures

This file contains the names of all of the images to be displayed in the current set, and the local imageset x and y coordinates of the bottom left corner of the image, in metres. The entries are tab delimited, with each image – coordinate set being on a new line.

File format

The file format for the .txt file is as follows:

TRL_2966_0_reproj.bmp	0.000	7.783
TRL_2967_0_reproj.bmp	0.000	6.345
TRL_2968_0_reproj.bmp	0.000	5.002
TRL_2969_0_reproj.bmp	0.000	3.720
TRL_2970_0_reproj.bmp	0.000	2.475
TRL_2971_0_reproj.bmp	0.000	1.242
TRL_2972_0_reproj.bmp	0.000	0.000
TRL_2973_0_reproj.bmp	1.970	7.310
TRL_2974_0_reproj.bmp	1.970	5.986
TRL_2975_0_reproj.bmp	1.970	4.748
TRL_2976_0_reproj.bmp	1.970	3.568
TRL_2977_0_reproj.bmp	1.970	2.421
TRL_2978_0_reproj.bmp	1.970	1.285
TRL_2979_0_reproj.bmp	1.970	0.141

What this means:

There are 14 images in the example shown above.

The bottom left pixel of image TRL_2966_0_reproj.bmp is from an x position of 0.000m across, and 7.783m up (in the local imageset coordinates). These images have been collected in two vertical strips, each containing 7 images. Images 2966 to 2972 have been taken in one vertical strip, and then the camera has moved across 1.970m, and up 7.310m, before starting to collect the second strip containing images 2973 to 2979.

[#] txt_files_structures_inspection

[#] The nbp file use for carrying out inspections of structures

This file contains information about the images and file structure. ChartCrack needs this to know where to look for information, and how to display the images.

File format

The file format for the .nbp file is as follows:

50
FACESIZE, 20.0, 10.0
LOCFILENAME,Frilsham_abutment_east_north_small_selection.txt
FULL,full\,1.0,1.0
THUMB,eighth\,8.0,8.0
RED,half\,2.0,2.0
RED,quarter\,4.0,4.0

What this means:

50 is a file identifier, telling ChartCrack that it is a structures file, and hence a structures inspection.

The **FACESIZE** defines how large the image set is, and how large the output data must be. This is in metres. The numbers define the horizontal extent of the data, and then the vertical extent of the data. In the example above, the output data will be **20.0** m wide, and **10.0** m high.

The **LOCFILENAME** tells ChartCrack where to find the file containing the image names and aligned position information.

The entry starting with **FULL** contains the location of the fullsize images, and the pixel resolution (x,y) in mm of these images (in this case the pixel resolution is **1**mm x **1**mm).

The **THUMB** entry tells the software where to find the thumbnail images of the dataset, and the pixel resolution of these. In this case the images have 1pixel per **8**mm x **8**mm of structure, and are in subdirectory '**eighth**'.

The **RED** entries contain the locations of the reduced image sets, and the resolutions of the reduced images. In the case shown there are reduced image sets at **half** resolution (**2**mm x **2**mm, in subdirectory '**half**'), and also at a **quarter** scale (**4**mm x **4**mm, in subdirectory '**quarter**').

[#] nbp_files_structures_inspection

[#] The list of defects that will be used for the inspection

ChartCrack uses a file to define the list of defects that will be used in an inspection of a structure.

The file is located in:

\ChartCrack Bridges\Release\INI Files\StructureDefectDefinitions.csv

To change the defects listed (or the names of the defects) simply edit the **.csv** file. The first entry in the file (for historical programming reasons) ***MUST*** be "Crack". **Do not change this**.

This list may be edited prior to starting a visual survey, but once a survey is started, the file MUST NOT be changed.

To edit the file it is simplest to use **Notepad** as other programs may append hidden characters which interfere with the reading of the file.

The following defects are suggested as a minimum starting point for any survey on a concrete structure, but others can be added as appropriate:

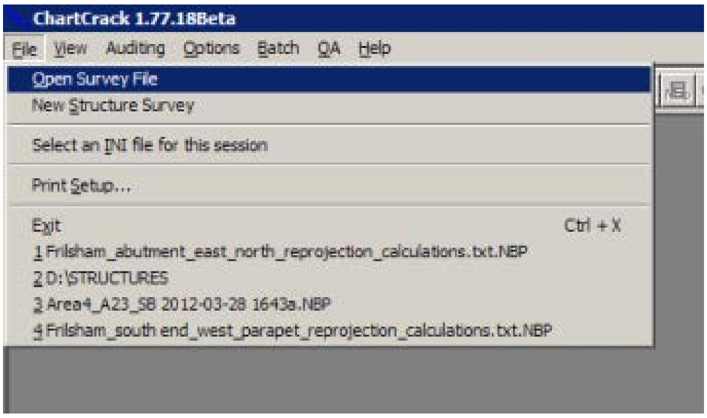
Crack
Visible Steel reinforcement
Spalling
Rust staining
Missing components
Loose components
Impact damage
Scour
Distortion/bulging
Leakage
Wet surface
Leaching
Fire damage
Other Defect
Cable/drainpipe
Drilled hole
Graffiti
Joint
Vegetation
Other Feature
Edge of structure/surface
Covered Up/Obscured
Poor quality/missing image

[#]defect_list_structures_inspection

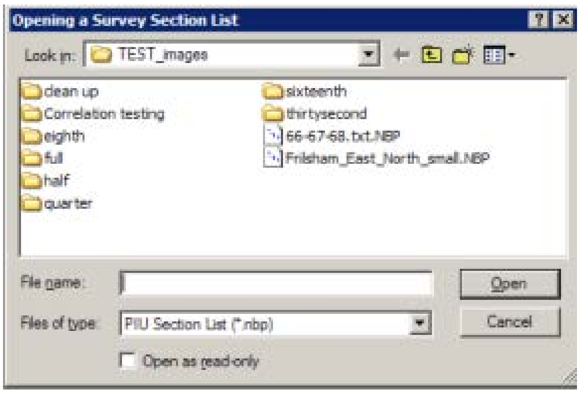
[#] Opening the image data files – using the nbp file

After starting up ChartCrack the easiest way to open a set of image files to carry out an inspection is to drag the **.nbp** file for the required image set into the main ChartCrack window.

Alternatively, select **File/Open Survey File**, as shown below:

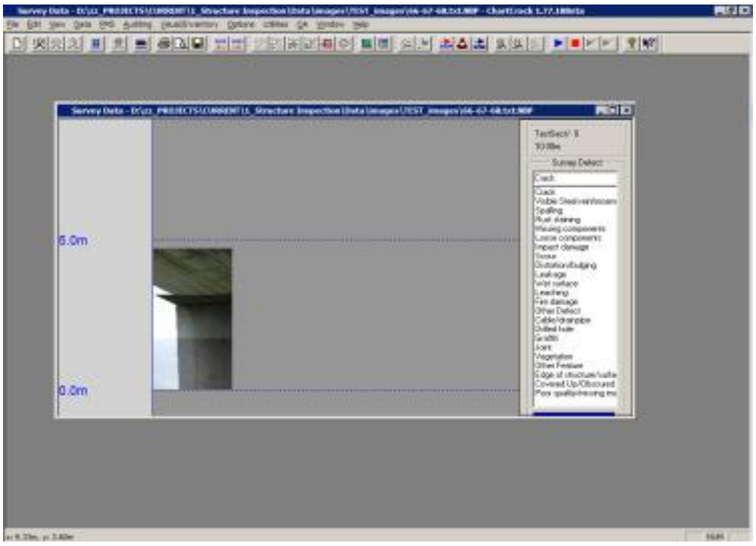


From the file dialog select the **.nbp** file for set of images that you which to inspect.



ChartCrack will automatically load the images for this survey, presenting a screen like:

[#]Opening_image_files_with_nbp_structures_inspection



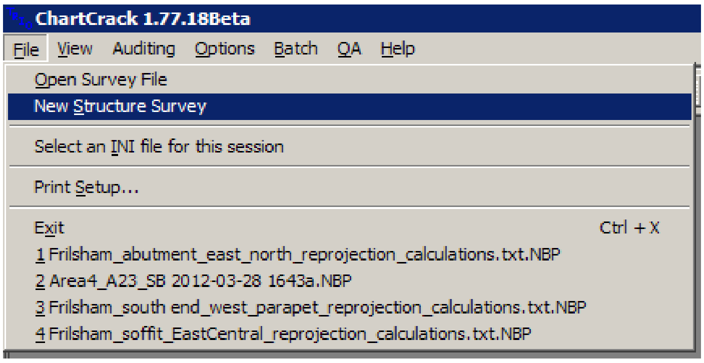
Note:

- It may take a few minutes to load the image data.
- When a new survey is opened, you may have to zoom in and out, or switch between full screen and window mode to get the screen to display and refresh correctly.

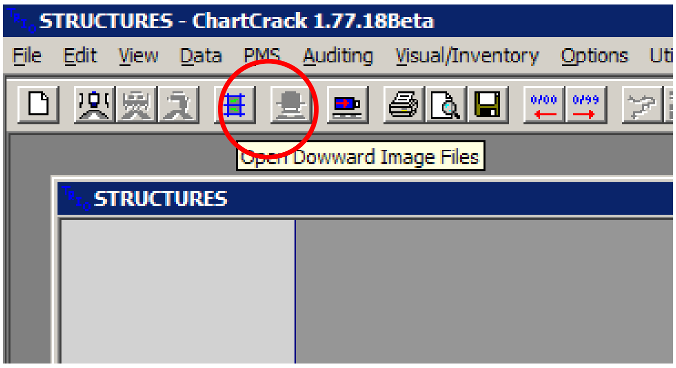
[#] Opening the image data files – using a blank survey

Note: *this is not the preferred method of opening image files for structures surveys. It is recommended that a structures nbp file is established and the method of "Opening the image data files – using the nbp file" be used.*

A "blank survey" can be opened by selecting **File/New Structure Survey**, as shown below.

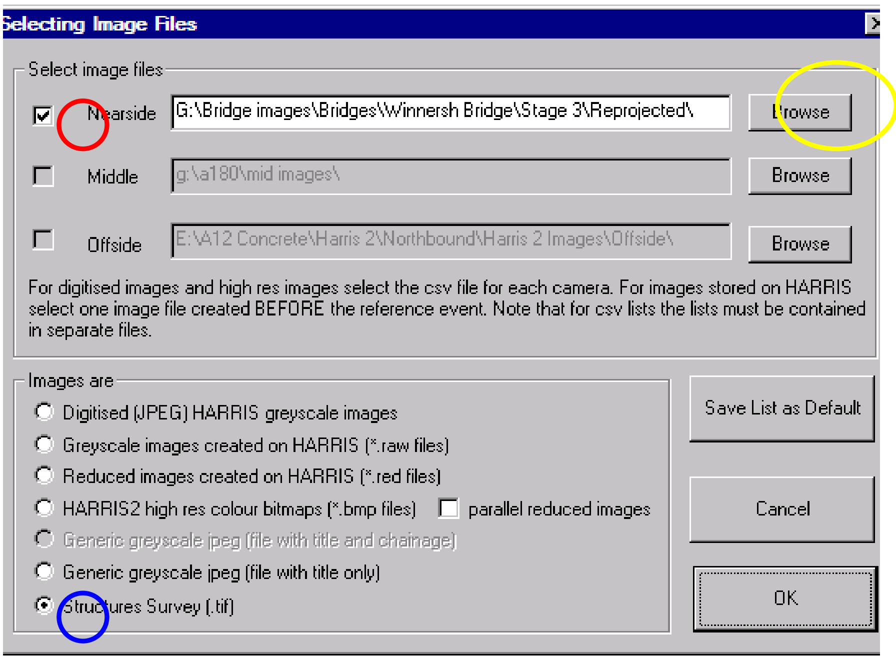


This will open an survey of a fixed face size (50m wide by 20m high) on which to overlay a set of images. To load the images you must open them manually be selecting the "**Open Downward Image Files**" button, shown below.



A dialog for selecting the images is shown. Tick only **Nearside** button, shown in red circle below.

[#]Opening_image_files_blank_structures_inspection



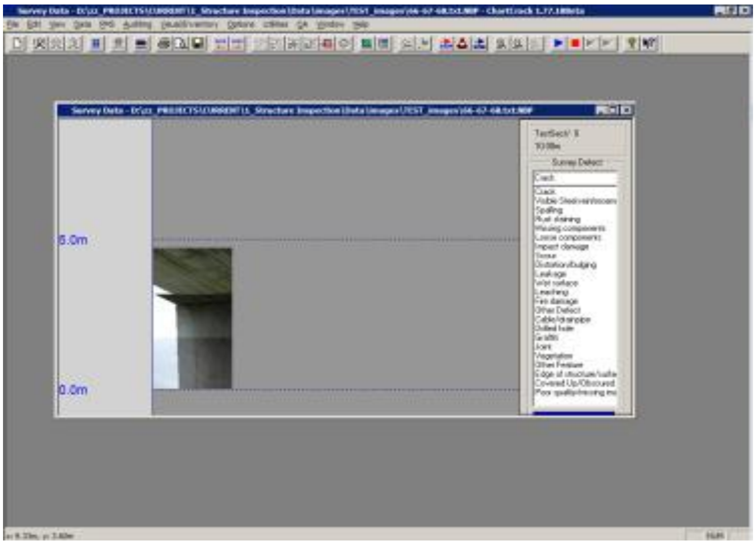
Select only the "**Structures survey (.tif)**" radio button (blue circle), nothing else should be selected.

Use the Nearside "**Browse**" button (yellow circle) to navigate to the correct directory and select the .txt file for the images of the face you want to inspect.

Note: These are the .txt files located in the "full" directory.

Click the **OK** button.

ChartCrack will load the images for this survey, presenting a screen like:



Note:

- It may take a few minutes to load the image data.
- When a new survey is opened, you may have to zoom in and out, or switch between full screen and window mode to get the screen to display and refresh correctly.

Optimising the display when carrying out inspections of structures

There are several factors which affect the appearance of the images in ChartCrack. These include:

- The zoom settings
- The settings for the size of each pixel

Note: the operations will only work if the image window is “active” (The active window is often shown in windows by the header bar being coloured, with the inactive windows having a grey header bar).

Scrolling

Once the images are loaded you can use the **scroll bars** to navigate around the image set using the vertical and horizontal scroll bars.

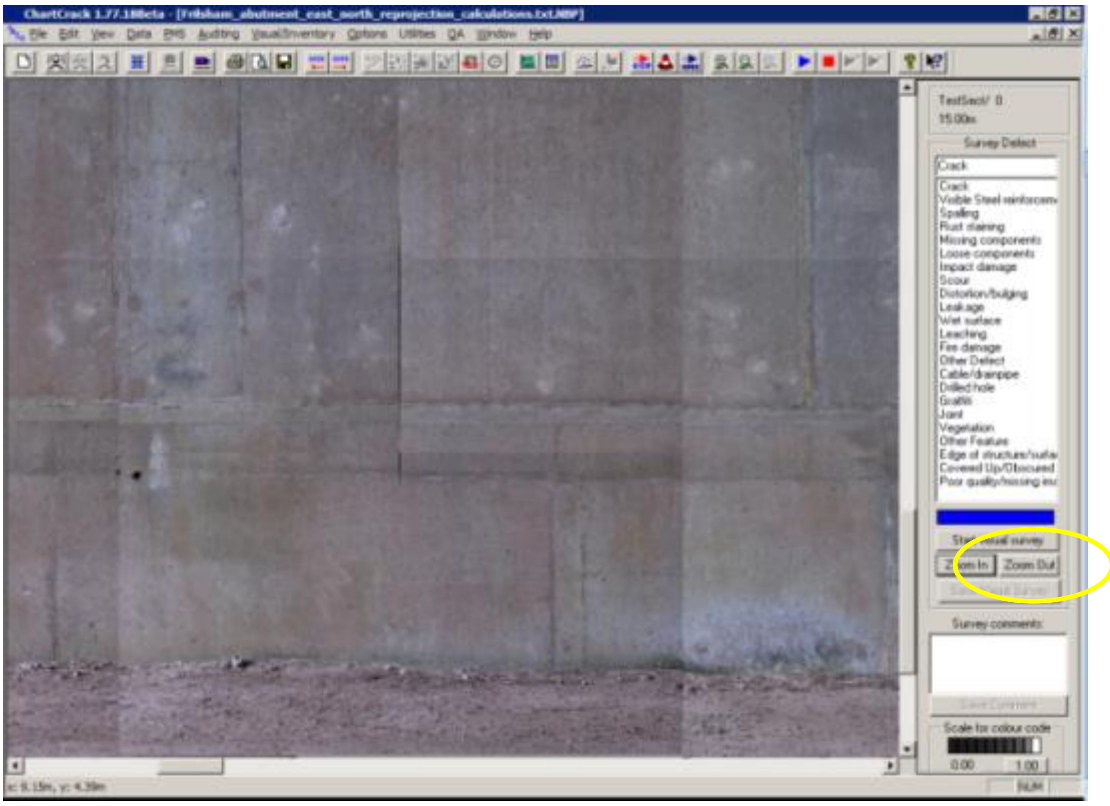
If your mouse has a scroll wheel, this can be used for vertical scrolling.

The Left/Right and Up/Down arrow keys can also be used for horizontal and vertical scrolling.

Zooming using the Zoom In and Zoom Out buttons

There are two methods of zooming into and out of the images.

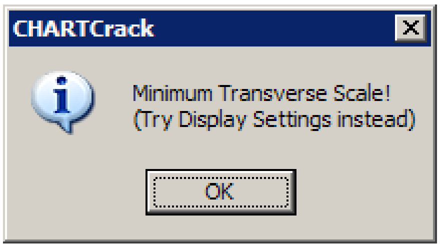
The “**Zoom In**” and “**Zoom Out**” buttons are located to the right hand side of the image:



#optimising_display_structures_inspection

- Pressing "**Zoom In**" will **double** the scale in both the vertical (x) and transverse (y) directions
- Pressing "**Zoom Out**" will **halve** the scale in both the vertical (x) and transverse (y) directions

There is a limit to the level of Zoom Out. When the maximum zoom out is achieved a message will be displayed to inform you that you can no longer zoom out.



Zooming using "magnifying glass" in the toolbar

There are **zoom in /out icons** in the tool bar

The use of these buttons is more complex than using the "**Zoom In**" and "**Zoom Out**" buttons.

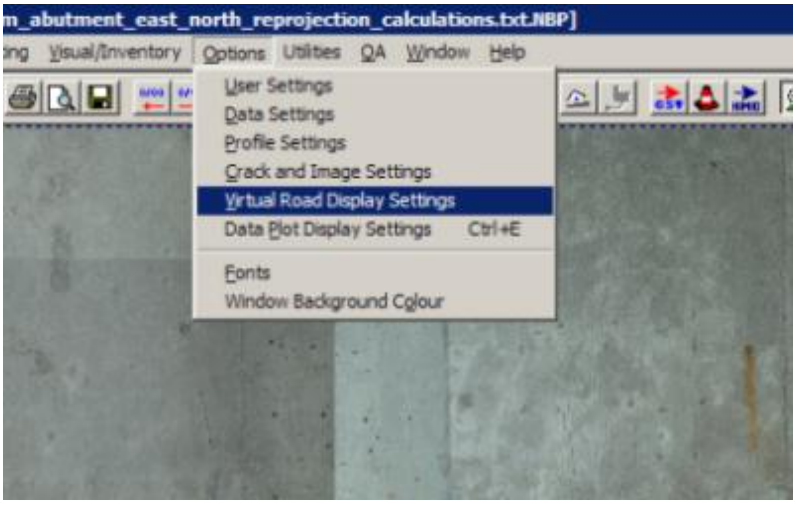
- Pressing the zoom magnifying glass  (containing a "**+**") switches on zooming.
  - When zoom is on, double clicking on the image will double the scale in the vertical (y) direction
  - When zoom is on, holding down Ctrl and double clicking on the image will double the scale in the transverse (x) direction
- Pressing the reduce magnifying glass  (containing a "**-**") switches on reducing.
  - When reduce is on, double clicking on the image will halve the scale in the vertical (y) direction
  - When reduce is on, holding down Ctrl and double clicking on the image will halve the scale in the transverse (x) direction

Note:

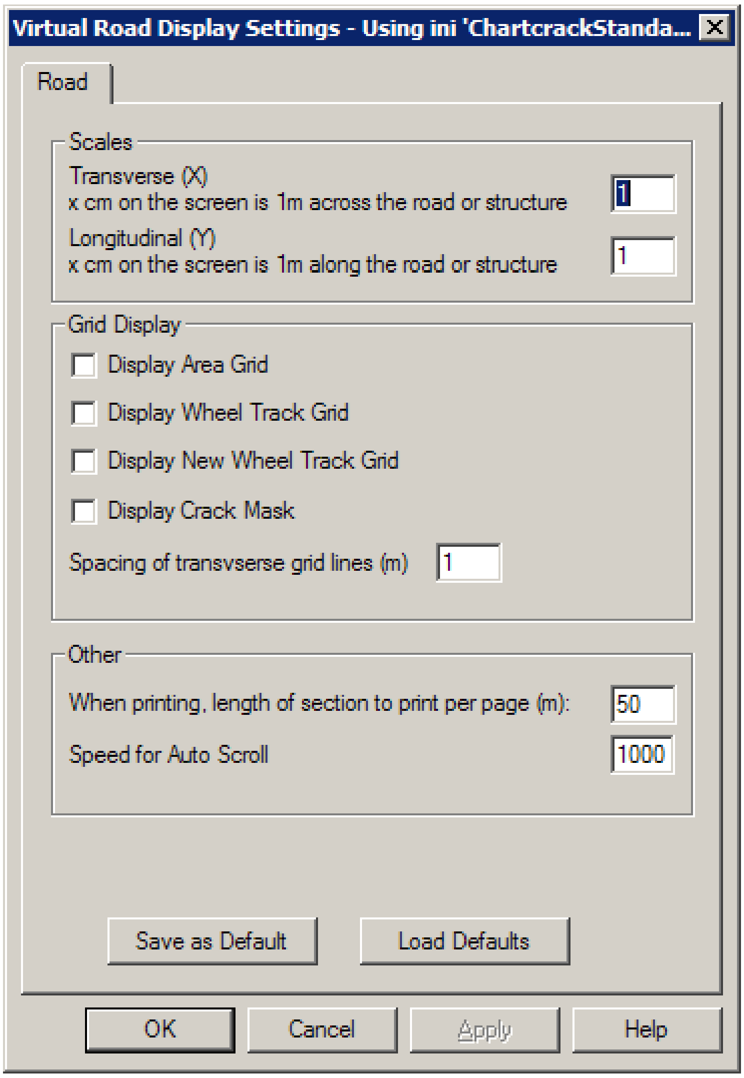
- It is recommended that the "**Zoom In**" and "**Zoom Out**" buttons are used instead of the toolbar buttons.

Changing the zoom using the display settings

The zoom level in the x and y direction can be changed manually by selecting "**Options / Virtual Road Display Settings**"



Changing the **x** and **y** pixel scale factors independently will result in distorted and misaligned images. The scale factors must be integers (minimum value of 1).

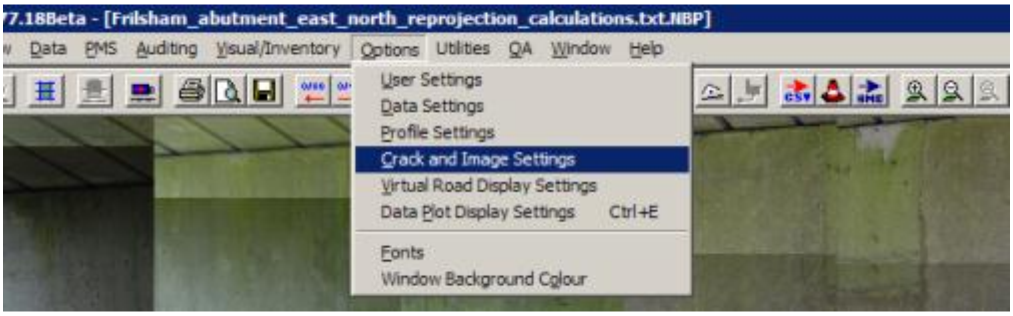


Checking the pixel size

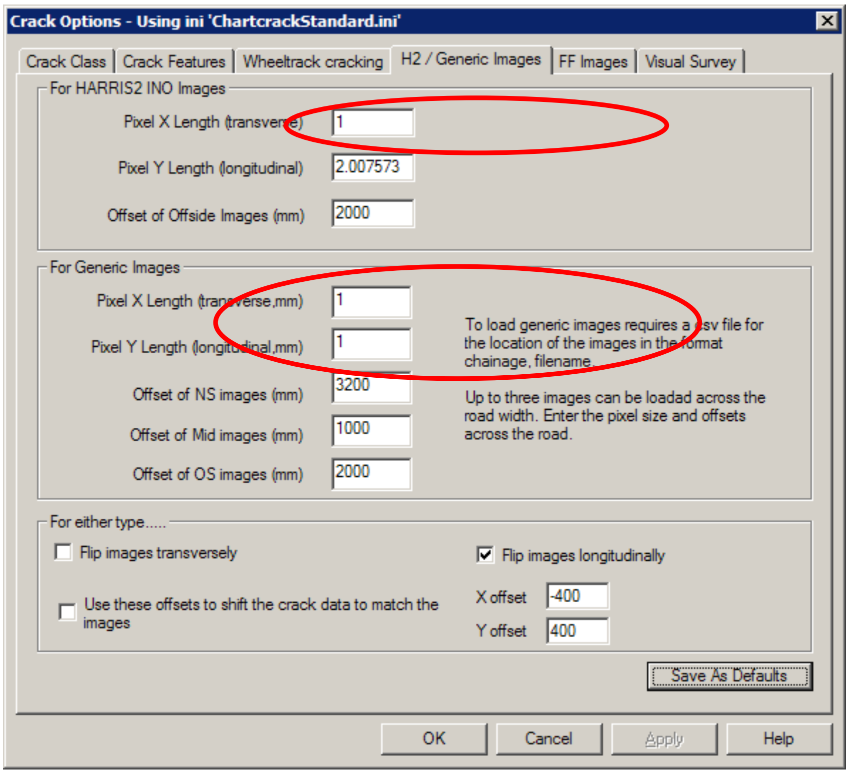
ChartCrack displays images using actual sizes of pixels in mm. Therefore the scaling and the visual inspection is affected by the definition of the pixel size for the current image dataset.

Note: When the images are opened using a structures .nbp file the pixel size is defined in the .nbp file. However, the operation defined below allows the pixel size to be redefined for the current session only (selecting Save as Default will not change the values defined in the .nbp file)

To check that the image pixel scaling is set correctly select ***Options / Crack and Image Settings***

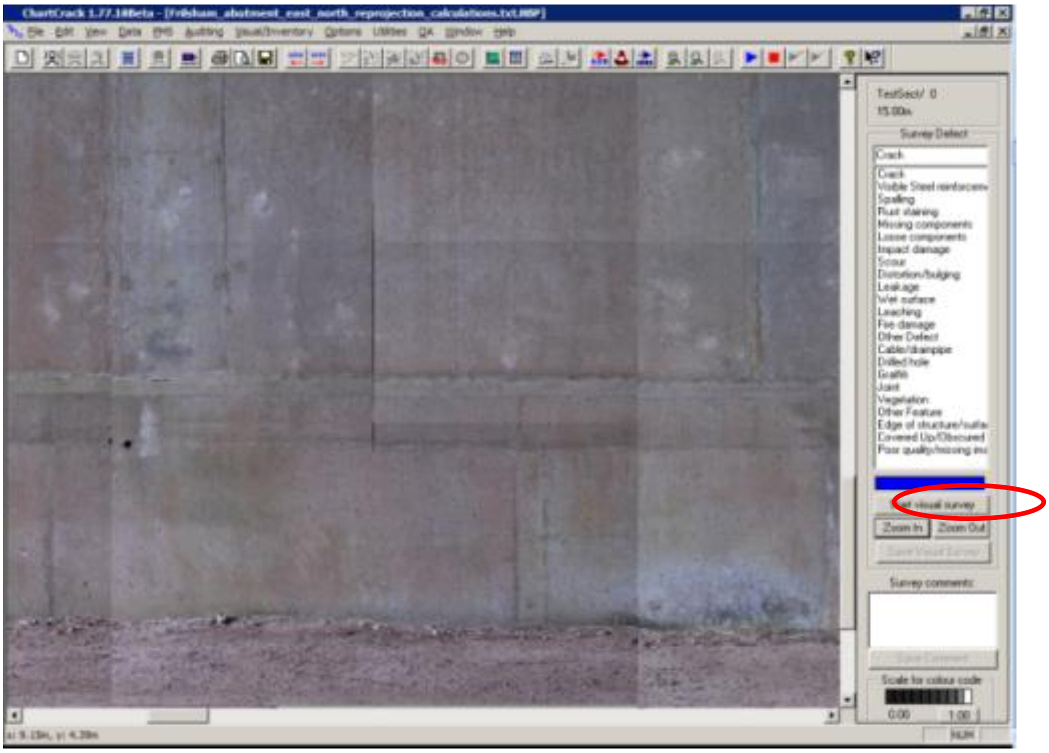


This will bring up the following dialog. Select the "**H2/Generic Images**" tab, and set the Generic Images ***Pixel X Length*** and ***Pixel Y Length*** values. In this example they are set to x=1 and y=1 (shown below), which tells ChartCrack that each pixel covers 1mm in the x direction and 1mm in the y direction on the surface of the structure.


Crack Options - Using ini 'ChartcrackStandard.ini'
Crack Class
Crack Features
Wheeltrack cracking
H2 / Generic Images
FF Images
Visual Survey
For HARRIS2 INO Images
Pixel X Length (transverse)
1
Pixel Y Length (longitudinal)
2.007573
Offset of Offside Images (mm)
2000
For Generic Images
Pixel X Length (transverse,mm)
1
Pixel Y Length (longitudinal,mm)
1
Offset of NS images (mm)
3200
Offset of Mid images (mm)
1000
Offset of OS images (mm)
2000
To load generic images requires a csv file for the location of the images in the format chainage, filename.
Up to three images can be loadad across the road width. Enter the pixel size and offsets across the road.
For either type.....
Flip images transversely
Flip images longitudinally
Use these offsets to shift the crack data to match the images
X offset
-400
Y offset
400
Save As Defaults
OK
Cancel
Apply
Help

Carrying out a visual inspection of structures images

To carry out a visual inspection of the images click on the **Start visual survey** button, shown below.



This will open a dialog box prompting you to enter the output file in which to store the results of the survey. Provide a meaningful filename, location and click the **OK** button.

Note: ChartCrack will create the file if it does not already exist. If you select an existing file then the new inspection results will overwrite the existing data. Be careful.

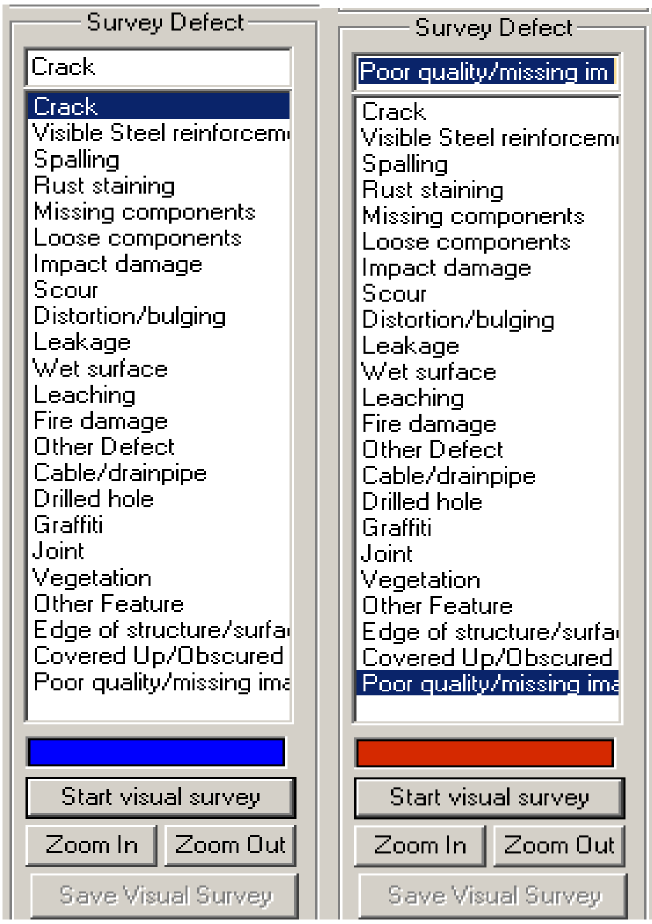
Visual inspections are carried out by

- Identifying a defect on the image
- Selecting the defect type from the list on the right hand side of the window
- Clicking the left mouse button at the location of the defect. This creates a “defect grid square” over the defect.
- Adding “survey comments” where required

Selecting the defect type

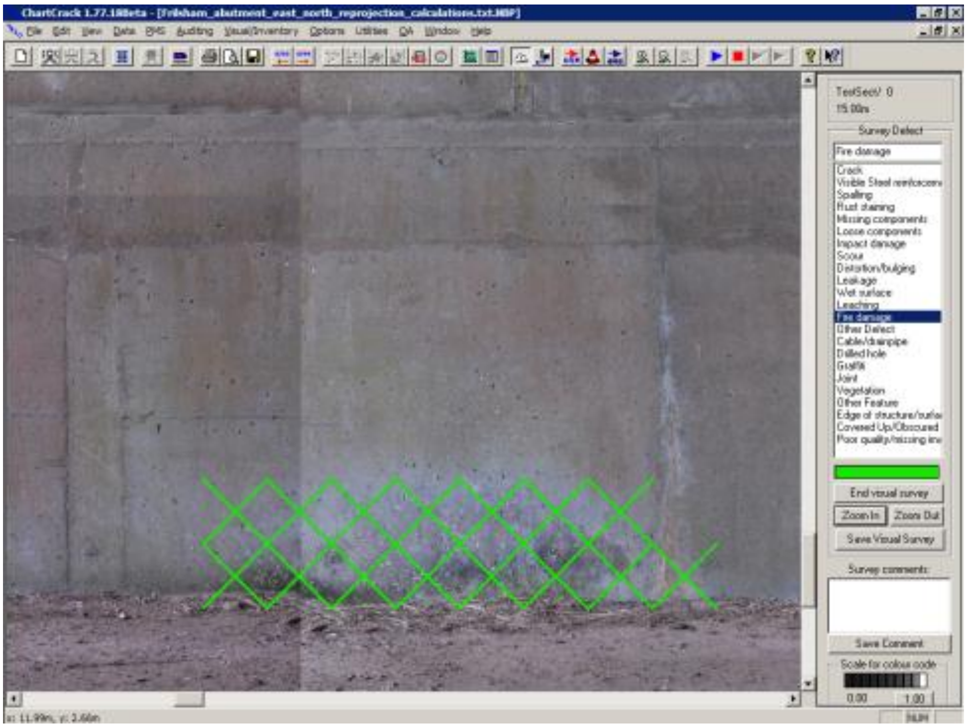
Use the defect selection panel (shown below) to select which defect you are marking on the bridge at any time. Different defects will be marked in different colours as shown below (i.e. **Cracks** will be marked in blue, **Poor quality/missing images** will be marked in orange).

[#] Carrying_out_a_structures_inspection



Recording and removing defects

To record the defect select the relevant survey defect from the panel, and **left-click** on the image. This creates a grid square on the image which is shown over the defect, as shown below



The following summarises different ways of recording defects and removing defects when incorrectly marked

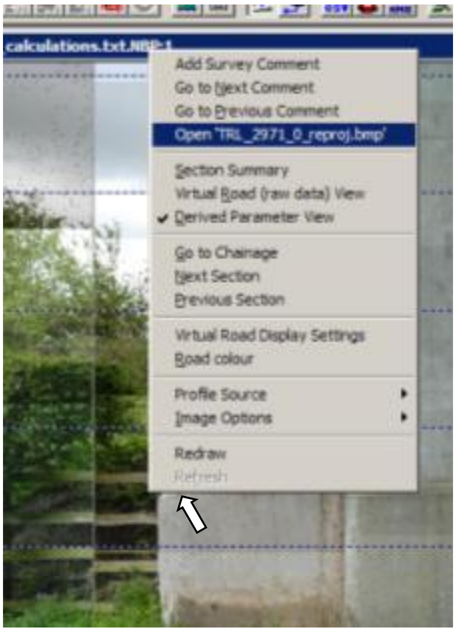
- To select an area of the images, hold the **SHIFT** key while **left-clicking** on the image, and drag the mouse over the area you wish to highlight.
- To remove a grid square (e.g. due to mis-clicking, or changing your mind) press **CTRL** and **left-click** the cross.
- To remove a set grid squares press **SHIFT** and **CTRL** and **left mouse button** while moving the mouse over the gird squares to want to remove.

Note: When carrying out these actions there may be a delay in the response of the display

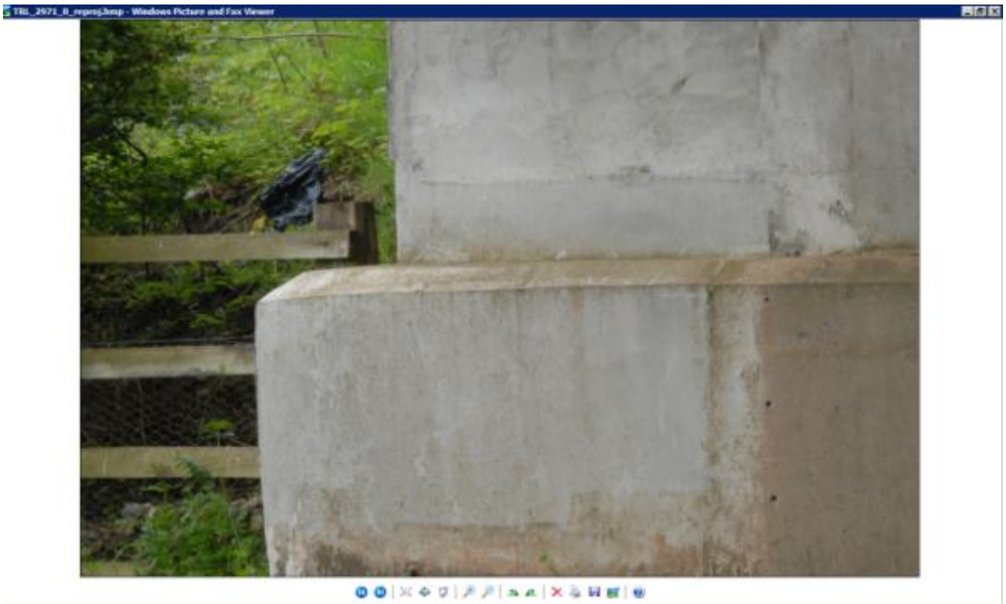
Opening Individual images

Sometimes, during an inspection, it may be desirable to open the particular image which is of interest for closer investigation, printing, or sharing with colleagues.

Right clicking on the main image view will bring up a menu containing an option to open the individual image which the mouse was over at the time.



Selecting the **Open '*image_file_name.bmp*'** option will open a new window in another application (usually Windows Picture and Fax Viewer) where the individual image can be inspected.



#Opening_Individual_Images

Recording and removing comments

Comments can be used to add additional information which may be of use later when interpreting the results.

To add a comment to the inspection data **right-click** on the image at the location where you wish to add the comment, and select “**Add Survey Comment**”

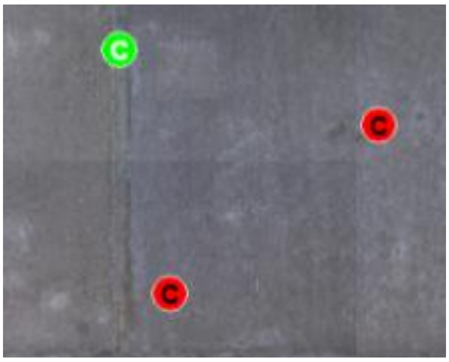
This will mark the image with a green © icon

The survey comments box at the lower right of the window shows the text for the current comment. The default text will say “Add comment here (n)”.

Type the comment text into the **Survey comments** box, and click the **Save Comment** button.

The active comment (the one associated with the text displayed in the **Survey comments** box) is shown in green, other comments are shown in red. Moving the mouse over a comment icon on the image will make it become active. An active comment will change its display icon from red to green, and display its associated text in the edit box.

#Recording_comments

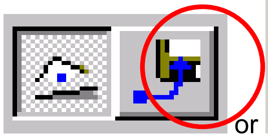


Note:

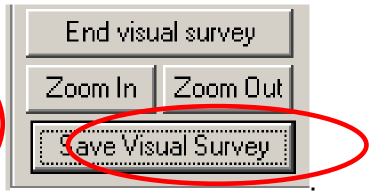
- Always remember to select **Save Comment**, if not the comment text will be lost as soon as you move to another comment.
- The **Save Comment** button only stores the comment in the PC memory NOT TO THE DISK, to save the data to the disk, follow the instructions for **Saving the Results**

Saving the results

To save all the results (the grid data and the comments) to a file select the save icon on the toolbar, or press "**Save Visual Survey**" on the right side of the window



or



.

Note: remember to save regularly to reduce the risk of loss of data (e.g. in the event of a software crash). If you need to restart the survey you can then load back in the partially completed survey and continue from where you left it – see **Continuing a visual inspection of structures images from a saved file.**

Saving the data creates the following files:

- A **.grd** file containing the grid survey data
- A **.cmt** file containing the comments

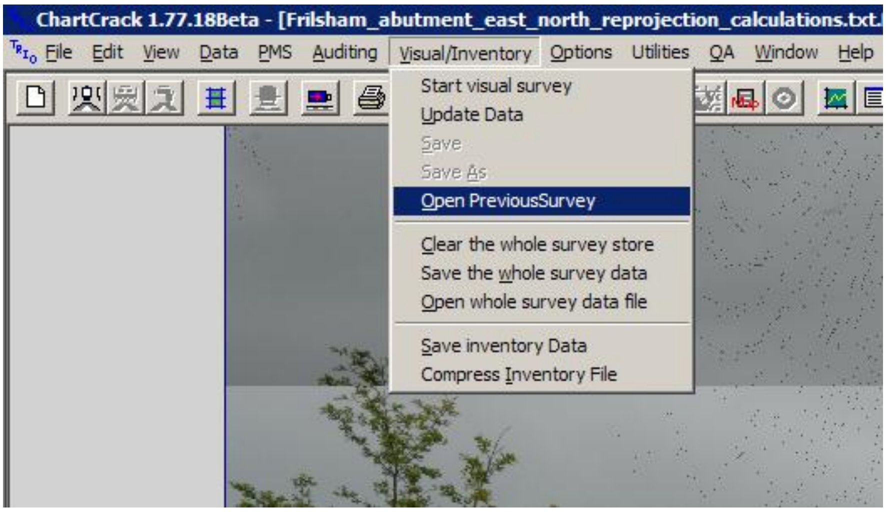
#Saving_the_results

[#] Continuing a visual inspection of structures images from a saved file

You can open a partially or fully completed visual survey to check the data or add further data.

Open the relevant **.nbp** file (drag it into main ChartCrack window) according to **Opening the image data files – using the nbp file** so that the images for the structure are displayed in ChartCrack

Select "**Visual/Inventory / Open Previous Survey**"



From the file dialog select the required **.grd** file created in the previous survey. You may have to browse to find it depending on how you set up the file structure for inspection results.

Once you have selected the correct **.grd** file, the previous survey data should open and any defects and comments should be displayed in the correct places.

WARNING: It is possible to open data from a previous survey which was not carried out on the images you have loaded into ChartCrack. For example you could open the images from "Face 1" of a bridge and the inspection data from the inspection carried out on "Face 2" of the bridge. **Take care not to do this.**

[#] Continuing_a_structures_inspection

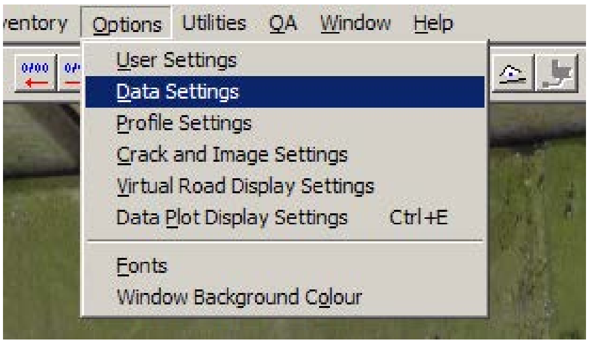
Setting up ChartCrack for a visual inspection of structures images

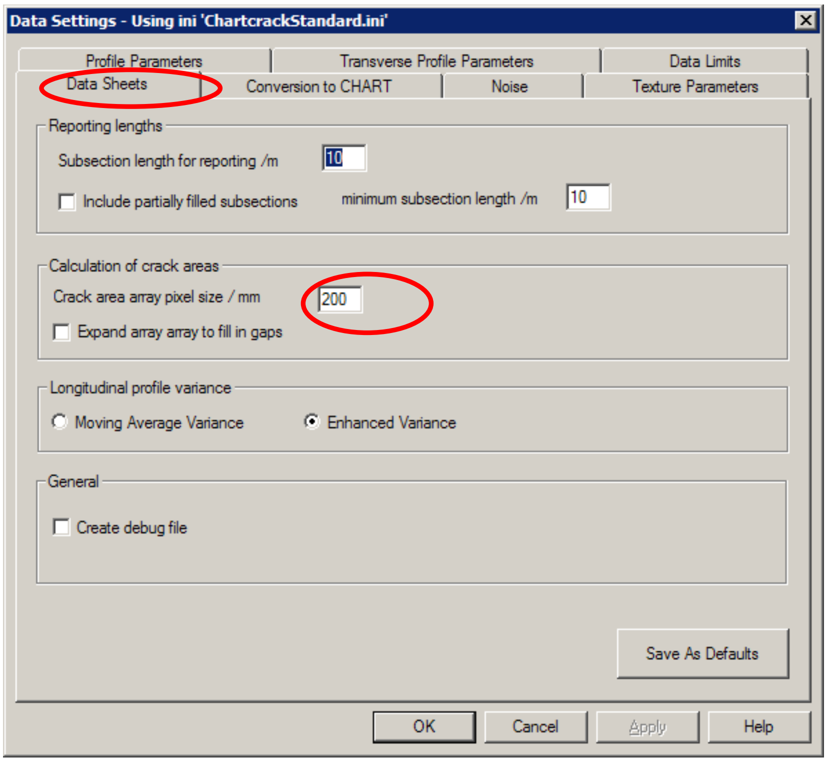
Setting the Grid Size

To produce output inspection results at the correct resolution it is important to ensure that the grid size is set correctly.

By default each grid square is 200mm x 200mm.

To change the grid size ***Options/Data Settings*** and select the "**Data Sheets**" tab.

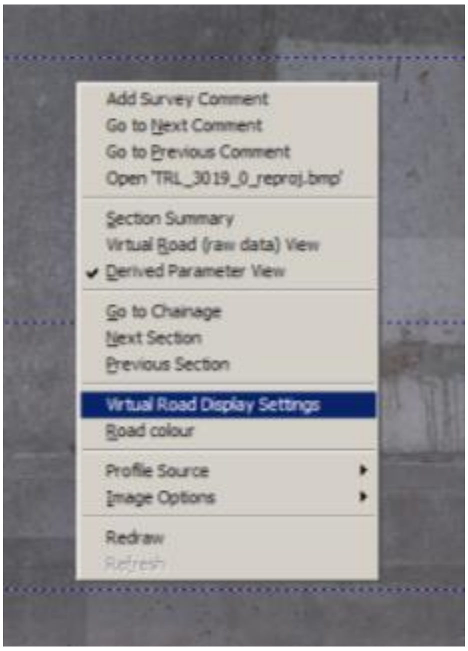




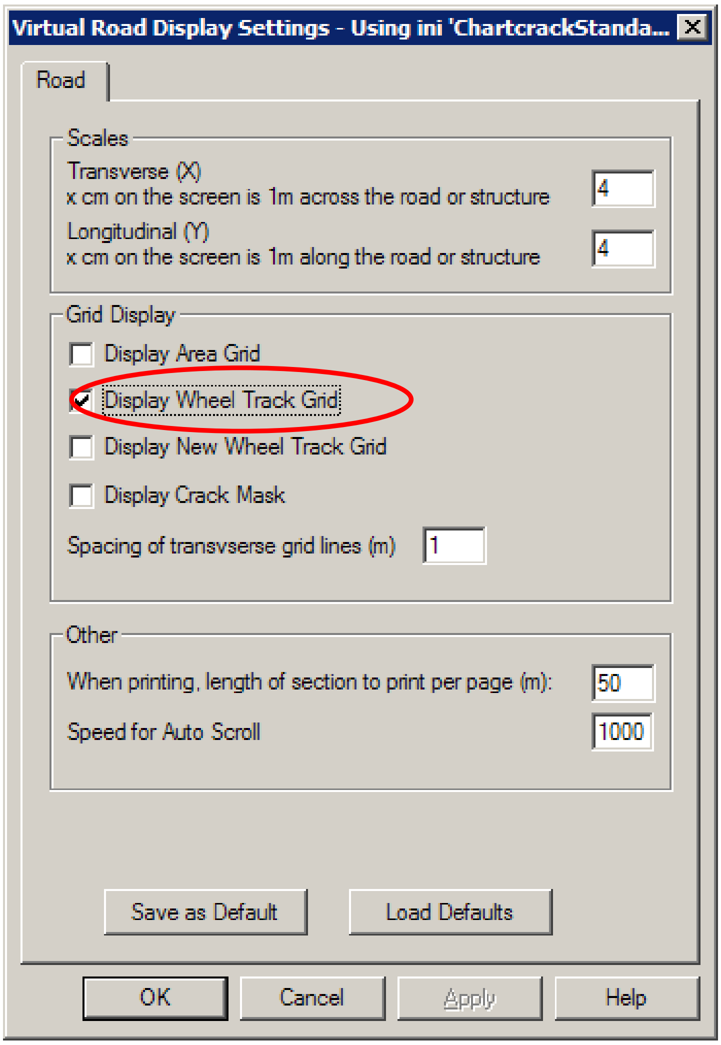
Displaying grid lines

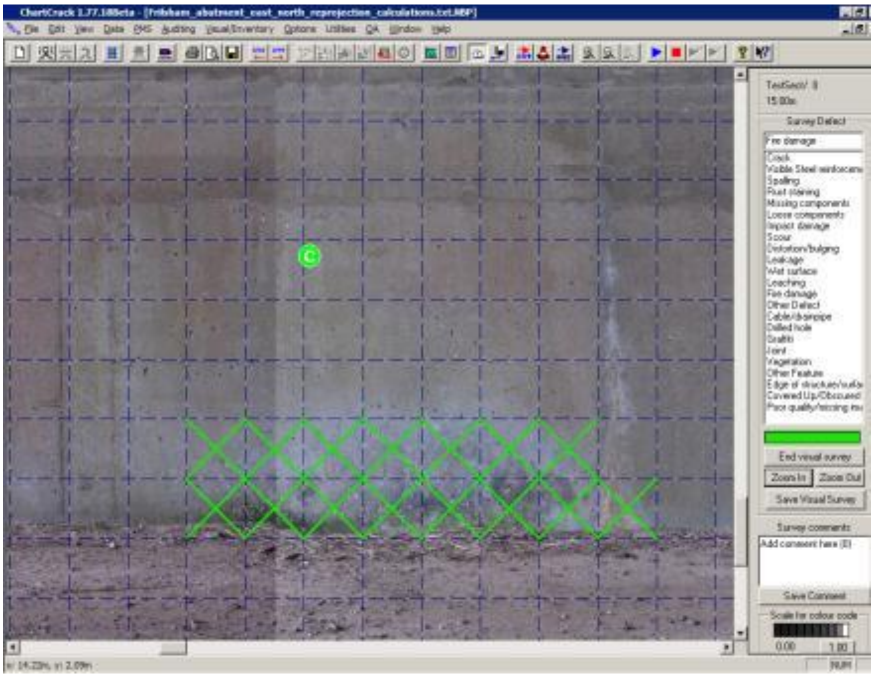
It is sometimes useful to have the grid overlaid on the images. This is more informative when closely zoomed in than at wide views. To display the grid lines right click on the images and select **Virtual Road Display Settings**

#Setup_a_structures_inspection



This will bring up the following window. The grid lines will be displayed on the images if the **Display Area Grid** check box is ticked, as shown below.



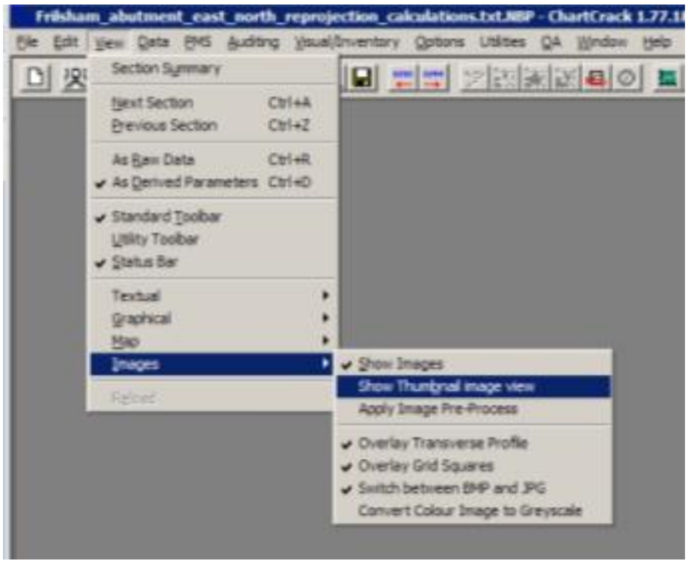


Using thumbnail images

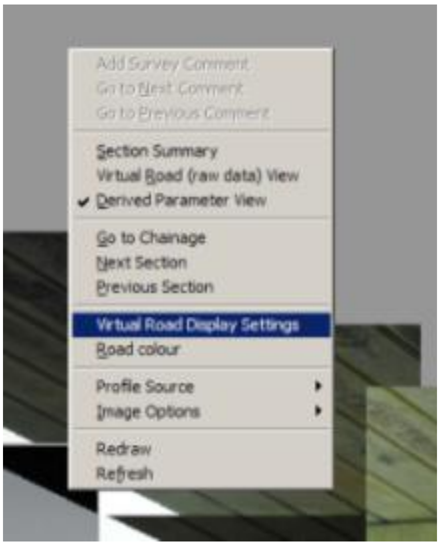
It can be difficult to maintain orientation on a large structure when viewing a lot of images at a zoomed in view. To help with the inspection process it is possible to display thumbnail images.

Because they have a lower resolution it is practical to show the thumbnails of the whole face of the structure in a single window.

Once a survey and a set of images has been loaded (see above), select **View/Images/Show Thumbnail image view**

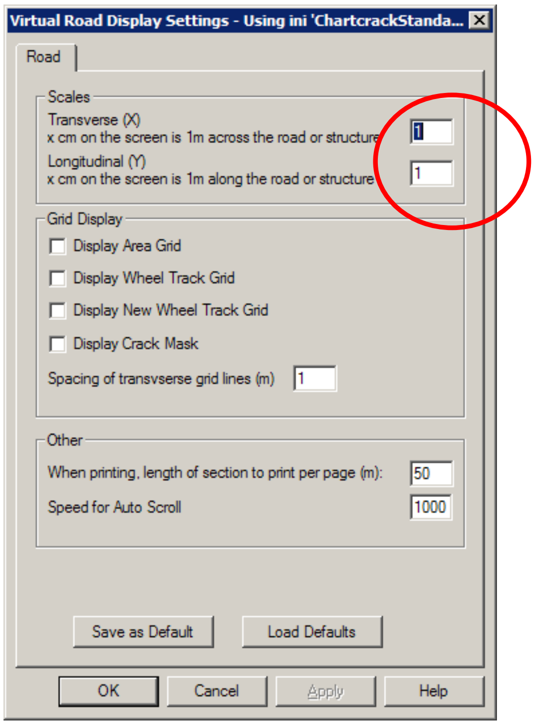


This will open the thumbnail images. At first, they may be incorrectly displayed. **Right click** on the thumbnail images, and select **Virtual Road Display Settings**

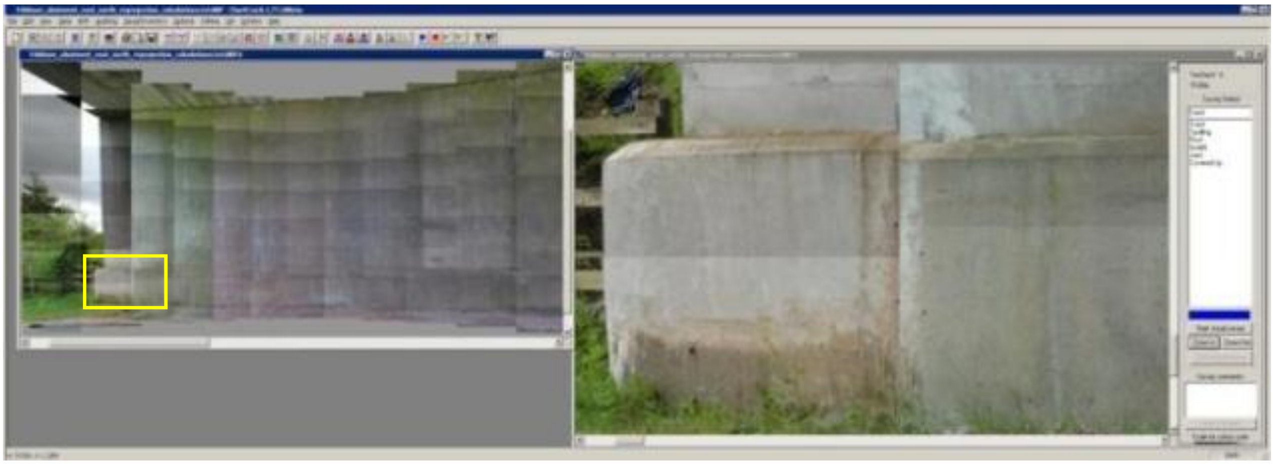


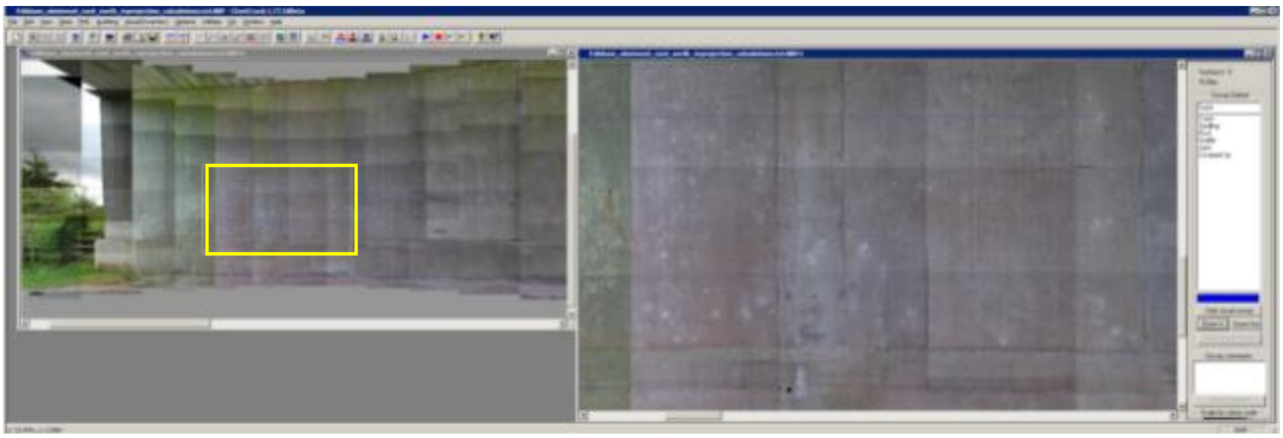
Enter the values as shown below, only the two values circled need to be adjusted (values of 1 and 1 should be correct):

#thumbnail_images



The display should now have a wide view showing all (or a large area of a part of the bridge) and a close up view of a portion of the bridge.





The extent of the images that are shown in the current inspection view is shown as a yellow rectangle in the thumbnail view, as shown in the left hand side of the above screenshots.

Zooming in, out, or moving around within the inspection window will move the yellow rectangle in the other window, meaning that you should always be sure which part of the bridge you are looking at.

Note: The above screen shots are taken from a dual screen set up. It can be useful to have the “full” inspection images on one screen and the thumbnail images on a separate screen.

[#] Interpreting and viewing inspection results

The inspection results will be saved and stored as a **.grd** file. These files can be viewed in Excel (or similar software).

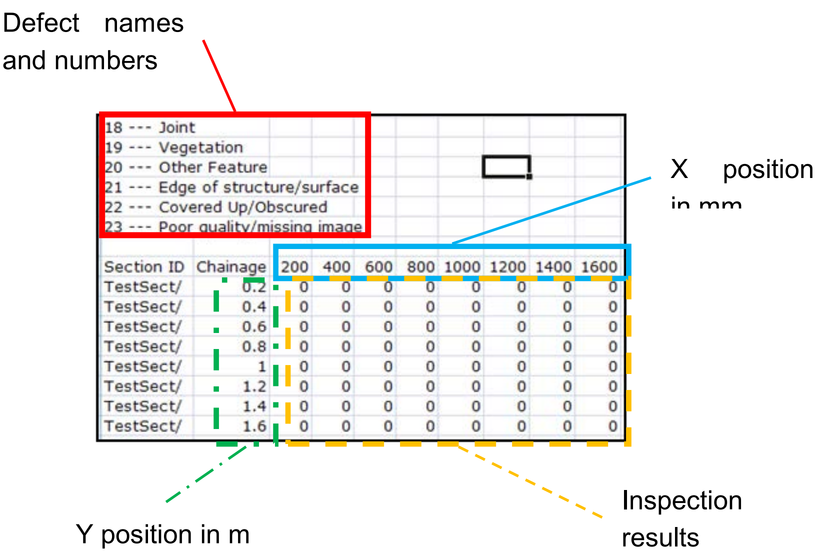
The **.grd** files contain a look up table containing all the defects from the defect list, and an associated number. These numbers are used in the data to indicate the presence of each defect.

Below the defect information there is a grid of data (the size of which is defined by the **FACESIZE** parameter in the **.nbp** file).

The first column of this data is headed Section ID, and all entries will say “TestSect/” and is not important.

The next column is headed “**Chainage**” and shows the **y** co-ordinate of the data.

The column headings for the rest of the columns give the **x** co-ordinate of the data.



It can be useful to select the inspection results and use the **conditional formatting** functionality of Excel. This will colour in the grid squares according to the defects seen, and can produce a visual defect map of the structure/part of the structure inspected. If viewing the results in this manner it is useful to have recorded the extent of the surface of interest during the inspection as this provides some shape and context in which to interpret the results.

The data is recorded in the **.grd** file with chainage (y position) increasing down the file. It may be useful to select the data and **sort** it all based on **descending chainage**. This will rearrange the data to have features which were at the bottom of the images, at the bottom of the image set, and make viewing the data simpler.

Inspection comments are saved as a **.cmt** file in the same location as the **.grd** file. This contains the x and y coordinates of the comment, and the comment text.

[#] Interpreting_structures_inspection

Appendix F Frequently voiced concerns about IBI approach, and counter arguments

The consultation, and subsequent discussions with engineers interested in aspects of the IBIS approach, have highlighted a number of common questions or doubts about the technique and its viability as a pragmatic, routine tool. This section addresses these common doubts.

Q: "Inspections are fine as they are, why bother?"

A: It has been shown that traditional inspection results are prone to errors, and that inspection results, even in controlled conditions, can be highly variable. It has been demonstrated that inspectors can see more detail in images at 1 mm per pixel than at 3m (a typical inspection distance).

One of the main problems with existing inspections is inconsistency in the reported condition. The improved consistency in levels of detail and viewing angles afforded by the IBIS approach could produce more consistent outputs?

Q: "It wouldn't work on all bridges, why bother?"

There will be some types of bridges where the IBIS approach is not suitable, either because of impracticalities of collecting images on all surfaces of concern, or the inability to see hidden elements which must be inspected. However, for those bridges where it is suitable, full image records would be produced which would enable inspections to be undertaken at consistent levels of detail, in comfortable and safe environments. This should improve the results obtained by inspection.

Traditional visual inspections are not necessarily the best way of collecting data on all bridges, but they are used where appropriate. The argument that a single inspection approach should work on all bridges or be abandoned is incorrect and the fact that any proposed approach does not work equally well on all bridges is does not invalidate the research done, or be allowed to impede progress and further development.

Q: "It would take much longer than a traditional inspection, why bother?"

The IBIS approach does, at the moment, need to spend longer on site collecting data than a traditional GI does. However there are two main counters to this argument: One is that the IBIS records more data, allowing all parts of the bridge to be inspected at a consistent level of detail, greater than that achievable from a 3m viewing distance. This data can be shared, stored, revisited and used in training without requiring further visits to the bridge. The second argument is that the time required on-site at this stage in the development of the IBI approach, and with the particular IBIS developed during this research, is indeed longer than a traditional GI, but that does not necessarily mean that it will always be slow. The basic technology behind the highly successful traffic speed pavement condition surveys (e.g. TRACS and SCANNER) was slow to collect data at first, but following years of development the systems now operate at traffic speed. Image Based Bridge Inspection Systems may be at the early, slow stages of data collection now, but this situation will not necessarily persist, and if the initial work and research is discarded because it has a number of teething problems, then it will never improve, and no progress will be made.

Q: "It would cost much more than a traditional inspection, why bother?"

Similar to the response about the time taken to collect data, it may indeed be the case that an IBIS inspection would cost more at the moment than a traditional GI however, the cost is likely to drop in future as the technology and methodology becomes more refined and robust. Understandably, engineers will be reluctant to commit more of their already limited resources to collect data which they can already get more cheaply. However, the IBIS system offers additional benefits. As well as enabling GI reports to be completed at similar levels of detail to traditional methods the engineers will also get a full, high resolution image record, collected at a consistent level of detail, with consistent viewing angles, which can be compared and shared as they see fit. This could have considerable benefits in training, QA, QC, defect trending, monitoring of repair effectiveness as well as potentially improving the basic inspection results through the improved detail of distant features.

Q: "Automated techniques work on pavements, why is this hard?"

Pavement condition monitoring vehicles are able to collect high resolution images of pavement surfaces at traffic speed, but this is an easier problem to solve than imaging bridges: the pavement is a single flat surface which is always located in the same location relative to the survey vehicle. It is therefore comparatively simple to design a system which can maintain focus on the pavement surface and cover the parts of interest. It is much more difficult to maintain focus at speed on all the different parts of a bridge, which are at different distances from, and orientations to, the camera.

Appendix G Publications resulting from this research

The following publications have been produced by the author during the course of this research.

McRobbie, S., & Lodge, R. (2006). Automated inspection of highway structures - Stage 1; UPR/IE/091/07. Crowthorne, UK: TRL Ltd.

McRobbie, S., Lodge, R., & Wright, A. (2007). Automated inspection of highway structures - Stage 2; PPR255. Crowthorne, UK: TRL Ltd.

McRobbie, S. (2008). PPR 338: Automated inspection of highway structures - Stage 3. Crowthorne, UK: TRL Ltd.

McRobbie, S. (2009). Automated inspection of highway structures - 2008/09. Crowthorne, UK: TRL Ltd.

McRobbie, S., Woodward, R., & Wright, A. (2010). Visualisation and display of automated bridge inspection results: PPR 530. Crowthorne, UK: TRL Ltd.

McRobbie, S., Wright, A., & Burrow, M. (2014). Image-Based Inspection System for routine visual inspection of UK Highways bridges. Proceedings of Structural Faults and Repair Conference. London, UK.

McRobbie, S., Wright, A., & Chan, A. (2014). Can technology improve routine visual bridge inspections? Proceedings of the ICE - Bridge Engineering.

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Adhikari, R. S., Moselhi, O. & Bagchi, A., 2014. Image-based retrieval of concrete crack properties for bridge inspection. *Automation in Construction ,* pp. 180-194.

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Bohn, J. & Teizer, J., 2010. Benefits and Barriers of Construction Project Monitoring using High-Resolution Automated Cameras. *Journal of Construction Engineering & Management,* 136(6), pp. 632-640.

Bowden, S., Thorpe, A. & Baldwin, A., 2003. *Usability testing of hand held computing on a construction site.* Auckland, NZ, CIB Report 284, pp. 47-55.

Brosnan, T. & Sun, D.-W., 2004. Improving quality inspection of food products by computer vision - a review. *Journal of food engineering,* Volume 61, pp. 3-16.

Bungey, J., 2004. Sub-surface radar testing of concrete: a review. *Construction and Building Materials,* 18(1), pp. 1-8.

Canon Europa NV, 2013. *EOS 600D - Instruction Manual.* [Online] Available at: http://www.canon.co.uk/Support/Consumer_Products/products/cameras/Digital_SLR/EOS_600D.aspx?type=manuals#EOS_600D.aspx?type=manuals&manualid=tcm

%3A14-955056&_suid=1412713888357022885749023984203
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