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The development of a digitally enhanced visual inspection framework for masonry bridges in the UK

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Abstract

Purpose: The utilisation of emerging technologies for the inspection of bridges has remarkably increased. In particular, Non-Destructive Testing (NDT) technologies are deemed a potential alternative for costly, labour intensive, subjective and unsafe conventional bridge inspection regimes. This research aims to develop a framework to overcome conventional inspection regimes' limitations by deploying multiple NDT technologies to carry out digital visual inspections of masonry railway bridges.

Design/methodology/approach: This research adopts an exploratory case study approach, and the empirical data is collected through exploratory workshops, interviews and document reviews. The framework is implemented and refined in five masonry bridges as part of the UK railway infrastructure. Four NDT technologies, namely, Terrestrial Laser Scanner (TLS), Infrared Thermography (IRT), 360-degree imaging, and Unmanned Aerial Vehicles (UAV), are used in this study.

Findings: The developed framework offers a consistent and safe inspection approach and high-quality records of assets. It requires fewer subjective interpretations compared to the conventional inspection regimes. This is due to the quantitative nature of the proposed framework.

Originality: This research is a step towards digitalising the inspection of bridges, and it is of particular interest to transport agencies and bridge inspectors and can potentially result in revolutionising the bridge inspection regimes and guidelines.

Keywords

visual inspection, masonry railway bridges, digitalisation, optical methods, Non-Destructive Testing, Infrared thermography, Terrestrial laser scanning, 360-degree imaging, Unmanned Aerial Vehicles, Bridge monitoring

1 Introduction

Bridges are critical for modern transport systems in European nations such as the UK, Slovenia, Hungary, Poland, Czech Republic, Austria, and Norway. Most bridges were built between 1945 and 1965. Among existing bridges, masonry arch bridges are a vital element of Europe's rail, road, and waterway infrastructure (Riveiro *et al.*, 2016). In the UK, there are approximately 18,000 masonry bridges as part of the rail network (Hearn, 2007). However, those bridges are subjected to deterioration due to excessive overloading, usage, environmental conditions, and ageing, and more attention is required to ensure that bridges last for the period of their intended design life and beyond (Ren *et al.*, 2019). Failure to maintain bridges can adversely impact a nation's economy, daily activities and even lead to loss of life (Sacks *et al.*, 2018, Johansen *et al.*, 2021).

The structural integrity and serviceability of bridges, including masonry railway bridges, can be deteriorated over time if a defect is not identified in a timely manner. Identifying and defining the extent of these defects in their initial stages is critical to ensure bridge safety (Dabous and Feroz, 2020). Hence, frequent condition assessment of masonry railway bridges is needed. Visual inspection is a primary method for the examination of the performance and serviceability of the current state of bridges. However, this technique is known to be time-consuming, laborious and suffers from certain drawbacks such as the subjective nature of the inspection, interpretability and reliability of results, and safety concerns for the inspector while accessing different elements of a bridge (Agdas *et al.*, 2016). Moreover, the procedure cannot be carried out on a regular basis due to (a) possible traffic disruption, (b) high labour cost, and (c) inaccessibility of sites (Liu *et al.*, 2014). Therefore, there is a strong need to move towards a more automated system with digital methods to provide more accuracy and a safer working environment for bridge inspection.

A comparison has been made between different national practices for bridge inspection by Hearn (2007). The inspection procedure, including the inspection frequency and level of detail, vary across countries and sectors. However, most of those procedures are based on more frequent and less detailed visual inspections than detailed but less frequent inspections (Artus and Koch, 2020).

In recent decades, Non-Destructive Testing (NDT) technologies have been developed to enhance the bridge inspection procedure and make it faster and more reliable. The NDT technology enables the assessment to be performed on structures that are difficult to access or under insecure conditions, such as poor lighting conditions or low temperatures (Artus and Koch, 2020). Also, NDT methods do not damage the structure under study and reduce the subjectivity and slowness of the traditional methods (Abdelkhalek and Zayed, 2021).

Among NDT technologies, optical methods function uses sensitive and accurate cameras to image objects, and they are known to be an advanced alternative to visual inspection (Popescu *et al.*, 2019). Terrestrial Laser Scanner (TLS), Infrared Thermography (IRT), 360-degree imaging, and Unmanned Aerial Vehicles (UAV) are common optical methods available on the market. Of note is that utilising NDT methods individually is often insufficient for infrastructure inspection (Rashidi et al., 2020), which necessitates complementary methods to produce a more reliable inspection outcome.

Several research efforts have attempted to compare the accuracy and reliability of NDT technologies to identify defects. However, NDT technology has not been yet widely accepted due to various reasons such as associated costs, unrealistic expectations, or improper use (Abdelkhalek and Zayed, 2021). Moreover, in most of the previous research studies, NDT technology is implemented in the laboratory (i.e. ideal) environment, which does not provide a reliable indication of the wide range of variables impacting the implementation of the NTD technology in real-world scenarios (Dabous and Feroz, 2020). In particular, as far as it is known, no literature could be found that attempts to utilise complementary NDT technologies to inspect masonry railway bridges, while most studies focus on concrete bridges. Despite the importance of masonry railway bridges in the UK, conducting routine visual inspections using technological solutions has not been fully addressed.

The research reported in this paper aims to develop a framework by which complementary optical methods are used to (a) address the difficulties and limitations of conventional inspection procedures and (b) to demonstrate the feasibility of deploying the multiple optical methods to perform visual inspections of masonry railway bridges in the UK. The paper is structured as follows. First, a background to the conventional inspection procedures of bridges as well as recent trends are given. The application of 360-degree panorama, TLS, IRT and UAV for condition monitoring purposes is presented. The research method adopted to collate and analyse data is addressed. The proposed framework is presented, and then its functionality is demonstrated in a case study. The findings and contributions to knowledge are discussed. Finally, conclusions drawn from the research and areas for further research are presented.

1.1 Scope of Research

The scope of this research focuses on the global (visual) inspection of masonry railway bridges in the UK. Global inspection detects the occurrence of defects, while local inspection identifies the location, extent and severity of damages (Network Rail, 2010). The proposed framework fits within the current inspection regime of transportation agencies in the UK. Although other types of bridges such as concrete and metallic as well as conventional inspection regimes of other countries are not in the scope of this study, the researchers believe that the findings can provide generalisable knowledge on inspection of all types of bridges across the globe.

1.2 Background

Conventionally, routine condition monitoring is accomplished by visual inspection, which is a primary technique for assessing the performance and serviceability of bridges all around the world (Robert, 2007). Visual inspection is about observing and documenting the overall bridge condition and then collecting information about issues such as cracks, settlements/ deflection and spalling (Bertola and Brühwiler, 2021). The inspection is expected to cover the whole structure on the ground so that no members of the substructure and superstructure are overlooked. The collected information is normally documented in an inspection report, including freehand observations, field observation notes, audio recordings, and photographs. Such documentation is used as input in the bridge management protocols of transportation agencies (Phares *et al.*, 2004, Getuli *et al.*, 2021).

Regarding the inspection procedures, transportation agencies may have different approaches. According to Hearn (2007), there are five prevalent types of condition assessment for bridges in the UK (Table 1). General inspections are the primary source of information, but they often do not capture all defects due to viewing distances, lighting conditions and the lack of special access arrangements. Principle inspections can detect visible defects or visible manifestation of hidden defects, while Special inspections are undertaken when principle / visual inspections have identified a defect (Chmielewski and Muzolf, 2021). Also, each type of condition assessment has three generic phases, namely planning, inspection and reporting (Bertola and Brühwiler, 2021).

Table 1. Different types of condition assessment for bridges in the UK (Hearn, 2007)

Inspection Type	Interval	Performed by	Description
Acceptance	-	-	When the responsible for a structure (e.g., inspection) changes
Superficial	Frequent	Contractor	To immediately report any damage or action needed to maintain the bridge
General	2 years	Contractor	To visually inspect all parts of the bridge without the need of special access equipment or lane closure
Principal	6 years	Contractor	To visually inspect all parts of the bridge in order to report all conditions and defects using the required access equipment
Special	As necessary	Contractor	To further investigate the identified defects during an earlier inspection using material sampling or NDT

Numerous studies have highlighted the drawbacks of the conventional condition assessment (Dabous and Feroz, 2020). To circumvent limitations of visual inspections, emerging new technologies and advanced monitoring practices have been used in bridge condition assessment and monitoring. Some of those technologies depend on Global Positioning Systems (GPS) or Global Navigation Satellite Systems (GNSS), electro-optical instruments, and different types of sensors (Kuzin *et al.*, 2018). Although satellite systems are beneficial in the dynamic measurement of long-span bridges, their accuracy cannot be guaranteed. Total stations and digital levels provide high accuracy, but they are unable to perform satisfactorily during unfavourable weather conditions and cannot provide a holistic overview of the bridge condition. Electronic sensing devices, including accelerometers, displacement transducers, and strain gauges, necessitate direct structural installation and connection with reference points to estimate absolute displacement (Jo *et al.*, 2018, Bakhshi *et al.*, 2022). They are complex tasks requiring disruption of traffic, and the working conditions of the bridge may be detrimental to the operation of the sensors. Moreover, often only discrete information can be extracted from these devices unless multiple sensors are installed (Kuzin *et al.*, 2018).

In this research study, optical methods are explored as an alternative for the condition assessment of masonry railway bridges. Such NDT technologies can provide accurate, detailed models of the inspected object in a non-invasive manner, quantify the bridge deformation (Baqersad *et al.*, 2017), facilitate a safe working environment, and eliminate the need for scaffolding. The increasing utilisation of NDT technologies, especially optical methods, has brought benefits to inspection regimes of infrastructure. All these have, in turn, supported timely necessary or remedial works in the built infrastructures alongside improved accuracy in inspection regimes as opposed to traditional techniques (Artus and Koch, 2020).

Four main optical methods, namely 360-degree imaging, TLS, IRT, and UAV, are introduced in the ensuing sections.

360-degree imaging

360-degree imaging as a visual inspection technique has gained broad appeal as part of a movement away from the time consuming, tedious, and expensive manual photography dominating much of current inspection regimes (Popescu *et al.*, 2019). Using 360-degree imaging, an immersive environment can be recreated to make offline inspections from large image data sets. This technique creates highly immersive experiences that give the user a feeling of being present in the field (Omer *et al.*, 2019). This process in recent years has been through automated complementary applications, which further reduce the need for the laborious presence and inspection seen in traditional practices (Eiris *et al.*, 2018).

Terrestrial Laser Scanner

Terrestrial laser scanning (TLS) is a widely used NDT for inspection purposes. Using this method allows inspection regimes to carry out any necessary metric surveys. One of the strengths of laser scanning is its relatively high reliability and accuracy of data collection alongside simple and relatively quick and safe processing (Selbesoglu *et al.*, 2016).

The principle of laser scanning is that either a pulse emission (radiation in the visible or infrared domain) or amplitude modulation (representing the phase difference between the sine modulated transmitted and the reflected beams) is measured (Riveiro *et al.*, 2016). The application of TLS for bridge assessment and monitoring has been widely studied (Rashidi *et al.*, 2020). There are two major applications of TLS in this field, namely (a) the generation of 3D models and reconstruction of the geometry model from obtained point cloud, and (b) the quality inspection, especially identification of surface damages (Brilakis *et al.*, 2010). Using laser scanning allows users to measure or extract geometric and semantic information as required (Gabara and Sawicki, 2018) to facilitate structural integrity inspections and identify defects using a rigorous method with a high degree of precision. For example, TLS can be used to measure deflections in bridge deck thickness regenerated from a point cloud dataset (Cha *et al.*, 2019).

However, the application of TLS is still dependent on environmental factors such as the distance to the target surface and weather conditions (Rashidi *et al.*, 2020). This calls into focus the process of planning to minimise the time on-site and maximise the integrity (i.e. quality and quantity) of the datasets (Aryan *et al.*, 2021). Additional processing is also required to translate the unstructured point clouds into structured models using third-party applications to increase the value of the dataset.

Infrared thermography

Infrared thermography (IRT) is a remote sensing technology used for the rapid inspection and visualisation of thermal images. IRT is known to be accurate and reliable that can produce both qualitative and quantitative indicators of a bridge condition. It can be utilised for measuring the thermal diffusivity of bricks and moisture mapping (Janků *et al.*, 2017).

There are two approaches of IRT, namely active and passive, depending on the presence or absence of an artificial and external mechanism of thermal excitation in the object (Omar *et al.*, 2018). Passive IRT means that there is a natural thermal excitation source, while active IRT means that artificial heat sources are used. With passive IRT, the analysis is carried out under natural conditions, and then the thermal behaviour of the object is assessed. When an artificial heat source is used for the active IRT, the heating or cooling processes of the object is monitored during and after the thermal excitation (Meola, 2007).

Moreover, depending on the purpose of the inspection, the thermographic analysis can be performed either qualitatively or quantitatively (Janků *et al.*, 2017, Birgonul, 2021). Qualitative IRT is applied when the focus is on the relative pixel values or the temperature distribution, and the exact measurement of temperature in the thermal images is not needed. This technique is particularly useful when the main objective is to identify thermal pathologies regardless of the thermal properties of the object and the severity of the identified defects (Garrido *et al.*, 2018). On the other hand, quantitative IRT is applied when the focus is on acquiring precise temperature values. This technique is used when possible thermal pathologies were detected through qualitative IRT in order to assess the severity or measure thermophysical properties of the identified anomalies (e.g., depth of cracks detected in the objects) (Bhatla *et al.*, 2012, Bulut *et al.*, 2021).

Most of the previous research studies performing thermographic testing are based on specimens prepared in the laboratory environment with stimulated defects (Raja *et al.*, 2020). Many algorithms have been developed based on the temperature of the pre-determined defects' locations and sizes with regards to the temperature of the surrounding materials (Lagüela *et al.*, 2014). Nevertheless, when applying thermographic testing in the context of a bridge, the characteristics of the defects are not known, and even quantitative IRT still heavily relies on the interpretation of the images. In other words, using IRT tests in a laboratory environment might not be consistent with when using in field studies.

Unmanned Aerial Vehicles

Current methods of inspection and producing as-built information are criticised for being labour-intensive and unsafe to be used at height (Elghaish *et al.*, 2020). The conventional air-or-space borne technologies depend on the terrain and the size of the area surveyed (Oskouie *et al.*, 2016) and their application is known to be costly, time-consuming, laborious with high measurement errors (Tang *et al.*, 2010). The utilisation of UAV technology for various applications, including surveying built assets, is increasing, especially because the accuracy of collected data by this technology is improving (Elghaish *et al.*, 2020). A recent study reveals that the geometric accuracy of a 3D model generated by UAV images is less than 4 cm (Shazali and Tahar, 2019, Mahmoudi *et al.*, 2021).

UAV-based photogrammetry can generate 3D models, which are found to be useful for the condition monitoring of structures. For example, Puppala *et al.* (2018) use a visual range camera mounted on the UAV to analyse the health conditions of structures and also Marmo *et al.* (2019) explore the feasibility of utilising UAV to create as-built models and carry out inspections. Moreover, it is possible to integrate data collected by UAV with other datasets in order to create more comprehensive 3D models for inspection purposes. For example, in a study undertaken by (Park *et al.*, 2019), a framework is developed to automate the integration of images taken by UAV with point cloud data using 2D local feature points.

Despite the recent advancements of using UAV, little literature on the utilisation of UAV technology in practice exists, while most of the literature is focused on technical aspects (Elghaish *et al.*, 2020). In particular, there is scarce literature that explores the use of UAVs for the inspection of bridges, while the UAV technology is expected to transform the bridge inspection practices due to its unique data collection capabilities (Asadi *et al.*, 2020). This has resulted in the lack of experience among railway authorities and inspectors when it comes to the use of UAV technology .

Research Gap

Masonry bridges are of prime importance for the railway network in the UK. Some researchers have demonstrated the application of optical methods to tackle the challenges that inspectors currently encounter. Evidence in the literature acknowledges that those methods should be considered as the alternative to conventional methods (Raja *et al.*, 2020, Artus and Koch, 2020, Dabous and Feroz, 2020). However, the available research studies on the topic often (a) have not gone beyond carrying out tests in a laboratory environment, (b) only focus on a specific optical method rather than the complementary application of those methods, and/or (c) focus on the technical aspect of such methods rather than practical recommendations to facilitate their implementation by railway agencies.

The above gap is one of the issues behind the low acceptance of optical methods amongst railway agencies. This study's outcome is intended to provide a practical framework whereby pertinent optical methods can be utilised together to improve the current inspection procedures of masonry railway bridges. The applicability and practicality of the method are also demonstrated in a real-life case study.

2 Method

This research aims to propose a practical and feasible solution for the digital inspection of masonry railway bridges. In particular, this study examines the applicability and validity of optical methods derived from the literature within a real-world setting. An exploratory case study is selected for accomplishing such an objective. This method is adopted when explaining, describing and exploring a contemporary phenomenon within a real-world context and when the research study answers "how" questions (Yin, 2013). The exploratory case study in this research aims to answer how optical methods can be used in the context of masonry railway bridges to identify specific types of defects. The real-world setting is an essential part of the exploratory case study, in which many variables may affect the outcome (Ghauri and Grønhaug, 2005). Evaluating the impacts of any proposed framework in a real-world setting may be affected by many variables that can be refined through the case study to produce reliable outcomes for research endeavours (Zellmer-Bruhn *et al.*, 2016).

The following steps have been undertaken together with an exploratory case study to address the gap in the current state of knowledge for the inspection of masonry railway bridges in the UK:

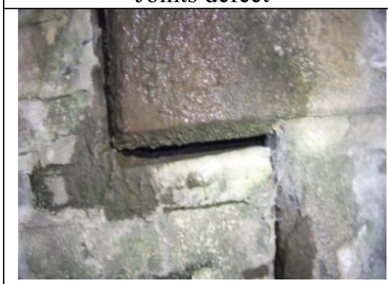
- A literature review was carried out to better understand the underlying concepts and principles of bridge inspection as well as to identify state-of-the-art for improving the inspection of masonry railway bridges. Key findings of the literature review are summarised in the Background section of the present paper.

- Document reviews were used to corroborate information collected from literature and to understand the current practice of bridge inspection carried out by the industry. Documents providing guidance on the examination of bridges and examination reports were reviewed. An important finding at this stage was the information about the prevailing defects in masonry bridges that must be detected (Table 2).

- Three exploratory workshops were conducted with experts within the industrial partner's organisation in order to capture the opinions of the industry practitioners concerning the challenges of the current practice of visual inspection as well as expectations from the digitalisation of bridge inspection. These exploratory workshops helped to define the problem and gained an understanding of how the potential solution should be devised. Moreover, three exploratory interviews with experts in IRT, TLS and UAV were carried out during the workshops. Through these interviews, the good practices of using these methods were explored. The findings captured helped ensure that the developming framework is pragmatic and relevant to the current industry practice.

- A masonry bridge inspection framework was developed based on a synthesis of the findings from the literature review as well as the collected information from the industry partner and semi-structured interviews.
- The proposed framework was implemented and refined in an explorative case study in five masonry bridges as part of the UK railway infrastructure. 360-degree imaging, TLS and UAV were utilised at three phases with two-three months intervals. IRT was utilised only in phase 3 for Bridge 5 and Bridge 6. The framework is presented in the Proposed Framework section. The findings from the implementation of this framework can be found in the Case Study section.

Table 2. List of common defects in masonry railway bridges, their descriptions and corresponding examples (Network Rail, 2010)

Bulging	Crack	Spalling
		
Refers to a local "blistering" type movement of the element, possibly associated with hollowness or loose masonry, or ring separation in an arch	Refers to cracks, possibly caused by ground movements and live loads	Refers to crumbling, peeling or flaking of masonry work caused by water entering
Joints defect	Loss of section	Water penetration
		
Refers to gaps in the joints between bricks. Such joint defects are possibly caused by ground movements and live loads	Refers to sections of bricks missing. The loss of section is caused by ground movements, live loads, impact damage and weathering conditions.	Refers to leakage in bridges

3 Result - Proposed Framework

This section presents the proposed framework (Figure 1) for the digital inspection of masonry railway bridges and shows the framework is compatible with the requirements of Superficial Inspection and General Inspection. This framework is composed of four general steps: (1) preparation for data collection, (2) data acquisition, (3) data processing, and (4) data analysing and reporting. The application of the proposed framework facilitates the digitalisation of the inspection of masonry railway bridges. The next subsections explain the details of each step.

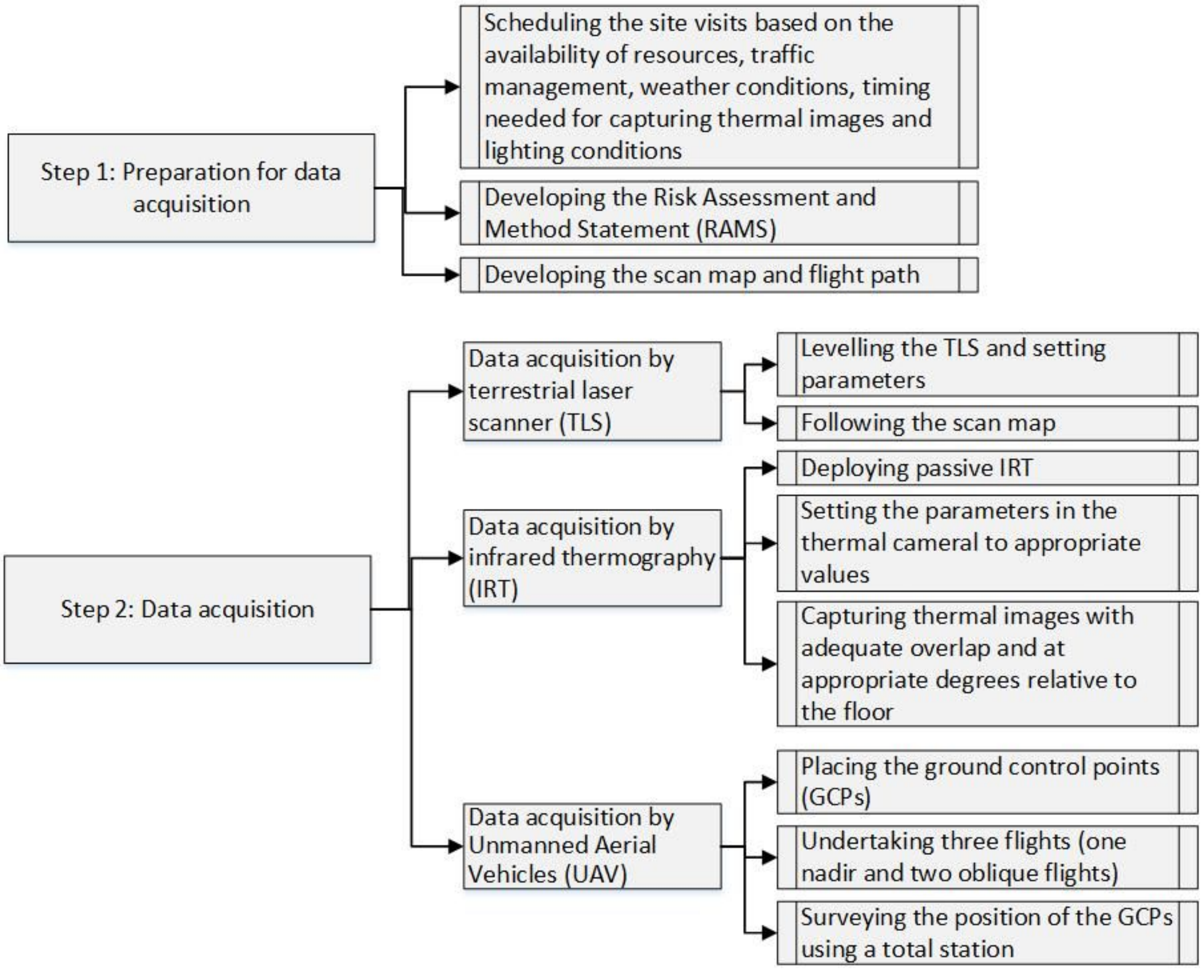


Figure 1. Proposed framework for digital inspection of masonry railway bridges.

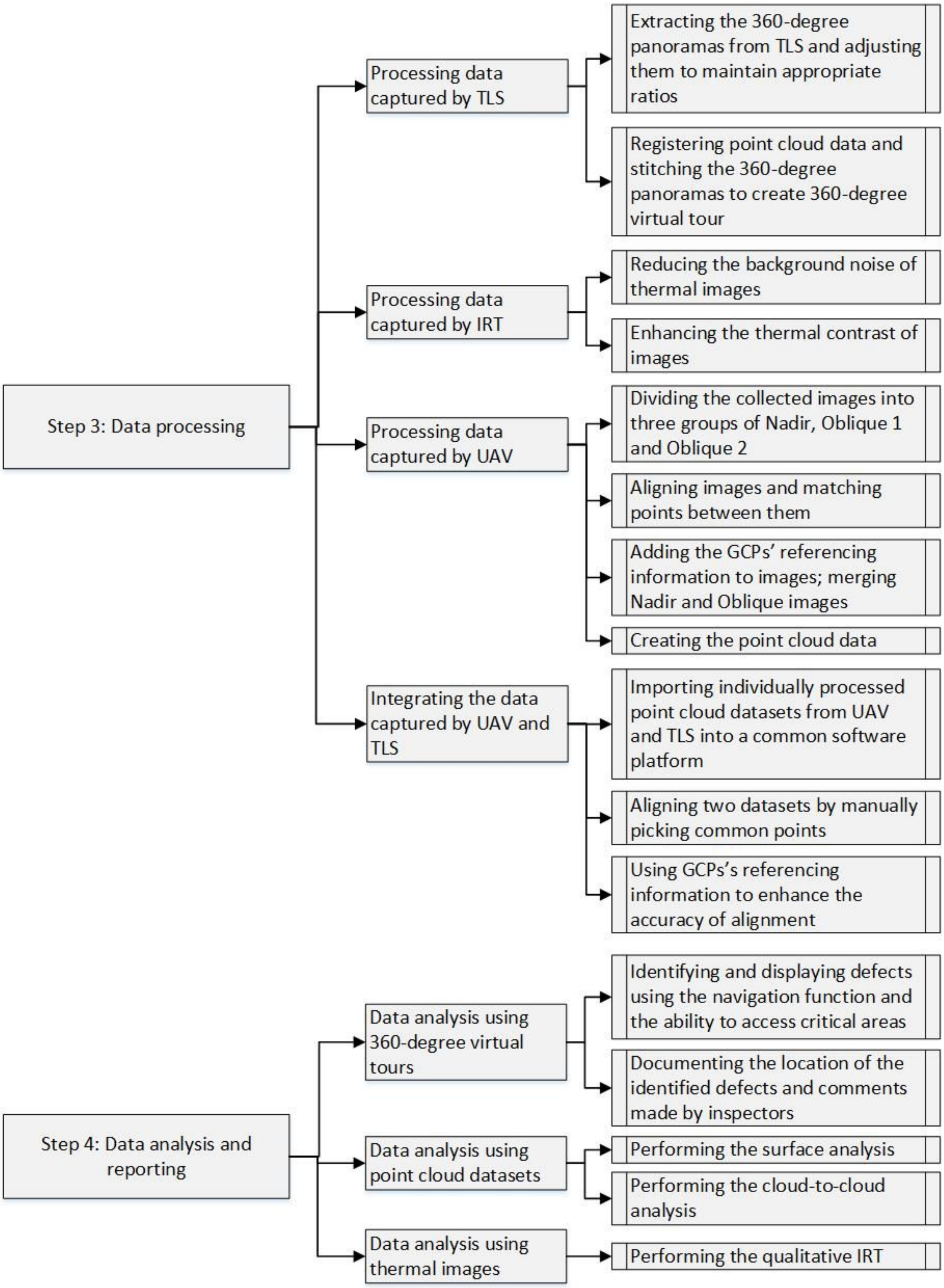


Figure 1. Proposed framework for the digital inspection of masonry railway bridges (continued).

Step 1: Preparation for data acquisition

The preparation for the data acquisition should be based on the availability of resources, traffic management and weather conditions. Prior to arrival on-site, the operators should familiarise themselves with the type and layout of the bridge. The Risk Assessment and Method Statement (RAMS) then needs to be prepared. RAMS includes a summary of the details of all the activities to be performed on-site, specifically any safety procedures and details of traffic management. After arriving on-site, a careful check is performed to confirm the information in RAMS, for example, to ensure it is safe to undertake the flights for UAV.

The environmental conditions, especially solar gain, wind speed and rain, should be taken into account before undertaking the measurements. The adversarial impacts of absorption of thermal energy during the day and wind on the thermographic survey can be mitigated by capturing thermal images nearly 2 hours after the sunset and avoiding days when the wind speed is over 5m/s. Rain may cause undesired noise in the scanned point cloud and may interfere with the thermographic survey. Wind and rain may also disturb the UAV flight.

A scan map should be prepared, which consists of a schematic drawing of the asset and demonstrates the scan positions of TLS with the corresponding scan numbers in the field. The scan positions should be marked along the way on the drawing. The scan map is useful to help plan the scan path in an optimum pattern (i.e. zigzag pattern) and optimum distances between scan positions. In other words, using this method will allow the operator to realise which scans have overlapping and common data, which is useful when processing the acquired point clouds. Furthermore, the scan positions can be recorded for future surveys. In addition to the scan map, a flight path should be created for UAV operation.

Step 2: Data acquisition

The acquisition of point cloud data, 360-degree imaging and thermographic data can be performed in parallel. 360-degree imaging can be captured by two means, namely using the TLS and using a specialised 360-degree imaging camera, such as iStar. The TLS has a camera that can produce high-quality 360-degree imaging while capturing point cloud data. Such 360-degree imagings are mainly used to colourise the point cloud but can also be used for other purposes, such as creating 360-degree virtual tours.

The TLS is attached to the tripod stand and should be levelled using tribrach or the sensors in the scanner. Successful registration of 3D data sets with a high accuracy largely depends on the position of scans and targets in the field. It is also important to consider the 'connector scans' and 'transition scans'. The connector scan is positioned in the border of the outside and inside of the asset to avoid deteriorated scans due to the difference in lighting; the transition scan is positioned between two spans in multi-span bridges.

UAV is used to produce a 3D model of the exterior of the asset (topside) for visual inspection purposes. Prior to starting the UAV survey, the ground control points (GCPs), which are a mixture of A3 sized black and white crosses, are placed on the ground at locations around the structure. In a UAV survey, three flights are undertaken. The flight path should be planned and set up so that the images are captured with 80% overlap forward and 75% overlap side to side. These parameters result in images being collected with a Ground Sample Distance of 4mm. Once the UAV survey is completed and data is collected, the position of the GCPs should be recorded.

For thermographic data acquisition, the passive approach is usually deployed. Thermographic cameras with resolutions of 320x240 pixels (i.e. a more basic camera) or 640x480 pixels (a current high-end camera) are recommended. General settings such as 'object distance', 'relative humidity, 'atmospheric temperature', and 'relative temperature' are set to appropriate values. The attenuation of the radiation due to the atmosphere will increase linearly with distance. Setting the 'object distance' on the camera allows the camera to take this attenuation into account. The thermographic data is collected with adequate overlap and at a known data acquisition path as well as at 60 – 90 degrees relative to the floor.

Step 3: Data processing

The captured point cloud data usually consists of multiple scans of the same asset from different positions. The registration process (target-based or target-less), a multi-step process aligning multiple, overlapping point clouds to form a detailed and accurate representation of the asset, is required. Target-based processing, which relies on targets, is used as opposed to target-less registration, which relies on vertical planes (e.g., walls, arches) in order to achieve a higher level of accuracy. The process is undertaken using native software supplied for the equipment, such as FARO SCENE (FARO, 2021) or other available commercial software packages.

The images captured by UAV are usually divided into three groups, namely Nadir, Oblique 1 and Oblique 2. The Nadir, Oblique 1 and Oblique 2 images are aligned, and points are matched between them and referenced with GCP data to create point cloud data using a photogrammetric process. The resultant point cloud data from UAV can be integrated with the data from TLS to form a 3D model, which provides a comprehensive overview of the structure with no areas of occlusion.

For the 360 images, a variety of tools, such as 3D Vista (3D Vista, 2021), can be used to create an interactive 360-degree virtual tour. The panoramic imagery from TLS may have different ratios. Ratios of 1:1 cube faces or 2:1 spheres can be maintained by adjusting those images.

The captured thermal images should be enhanced utilising software such as ResearchIR (Flir, 2021) to perform surface temperature distribution analysis.

Step 4: Data analysis and reporting

For point cloud datasets, two types of analysis methods can be applied, namely surface analysis and cloud-to-cloud comparison. The surface analysis is used to identify any changes in the primitive surface of assets to identify defects, such as cracks, joints deterioration, spalling. Specialised software packages such as VisionLidar (Geo-Plus, 2021) can be used for this purpose. The cloud-to-cloud analysis is to compare multiple scans of the same area captured at a different time to detect any changes, such as displacement, bulging, etc. Open-source software packages like CloudCompare (CloudCompare, 2021) can be used for cloud-to-cloud comparison.

The 360-degree virtual tours developed from the imaging images can be used as an asset inspection platform for asset inspectors to identify and record defects as well as document any additional supporting comments.

For the thermal images, the qualitative analysis can be applied because this approach does not require evaluation of the captured thermographic data, and it is a fast methodology compared to quantitative analysis. This common type of analysis for condition monitoring of infrastructure investigates the difference in temperature of the area of interest and provides quick decisions. For example, when a material is penetrated by water, the specific heat capacity and thermal conductivity are affected. In other words, the energy needed to raise the temperature of a moist area is higher than an area that is unaffected by water. Therefore, the surface temperature difference occurs.

4.0 Case Study

The case study demonstrated how the proposed framework could be applied to real-world masonry bridges when digital inspection methods were implemented. The data were acquired from five railway bridges in the UK. In Table 3, details of those bridges are presented.

Table 3. Details of bridges in the case study.

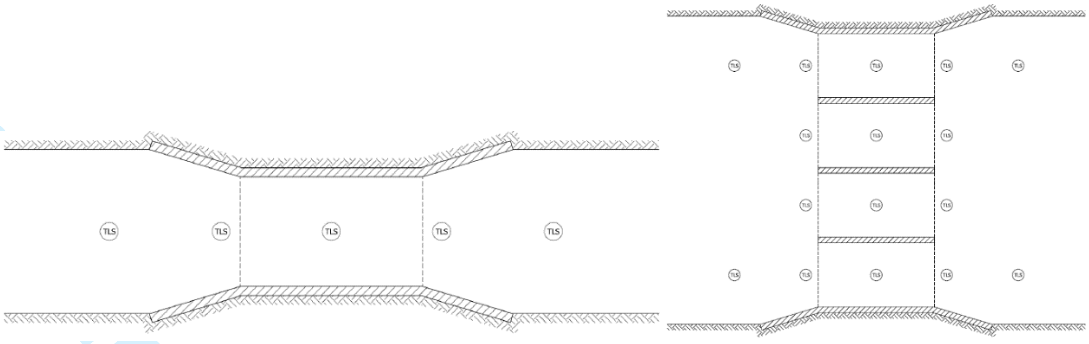
<table>
<tr><td colspan="2">Bridge 1</td><td colspan="2">Bridge 2</td><td colspan="2">Bridge 3</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Underline bridge, masonry, brick arch, single span</td><td colspan="2">Underline bridge, masonry, brick arch, single span</td><td colspan="2">Underline bridge, masonry, brick arch, single span</td></tr>
<tr><td colspan="3">Bridge 4</td><td colspan="3">Bridge 5</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">Underline bridge, masonry, brick arch with steel and timber deck, single span</td><td colspan="3">Underline bridge, masonry, brick arch, viaduct, multi-span</td></tr>
</table>

The case study consists of four single-span underbridges and one multi-span viaduct. The width is an average of 4m, with end arches buried on firm ground. The height of the bridges averages over 8m. The bridge archways form part of the local traffic networks for both pedestrians and vehicles.

Three site visits were conducted for each bridge between September 2019 and July 2020, and data was collected through TLS (FARO X130x), two 360-degree imaging cameras (iSTAR and Matterport Pro) and a thermographic camera (FLIR T640). The topsides of the bridges were also captured by a UAV specialist (due to the commercial restrictions, the specific detailed UAV process are not included in the paper). Each examination included the underside of the bridge and substructure elements such as abutments and wing walls. A summary of the implementation of each step of the framework is presented in the following sections.

Step 1: Preparation for data acquisition

A careful and planned process of pre-inspection was carried out to organise the data acquisition from the field. The authors downloaded and reviewed the latest examination report available on the industry partner's Structures Dashboard, identifying the size, location and scope of survey required. This insight was used to complete an asset-specific RAMS, taking into account the location and environment of an asset. Google Earth and Google Street View imagery were utilised to gain the best possible insight into each bridge. Weather forecasts were monitored for rainfall intensity, humidity and wind to establish if capture could go ahead as scheduled without disruption to the data quality. The scan map for each bridge was created, and the scan positions were marked along the way on the drawings. Figure 2 shows an example of a scan map.



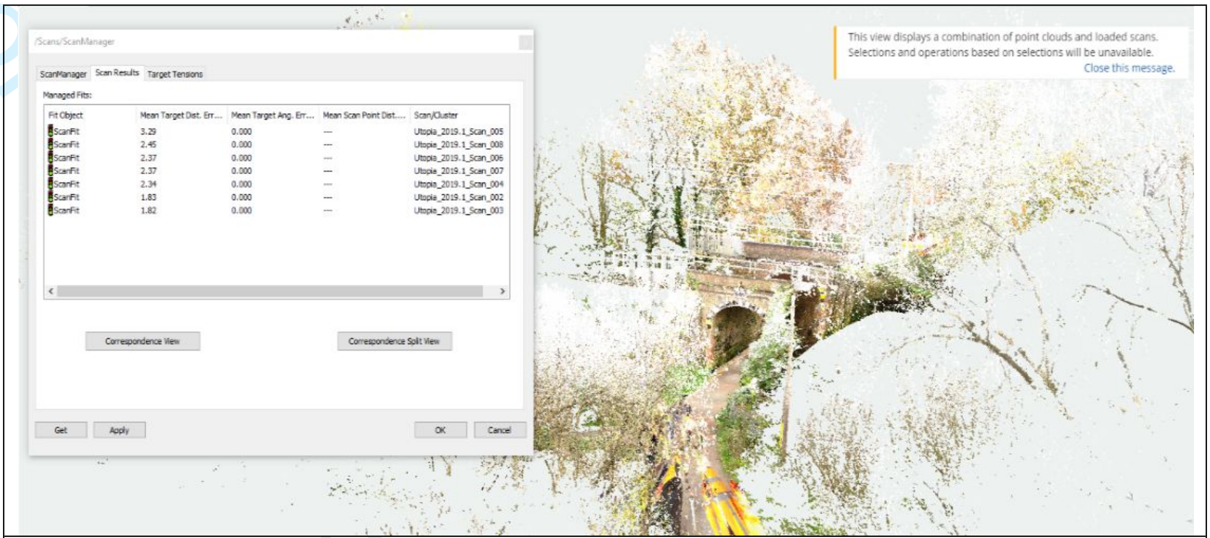
(a) (b)

Figure 2. Example of the scan map for (a) a single-span bridge and (b) a viaduct

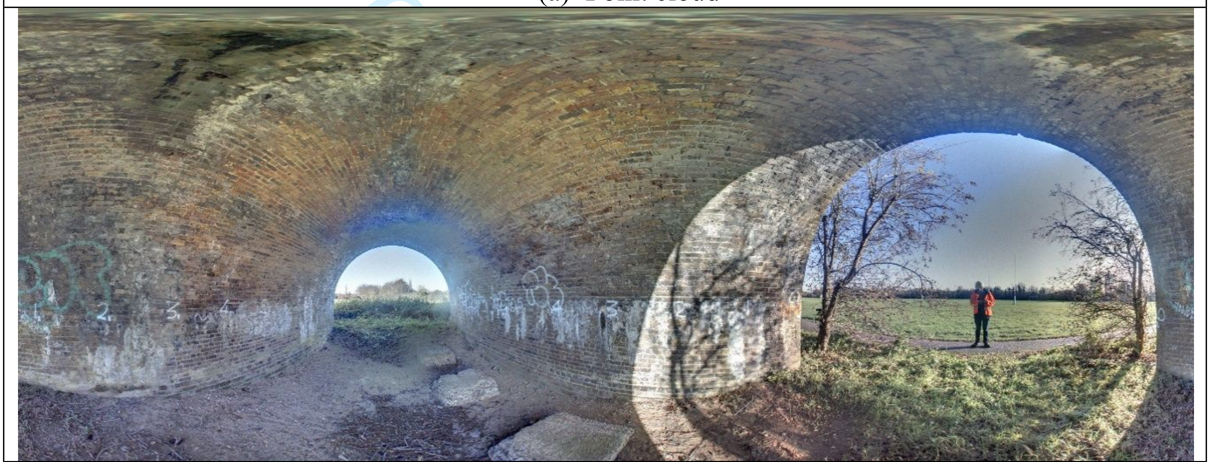
Step 2: Data acquisition

TLS was used to capture point cloud data and 360-degree imagings, and then the thermographic camera was used to capture thermographic data. During the case study, it was found that utilising the imagery taken with a TLS to produce the imagings is a possible solution to mitigate the need to take a separate 360-degree imaging camera on-site. Although TLS takes longer to capture a panoramic image, the quality and field of view of the image produced were considerably higher than the high-resolution 360-degree imaging camera (see Table 3). The resolution, Quality and Distance Range of TLS are set to 1/8, 2X and Normal, respectively. Table 4 shows an example of general settings in the thermographic camera for the FLIR T640.

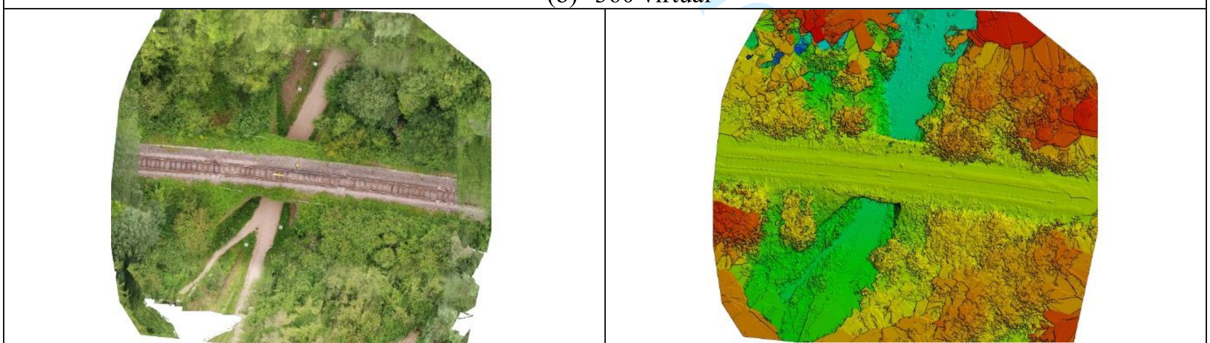
The UAV used in this project was DJI Matrice M210 Quadcopter fitted with a Zenmuse X5S RGB 20MP camera with a 45mm lens. Each survey takes around 30 minutes and the UAV flies at nearly 40m above ground level. In Figure 3, an example of a captured dataset is given.



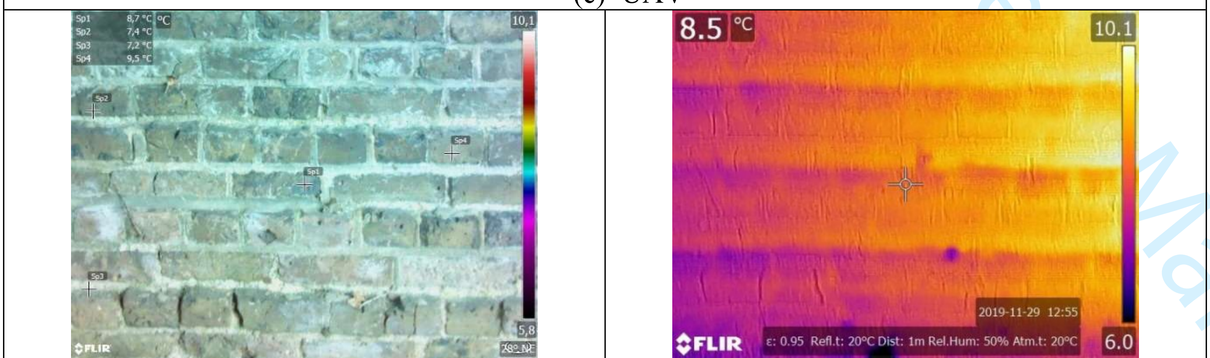
(a) Point cloud



(b) 360 virtual



(c) UAV



(d) Thermal image

Figure 3. Captured dataset for Bridge 3 in phase 2.

Table 3. Comparison between the imaging image taken by TLS and 360-degree imaging camera.

Equipment	Imaging capture time	Imaging quality	Field of view
TLS	3 minutes	165MP	360°x300°
360-degree imaging camera	1 minute	50MP	360x317.5

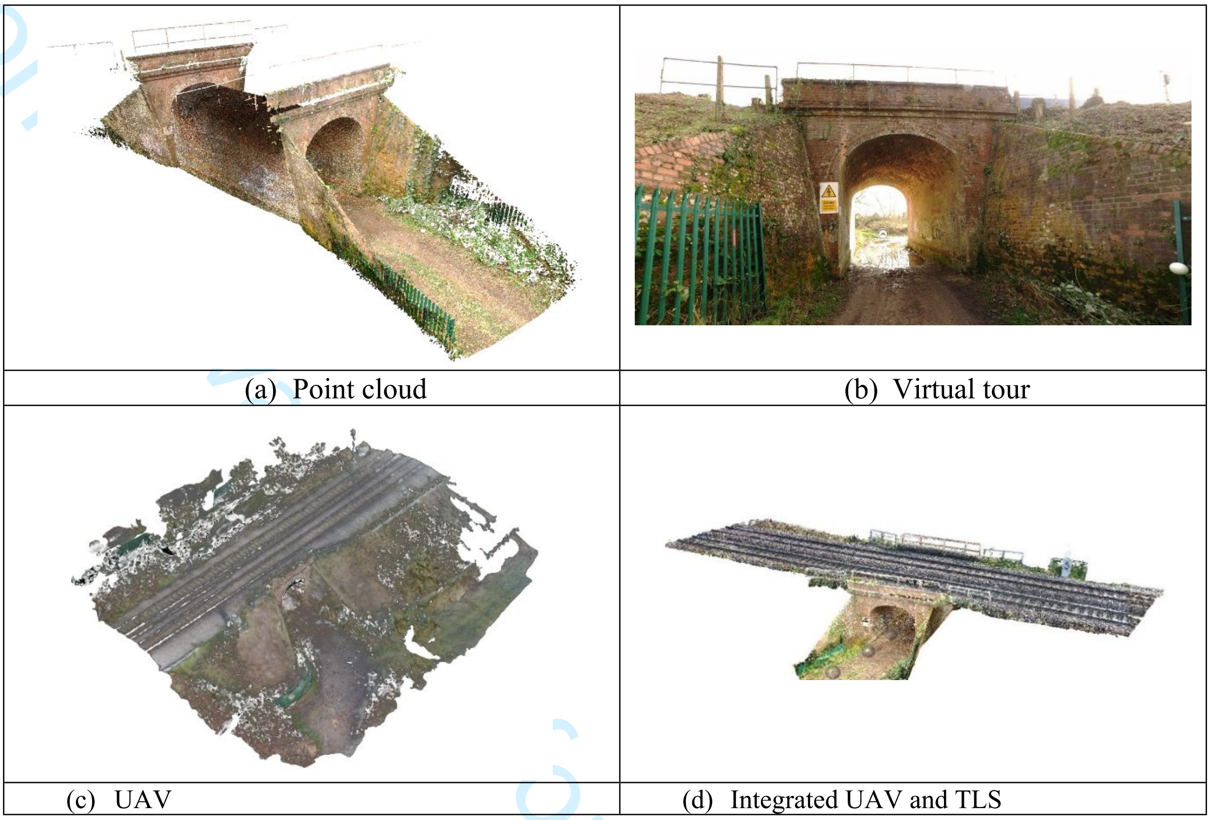
Table 4. Settings in the thermographic camera for FLIR T640

Settings	Values
Object distance	2 meters
Relative humidity	79
Atmospheric temperature	14
Relative temperature	23
Emissivity	0.91

Step 3: Data processing

The point cloud datasets from the FARO laser scanner were registered using FARO SCENE to generate a single 3D point cloud of the bridges. Colour information based on the 360 images was added that every point in the point cloud data was coloured with Red-Green-Blue (RGB) values. The UAV data was processed using the commercial software of Pix4Dsurvey (PIX4D, 2021), and it was then integrated with the data collected from TLS using Recap Pro (Autodesk, 2021) to form a holistic model cover top and underside of the bridge.

3D Vista is used to create an interactive panoramic virtual tour of the project, and thermal images were processed and tuned by ResearchIR MAX software. The Gaussian smoothing filter and the histogram equalisation function were applied to the thermal images. The former function is to minimise the background noise of images and facilitate the view of small objects, and the latter function is to distribute the intensities on the histogram, which results in enhancing the thermal contrast of images. Examples of processed datasets can be seen in Figure 4.



(a) Point cloud

(b) Virtual tour

(c) UAV

(d) Integrated UAV and TLS

Figure 4. Examples of processed datasets for Bridge 2 and in phase 1

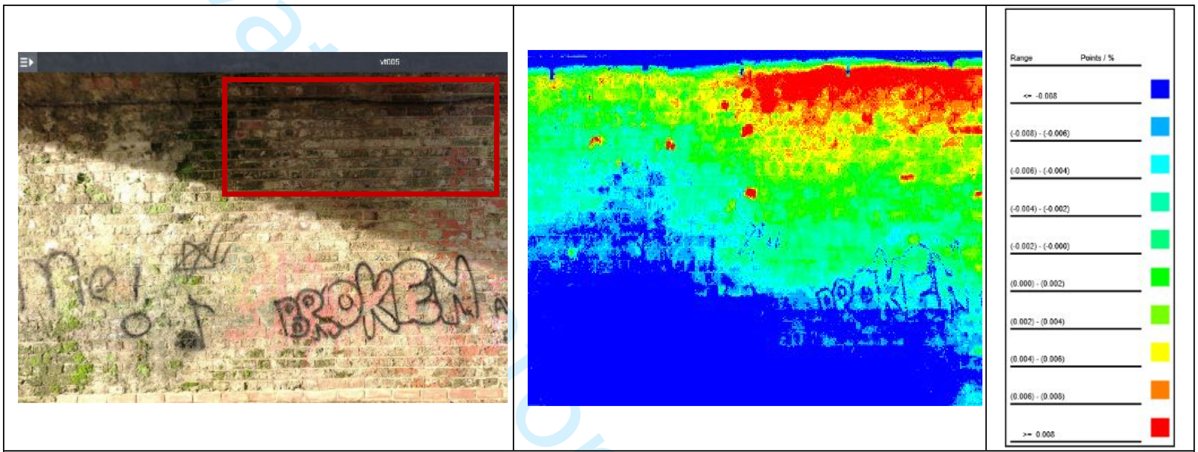
Step 4: Data analysis and reporting

The case study suggested that vegetation, spalling, cracks, loss of section and defective joints can be sufficiently identified and recorded in the 360-degree virtual tour by inspectors. Figure 5 shows examples of the identified defects highlighted by white circles. Assessing areas affected by bulging and spalling as well as identifying the cracks, loss of section, defective joints and deformation requires more detailed analysis through the point cloud data. Moreover, the presence of water penetration can be analysed through the IRT analysis. In Figure 6a and Figure 6b, examples of identified spalling in this research are presented. Figure 6c demonstrate the cloud to cloud analysis for Bridge 1 to investigate any deterioration between phase 1 and phase 3 of this study. However, the analysis delineates that no detectable changes have occurred in this timeframe. Figure 7 demonstrates the identified moisture in Bridge 5 and Bridge 6.

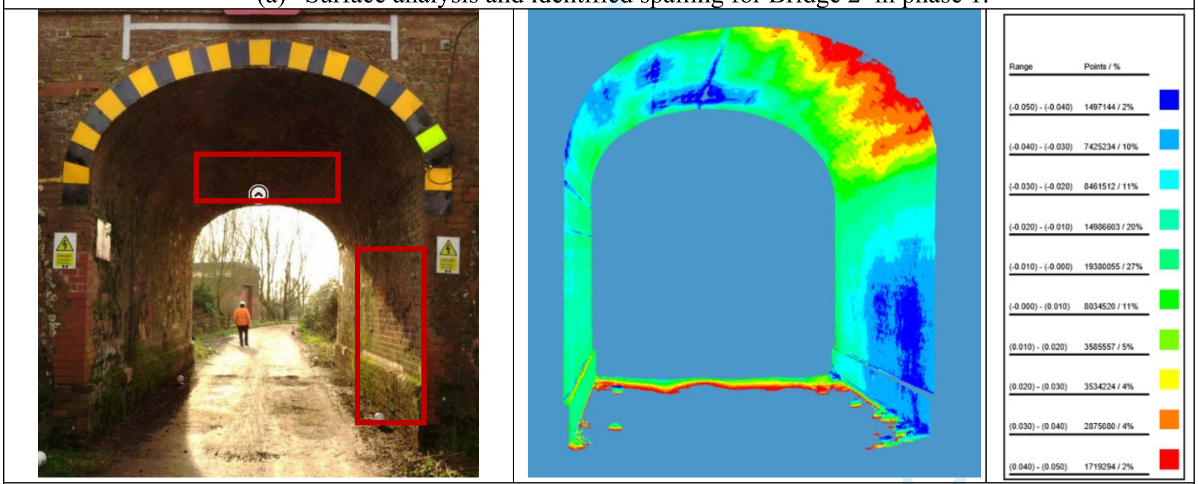
(a) Spalling | (b) Loss of section

Bridge 03

Figure 5. Example of identified defects in the 360-degree virtual tour for Bridge 3 in phase 3.



(a) Surface analysis and identified spalling for Bridge 2 in phase 1.



(b) Surface analysis and identified spalling for Bridge 1 in phase 1`.

(c) Cloud to cloud analysis for Bridge 1 in phase 1 and phase 3

Figure 6. Examples of identified defects by comparing heat maps with 360-degree virtual tours for Bridge 2.

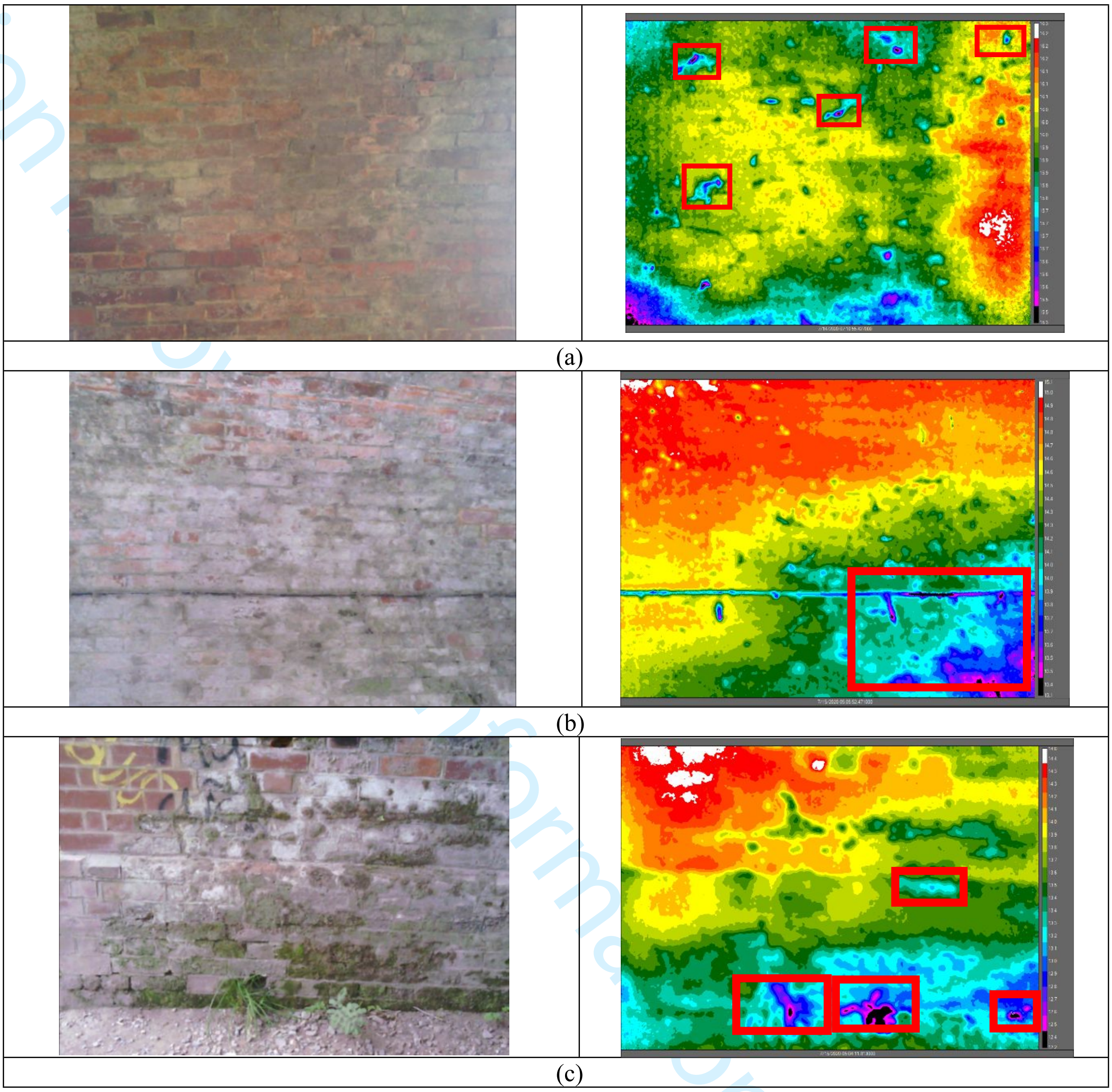


Figure 7. Examples of identified moisture in Bridge 5 and Bridge 6 in phase 3.

5 Discussion

The current masonry railway bridges inspection (i.e. Superficial Inspection and General Inspection) mainly depends on subjective assessments of inspectors, while any incomplete information collected during the inspection can easily result in inconsistency of assessment outcomes with potential disastrous consequences. The proposed framework offers a consistent approach and complete record of assets, and the proposed analysis methods require fewer needs of subjective interpretations due to the quantitative nature of the analysis outcome. The captured data can be shared with inspectors who have not even visited the asset, and their input can be used to analyse the findings while the conventional inspection is only limited to the inspectors on-site, and the knowledge transfer to successive inspectors is difficult. This is particularly important where transportation agencies globally have limited qualified inspectors (Omer *et al.*, 2019).

The reliability of documentation created by 360-degree imaging is important when it comes to the allocation of resources for maintenance and construction. The conventional reporting format is quite restrictive in terms of a full and detailed understanding of the wider environment and the overall context of the asset when reviewed by the asset management teams in offices. The focus of reports in conventional inspection is usually on the inside of the bridge, and they only provide a partial record of the bridge condition. However, the digital approach also includes the surrounding environment (including the topside), enabling the bridge to be understood within the context of its comprehensive settings. Compared to a current examination report, the 360-degree virtual tour offers an interactive and easy to understand format, especially for those who have not yet visited the bridge.

The digital capture approach, including 360 imaging, TLS and UAV, can be deployed consistently overtime to ensure thorough and consistent inspections. The additional data after each inspection can be easily integrated into the previous outputs to show the condition of a bridge over time and to allow for further analysis between inspections.

The quality of inspection will improve due to the high-level accuracy and resolution of point cloud datasets and 360-degree images of the asset. The cost of an inspection will fall when the data acquisition process is standardised and digital capture equipment becomes more affordable. Moreover, the site visit can be carried out by qualified digital operators instead of qualified Inspection Engineers. The actual inspection can be performed remotely by qualified engineers to improve overall efficiency and productivity. Furthermore, the captured data can be stored and revisited over time to inform more detailed levels of analysis, which presents a strong business case to adjust the interval of the current inspection regime, i.e. the reduced need for general inspection as the digital superficial inspection can meet the majority of the requirements of the general inspection.

Preparation and data acquisition

The case study indicated that it is critical to take the following environmental conditions into account during the preparation and data acquisition.

Site condition

Although the digital approach allows inspecting the assets at height and distance without the need to deploy special cranes or scaffolding, access to bridges often requires a long walk on muddy side roads with heavy and expensive equipment. In some cases, the operator might need to stay days on sites for a large asset, e.g. a multi-span viaduct. Therefore, planning for transport and logistics is always required. Traffic management should also be considered to avoid constant interruptions during the capture.

Vegetation, obstructions (e.g., fences) are concerns for digital capture. Excessive vegetation obscures the bridge surface and prevents data acquisitions. Vegetation, such as overhanging trees, obscures many structural elements such as wing walls and parapets from UAV. By combining the UAV and TLS dataset, a comprehensive point cloud is still able to be created. However, it is recommended that vegetation needs to be routinely cleared prior to attending the site where time and cost permits to achieve a fully captured examination.

If the obstructions are permanent and unable to be removed or would cause a potential risk of trespass on the line, such as fence removal, Occlusions in data from obstructions can be mitigated by varying scanning locations to capture as much of each structure as possible.

Weather conditions

During daylight captures, there is a single source of bright light in an otherwise balanced scene (e.g., low sun or bright sunshine in the entrance to an unlit wide underbridge). Big differences between the light and dark values leave dark shadows or highlights. High Dynamic Range (HDR) images are recommended while using the TLS. For areas where the use of HDR alone are not sufficient, LED panels (output: 1100 Lumens with an average light intensity of 57 Lux) attached to individual tripod legs via specialist photography clamps are used to provide even lighting across the entire 360-degree scan field of view. Point cloud data and thermography images are not dependent on the lighting condition. The capture can take place in poor light conditions without the need for additional site lighting. The resulting point cloud, although not colourised, can still be utilised for further analysis.

Precipitation observed to be over the acceptable level of the TLS IP rating (IP54) was encountered at some structures, resulting in the deployment of a canopy to ensure capture could be completed. Although the canopy is visible in the dataset, it has no significant adverse effect on the point cloud datasets. In some visits, it appeared that the bridge was subject to flood, and the surveys were in very muddy and sometimes submerged conditions. Whilst the structure itself was successfully captured to the same level of detail as other assets, and the water obscured a large proportion of the surrounding land and base of underside walls. If the floodwaters had been clear, light refracting through the water would have made results unreliable. Where areas of ground were saturated/muddy but not flooded, light reflected off of the surface, reducing the number of points recorded.

Data processing, data analysis and reporting

All captured data has to be processed to create viewable results (point cloud registration, 360 virtual tours and thermal analysis). It can be done through the software provided by the device manufacturer or specialist suppliers. The data size is very large (Gigabytes for each bridge), and the processing time is in hours with a high-performance desktop workstation, which has to be taken into account in the workflow.

UAV offers significant advantages to capture the topside (trackside) of the bridge; the resultant images can be integrated with TLS data to form a complete picture of a bridge asset. Despite the different accuracy levels between the UAV data and TLS data might reduce the overall precision of the integrated model.

360-degree images obtained from TLS while capturing point cloud data provide comprehensive and high-quality visual information of an asset and its surrounding for each inspection. The virtual tour offers an integrated environment to identify, record and visualise common masonry defects such as bulging, crack, spalling, joint defect, vegetation, and loss of section, as well as engineering comments as part of the inspection.

The point cloud analysis can detect small surface changes, such as bulging, together with high precision location data, it can also detect displacement /movement between multiple scans, and Thermal imaging is effective to detect certain defects related to moisture and water penetration. However, the images have to be captured at a particular time of the day (i.e. after sunset), which might not be suitable for a routine inspection.

6 Conclusion

The conventional visual inspection is time-consuming, lack consistency, prone to human errors and safety concerns. The aim of this research was to develop a framework whereby complementary NDT technologies are adopted to digitise the visual inspection of masonry railway bridges in the UK. An exploratory case study adopted in this research allowed to collect empirical data. The findings from the literature and empirical studies were used to develop a masonry bridge inspection framework. This framework has four steps: (1) preparation for data collection, (2) data acquisition, (3) data processing, and (4) data analysing and reporting. The proposed digitally enhanced visual inspection framework presents an entirely new approach by taking advantage of the existing digital capture technologies for the asset inspection process. The case study demonstrated a successful practical implementation of the framework on five bridges in the UK. The framework facilitates fast, easy and reliable inspection of bridges without the necessity of inspectors visiting the asset and the approach enables inspectors to understand the bridge within the context of its comprehensive setting. It offers a consistent and safe process supported by qualitative and quantitative analysis methods while it can be less costly in the long run than conventional visual inspection.

The main limitation of the study is the limited assets used in the case study. Most of the bridges in the case study are small single-span underbridges. It is envisaged that the framework will face challenges when applies to a large bridge at a significant height, and UAV is the primary method for data capture. The high accuracy point cloud data and 360 images might not be readily available, and different capture devices (UAV payload) might be required to overcome the problems. For future development, other emerging imaging devices, such as Matterport and Geoslam Zeb, offer rapid capture for 360 images and low-resolution point cloud, which might be suitable for the specific surveying tasks, should be investigated. A fully automated scan to BIM process can be developed to transform the point cloud model to fully-fledged BIM models. Computer vision based machine learning techniques can be deployed to assist inspection engineers to identify the common defects.

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References

3D VISTA. 2021. *Virtual Tour Pro* [Online]. Available: https://www.3dvista.com/en/products/virtualtour [Accessed 3rd July 2021].

ABDELKHALEK, S. & ZAYED, T. 2021. Performance assessment model of non-destructive technologies in inspecting concrete bridge decks. *Structure and Infrastructure Engineering*, 1-22.

AGDAS, D., RICE, J. A., MARTINEZ, J. R. & LASA, I. R. 2016. Comparison of visual inspection and structural-health monitoring as bridge condition assessment methods. *Journal of Performance of Constructed Facilities,* 30**,** 04015049.

ARTUS, M. & KOCH, C. 2020. State of the art in damage information modeling for RC bridges–A literature review. *Advanced Engineering Informatics,* 46**,** 101171.

ARYAN, A., BOSCHÉ, F. & TANG, P. 2021. Planning for terrestrial laser scanning in construction: A review. *Automation in Construction,* 125**,** 103551.

ASADI, K., SURESH, A. K., ENDER, A., GOTAD, S., MANIYAR, S., ANAND, S., NOGHABAEI, M., HAN, K., LOBATON, E. & WU, T. 2020. An integrated UGV-UAV system for construction site data collection. *Automation in Construction,* 112**,** 103068.

BAKHSHI, S., CHENAGHLOU, M. R., RAHIMIAN, F. P., EDWARDS, D. J. & DAWOOD, N. 2022. Integrated BIM and DfMA parametric and algorithmic design based collaboration for supporting client engagement within offsite construction. *Automation in Construction,* 133**,** 104015.

BAQERSAD, J., POOZESH, P., NIEZRECKI, C. & AVITABILE, P. 2017. Photogrammetry and optical methods in structural dynamics–A review. *Mechanical Systems and Signal Processing,* 86**,** 17-34.

BERTOLA, N. J. & BRÜHWILER, E. 2021. Risk-based methodology to assess bridge condition based on visual inspection. *Structure and Infrastructure Engineering***,** 1-14.

BHATLA, A., CHOE, S. Y., FIERRO, O. & LEITE, F. 2012. Evaluation of accuracy of as-built 3D modeling from photos taken by handheld digital cameras. *Automation in Construction,* 28**,** 116-127.

BIRGONUL, Z. 2021. A receptive-responsive tool for customizing occupant's thermal comfort and maximizing energy efficiency by blending BIM data with real-time information. *Smart and sustainable built Environment*.

BRILAKIS, I., LOURAKIS, M., SACKS, R., SAVARESE, S., CHRISTODOULOU, S., TEIZER, J. & MAKHMALBAF, A. 2010. Toward automated generation of parametric BIMs based on hybrid video and laser scanning data. *Advanced Engineering Informatics,* 24**,** 456-465.

BULUT, M. B., WILKINSON, S., KHAN, A., JIN, X.-H. & LEE, C. L. 2021. Thermal performance of retrofitted secondary glazed windows in residential buildings–two cases from Australia. *Smart and sustainable built environment*.

CHA, G., PARK, S. & OH, T. 2019. A terrestrial lidar-based detection of shape deformation for maintenance of bridge structures. *Journal of Construction Engineering and Management,* 145**,** 04019075.

CHMIELEWSKI, R. & MUZOLF, P. 2021. Analysis of degradation process of a railway steel bridge in the final period of its operation. *Structure and Infrastructure Engineering***,** 1-17.

CLOUDCOMPARE. 2021. *CloudCompare: 3D point cloud and mesh processing software* [Online]. Available: https://www.danielgm.net/cc/ [Accessed 4th June 2021].

DABOUS, S. A. & FEROZ, S. 2020. Condition monitoring of bridges with non-contact testing technologies. *Automation in Construction,* 116**,** 103224.

EIRIS, R., GHEISARI, M. & ESMAEILI, B. 2018. PARS: Using augmented 360-degree panoramas of reality for construction safety training. *International journal of environmental research and public health,* 15**,** 2452.

ELGHAISH, F., MATARNEH, S., TALEBI, S., KAGIOGLOU, M., HOSSEINI, M. R. & ABRISHAMI, S. 2020. Toward digitalization in the construction industry with immersive and drones technologies: a critical literature review. *Smart and sustainable built Environment*.

FARO. 2021. *FARO SCENE Software* [Online]. Available: https://www.faro.com/en/Products/Software/SCENE-Software [Accessed 3rd June 2021].

FLIR. 2021. *ResearchIR* [Online]. Available: https://www.flir.co.uk/support/products/researchir#Overview [Accessed 3rd June 2021].

GABARA, G. & SAWICKI, P. 2018. A new approach for inspection of selected geometric parameters of a railway track using image-based point clouds. *Sensors,* 18**,** 791.

GARRIDO, I., LAGÜELA, S. & ARIAS, P. 2018. Infrared thermography's application to infrastructure inspections. *Infrastructures,* 3**,** 35.
GEO-PLUS. 2021. *VisionLidar* [Online]. Available: https://www.geo-plus.com/point-cloud-software/ [Accessed 2nd June 2021].
GETULI, V., CAPONE, P., BRUTTINI, A. & RAHIMIAN, F. P. 2021. On-demand generation of as-built infrastructure information models for mechanised Tunnelling from TBM data: A computational design approach. *Automation in Construction,* 121**,** 103434.
GHAURI, P. N. & GRØNHAUG, K. 2005. *Research methods in business studies: A practical guide,* London, UK, Pearson Education.
HEARN, G. 2007. *Bridge inspection practices*, Transportation Research Board.
JANKŮ, M., BŘEZINA, I. & GROŠEK, J. 2017. Use of infrared thermography to detect defects on concrete bridges. *Procedia engineering,* 190**,** 62-69.
JO, B.-W., LEE, Y.-S., JO, J. H. & KHAN, R. M. A. 2018. Computer vision-based bridge displacement measurements using rotation-invariant image processing technique. *Sustainability,* 10**,** 1785.
JOHANSEN, K. W., NIELSEN, R., SCHULTZ, C. & TEIZER, J. 2021. Automated activity and progress analysis based on non-monotonic reasoning of construction operations. *Smart and sustainable built environment*.
KUZIN, A., VALKOV, V. & KAZANTSEV, A. 2018. Satellite-based techniques for monitoring of bridge deformations. *Journal of Physics: Conference Series,* 1118**,** 012022.
LAGÜELA, S., DÍAZ-VILARIÑO, L., ARMESTO, J. & ARIAS, P. 2014. Non-destructive approach for the generation and thermal characterization of an as-built BIM. *Construction and Building Materials,* 51**,** 55-61.
LIU, P., CHEN, A. Y., HUANG, Y.-N., HAN, J.-Y., LAI, J.-S., KANG, S.-C., WU, T.-H., WEN, M.-C. & TSAI, M.-H. 2014. A review of rotorcraft unmanned aerial vehicle (UAV) developments and applications in civil engineering. *Smart Structures and Systems,* 13**,** 1065-1094.
MAHMOUDI, E., STEPIEN, M. & KÖNIG, M. 2021. Optimisation of geotechnical surveys using a BIM-based geostatistical analysis. *Smart and sustainable built Environment*.
MARMO, F., DEMARTINO, C., CANDELA, G., SULPIZIO, C., BRISEGHELLA, B., SPAGNUOLO, R., XIAO, Y., VANZI, I. & ROSATI, L. 2019. On the form of the Musmeci's bridge over the Basento river. *Engineering Structures,* 191**,** 658-673.
MEOLA, C. 2007. Infrared thermography of masonry structures. *Infrared physics & technology,* 49**,** 228-233.
NETWORK RAIL 2010. Handbook for the examination of structures.
OMAR, T., NEHDI, M. L. & ZAYED, T. 2018. Infrared thermography model for automated detection of delamination in RC bridge decks. *Construction and Building Materials,* 168**,** 313-327.
OMER, M., MARGETTS, L., HADI MOSLEH, M., HEWITT, S. & PARWAIZ, M. 2019. Use of gaming technology to bring bridge inspection to the office. *Structure and Infrastructure Engineering,* 15**,** 1292-1307.
OSKOUIE, P., BECERIK-GERBER, B. & SOIBELMAN, L. 2016. Automated measurement of highway retaining wall displacements using terrestrial laser scanners. *Automation in Construction,* 65**,** 86-101.
PARK, J., KIM, P., CHO, Y. K. & KANG, J. 2019. Framework for automated registration of UAV and UGV point clouds using local features in images. *Automation in Construction,* 98**,** 175-182.
PHARES, B. M., WASHER, G. A., ROLANDER, D. D., GRAYBEAL, B. A. & MOORE, M. 2004. Routine highway bridge inspection condition documentation accuracy and reliability. *Journal of Bridge Engineering,* 9**,** 403-413.
POPESCU, C., TÄLJSTEN, B., BLANKSVÄRD, T. & ELFGREN, L. 2019. 3D reconstruction of existing concrete bridges using optical methods. *Structure and Infrastructure Engineering,* 15**,** 912-924.

PUPPALA, A. J., CONGRESS, S. S., BHEEMASETTI, T. V. & CABALLERO, S. R. 2018. Visualization of civil infrastructure emphasizing geomaterial characterization and performance. *Journal of Materials in Civil Engineering,* 30**,** 04018236.

RAJA, B. N. K., MIRAMINI, S., DUFFIELD, C., SOFI, M., MENDIS, P. & ZHANG, L. 2020. The influence of ambient environmental conditions in detecting bridge concrete deck delamination using infrared thermography (IRT). *Structural Control and Health Monitoring,* 27.

RASHIDI, M., MOHAMMADI, M., SADEGHLOU KIVI, S., ABDOLVAND, M. M., TRUONG-HONG, L. & SAMALI, B. 2020. A decade of modern bridge monitoring using terrestrial laser scanning: Review and future directions. *Remote Sensing,* 12**,** 3796.

REN, G., DING, R. & LI, H. 2019. Building an ontological knowledgebase for bridge maintenance. *Advances in Engineering Software,* 130**,** 24-40.

RIVEIRO, B., DEJONG, M. & CONDE, B. 2016. Automated processing of large point clouds for structural health monitoring of masonry arch bridges. *Automation in Construction,* 72**,** 258-268.

ROBERT, R. 2007. Traditional inspection techniques: The foundation of structural health monitoring. *Structural Health Monitoring,* 17**,** 1225–1244.

SACKS, R., KEDAR, A., BORRMANN, A., MA, L., BRILAKIS, I., HÜTHWOHL, P., DAUM, S., KATTEL, U., YOSEF, R. & LIEBICH, T. 2018. SeeBridge as next generation bridge inspection: overview, information delivery manual and model view definition. *Automation in Construction,* 90**,** 134-145.

SELBESOGLU, M., BAKIRMAN, T. & GOKBAYRAK, O. 2016. Deformation measurement using terrestrial laser scanner for cultural heritage. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences,* 42.

SHAZALI, A. S. A. & TAHAR, K. N. 2019. Virtual 3D model of Canseleri building via close-range photogrammetry implementation. *International Journal of Building Pathology and Adaptation,* 38**,** 217-227.

TANG, P., HUBER, D. & AKINCI, B. 2010. Characterization of laser scanners and algorithms for detecting flatness defects on concrete surfaces. *Journal of Computing in Civil Engineering,* 25**,** 31-42.

YIN, R. K. 2013. *Case study research: Design and methods,* California, USA, SAGE Publications.

ZELLMER-BRUHN, M., CALIGIURI, P. & THOMAS, D. C. 2016. *From the editors: Experimental designs in international business research,* London, Springer.

The development of a digitally enhanced visual inspection framework for masonry bridges in the UK

Abstract

Purpose: The utilisation of emerging technologies for the inspection of bridges has remarkably increased. In particular, Non-Destructive Testing (NDT) technologies are deemed a potential alternative for costly, labour intensive, subjective and unsafe conventional bridge inspection regimes. This research aims to develop a framework to overcome conventional inspection regimes' limitations by deploying multiple NDT technologies to carry out digital visual inspections of masonry railway bridges.

Design/methodology/approach: This research adopts an exploratory case study approach, and the empirical data is collected through exploratory workshops, interviews and document reviews. The framework is implemented and refined in five masonry bridges as part of the UK railway infrastructure. Four NDT technologies, namely, Terrestrial Laser Scanner (TLS), Infrared Thermography (IRT), 360-degree imaging, and Unmanned Aerial Vehicles (UAV), are used in this study.

Findings: A digitally enhanced visual inspection framework is developed by utilising complementary optical methods. Compared to the conventional inspection regimes, the new approach requires fewer subjective interpretations due to the additional qualitative and quantitative analysis. Also, it is safer and needs fewer operators on site as the actual inspection can be carried out remotely.

Originality: This research is a step towards digitalising the inspection of bridges, and it is of particular interest to transport agencies and bridge inspectors and can potentially result in revolutionising the bridge inspection regimes and guidelines.

Keywords

visual inspection, masonry railway bridges, digitalisation, optical methods, Non-Destructive Testing, Infrared thermography, Terrestrial laser scanning, 360-degree imaging, Unmanned Aerial Vehicles, Bridge monitoring

1 Introduction

Bridges are critical for modern transport systems in European nations such as the UK, Slovenia, Hungary, Poland, Czech Republic, Austria, and Norway. Most bridges were built between 1945 and 1965. Among existing bridges, masonry arch bridges are a vital element of Europe's rail, road, and waterway infrastructure (Riveiro *et al.*, 2016). In the UK, there are approximately 18,000 masonry bridges as part of the rail network (Hearn, 2007). However, those bridges are subjected to deterioration due to excessive overloading, usage, environmental conditions, and ageing, and more attention is required to ensure that bridges last for the period of their intended design life and beyond (Ren *et al.*, 2019). Failure to maintain bridges can adversely impact a nation's economy, daily activities and even lead to loss of life (Sacks *et al.*, 2018, Johansen *et al.*, 2021).

The structural integrity and serviceability of bridges, including masonry railway bridges, can be deteriorated over time if a defect is not identified in a timely manner. Identifying and defining the extent of these defects in their initial stages is critical to ensure bridge safety (Dabous and Feroz, 2020). Hence, frequent condition assessment of masonry railway bridges is needed. Visual inspection is a primary method for the examination of the performance and serviceability of the current state of bridges. However, this technique is known to be time-consuming, laborious and suffers from certain drawbacks such as the subjective nature of the inspection, interpretability and reliability of results, and safety concerns for the inspector while accessing different elements of a bridge (Agdas *et al.*, 2016). Moreover, the procedure cannot be carried out on a regular basis due to (a) possible traffic disruption, (b) high labour cost, and (c) inaccessibility of sites (Liu *et al.*, 2014). Therefore, there is a strong need to move towards a more automated system with digital methods to provide more accuracy and a safer working environment for bridge inspection.

A comparison has been made between different national practices for bridge inspection by Hearn (2007). The inspection procedure, including the inspection frequency and level of detail, vary across countries and sectors. However, most of those procedures are based on more frequent and less detailed visual inspections than detailed but less frequent inspections (Artus and Koch, 2020).

In recent decades, Non-Destructive Testing (NDT) technologies have been developed to enhance the bridge inspection procedure and make it faster and more reliable. The NDT technology enables the assessment to be performed on structures that are difficult to access or under insecure conditions, such as poor lighting conditions or low temperatures (Artus and Koch, 2020). Also, NDT methods do not damage the structure under study and reduce the subjectivity and slowness of the traditional methods (Abdelkhalek and Zayed, 2021).

Among NDT technologies, optical methods function uses sensitive and accurate cameras to image objects, and they are known to be an advanced alternative to visual inspection (Popescu *et al.*, 2019, Abdallah *et al.*, 2022). Terrestrial Laser Scanner (TLS), Infrared Thermography (IRT), 360-degree imaging, and Unmanned Aerial Vehicles (UAV) are common optical methods available on the market. Of note is that utilising NDT methods individually is often insufficient for infrastructure inspection (Rashidi et al., 2020), which necessitates complementary methods to produce a more reliable inspection outcome.

Several research efforts have attempted to compare the accuracy and reliability of NDT technologies to identify defects. However, NDT technology has not been yet widely accepted due to various reasons such as associated costs, unrealistic expectations, or improper use (Abdelkhalek and Zayed, 2021). Moreover, in most of the previous research studies, NDT technology is implemented in the laboratory (i.e. ideal) environment, which does not provide a reliable indication of the wide range of variables impacting the implementation of the NTD technology in real-world scenarios (Dabous and Feroz, 2020). In particular, as far as it is known, no literature could be found that attempts to utilise complementary NDT technologies to inspect masonry railway bridges, while most studies focus on concrete bridges. Despite the importance of masonry railway bridges in the UK, conducting routine visual inspections using technological solutions has not been fully addressed.

The research reported in this paper aims to develop a framework by which complementary optical methods are used to (a) address the difficulties and limitations of conventional inspection procedures and (b) to demonstrate the feasibility of deploying the multiple optical methods to perform visual inspections of masonry railway bridges in the UK. This novel research is amongst very few studies that have utilised complementary optical methods in the field and have provided a comprehensive, practical framework by which other researchers and transportation agencies can tackle the limitations posed by conventional inspection regimes. The paper is structured as follows. First, a background to the conventional inspection procedures of bridges as well as recent trends are given. The application of 360-degree panorama, TLS, IRT and UAV for condition monitoring purposes is presented. The research method adopted to collate and analyse data is addressed. The proposed framework is presented, and then its functionality is demonstrated in a case study. The findings and contributions to knowledge are discussed. Finally, conclusions drawn from the research and areas for further research are presented.

1.1 Scope of Research

The scope of this research focuses on the global (visual) inspection of masonry railway bridges in the UK. Global inspection detects the occurrence of defects, while local inspection identifies the location, extent and severity of damages (Network Rail, 2010). The proposed framework fits within the current inspection regime of transportation agencies in the UK. Although other types of bridges such as concrete and metallic as well as conventional inspection regimes of other countries are not in the scope of this study, the researchers believe that the findings can provide generalisable knowledge on inspection of all types of bridges across the globe.

1.2 Background

Conventionally, routine condition monitoring is accomplished by visual inspection, which is a primary technique for assessing the performance and serviceability of bridges all around the world (Robert, 2007). Visual inspection is about observing and documenting the overall bridge condition and then collecting information about issues such as cracks, settlements/ deflection and spalling (Bertola and Brühwiler, 2021). The inspection is expected to cover the whole structure on the ground so that no members of the substructure and superstructure are overlooked. The collected information is normally documented in an inspection report, including freehand observations, field observation notes, audio recordings, and photographs. Such documentation is used as input in the bridge management protocols of transportation agencies (Phares *et al.*, 2004, Getuli *et al.*, 2021).

Regarding the inspection procedures, transportation agencies may have different approaches. According to Hearn (2007), there are five prevalent types of condition assessment for bridges in the UK (Table 1). General inspections are the primary source of information, but they often do not capture all defects due to viewing distances, lighting conditions and the lack of special access arrangements. Principle inspections can detect visible defects or visible manifestation of hidden defects, while Special inspections are undertaken when principle / visual inspections have identified a defect (Chmielewski and Muzolf, 2021). Also, each type of condition assessment has three generic phases, namely planning, inspection and reporting (Bertola and Brühwiler, 2021).

Table 1. Different types of condition assessment for bridges in the UK (Hearn, 2007)

Inspection Type	Interval	Performed by	Description
Acceptance	-	-	When the responsible for a structure (e.g., inspection) changes
Superficial	Frequent	Contractor	To immediately report any damage or action needed to maintain the bridge
General	2 years	Contractor	To visually inspect all parts of the bridge without the need for special access equipment or lane closure
Principal	6 years	Contractor	To visually inspect all parts of the bridge to report all conditions and defects using the required access equipment
Special	As necessary	Contractor	To further investigate the identified defects during an earlier inspection using material sampling or NDT

Numerous studies have highlighted the drawbacks of the conventional condition assessment (Dabous and Feroz, 2020). To circumvent limitations of visual inspections, emerging new technologies and advanced monitoring practices have been used in bridge condition assessment and monitoring. Some of those technologies depend on Global Positioning Systems (GPS) or Global Navigation Satellite Systems (GNSS), electro-optical instruments, and different types of sensors (Kuzin *et al.*, 2018). Although satellite systems are beneficial in the dynamic measurement of long-span bridges, their accuracy cannot be guaranteed. Total stations and digital levels provide high accuracy, but they are unable to perform satisfactorily during unfavourable weather conditions and cannot provide a holistic overview of the bridge condition. Electronic sensing devices, including accelerometers, displacement transducers, and strain gauges, necessitate direct structural installation and connection with reference points to estimate absolute displacement (Jo *et al.*, 2018, Bakhshi *et al.*, 2022). They are complex tasks requiring disruption of traffic, and the working conditions of the bridge may be detrimental to the operation of the sensors. Moreover, often only discrete information can be extracted from these devices unless multiple sensors are installed (Kuzin *et al.*, 2018).

In this research study, optical methods are explored as an alternative for the condition assessment of masonry railway bridges. Such NDT technologies can provide accurate, detailed models of the inspected object in a non-invasive manner, quantify the bridge deformation (Baqersad *et al.*, 2017), facilitate a safe working environment, and eliminate the need for scaffolding. The increasing utilisation of NDT technologies, especially optical methods, has brought benefits to inspection regimes of infrastructure. All these have, in turn, supported timely necessary or remedial works in the built infrastructures alongside improved accuracy in inspection regimes as opposed to traditional techniques (Artus and Koch, 2020).

Four main optical methods, namely 360-degree imaging, TLS, IRT, and UAV, are introduced in the ensuing sections.

360-degree imaging

360-degree imaging as a visual inspection technique has gained broad appeal as part of a movement away from the time consuming, tedious, and expensive manual photography dominating much of current inspection regimes (Popescu *et al.*, 2019). Using 360-degree imaging, an immersive environment can be recreated to make offline inspections from large image data sets. This technique creates highly immersive experiences that give the user a feeling of being present in the field (Omer *et al.*, 2019). This process in recent years has been through automated complementary applications, which further reduce the need for the laborious presence and inspection seen in traditional practices (Eiris *et al.*, 2018).

Terrestrial Laser Scanner

Terrestrial laser scanning (TLS) is a widely used NDT for inspection purposes. Using this method allows inspection regimes to carry out any necessary metric surveys. One of the strengths of laser scanning is its relatively high reliability and accuracy of data collection alongside simple and relatively quick and safe processing (Selbesoglu *et al.*, 2016).

The principle of laser scanning is that either a pulse emission (radiation in the visible or infrared domain) or amplitude modulation (representing the phase difference between the sine modulated transmitted and the reflected beams) is measured (Riveiro *et al.*, 2016). The application of TLS for bridge assessment and monitoring has been widely studied (Rashidi *et al.*, 2020). There are two major applications of TLS in this field, namely (a) the generation of 3D models and reconstruction of the geometry model from obtained point cloud, and (b) the quality inspection, especially identification of surface damages (Brilakis *et al.*, 2010). Using laser scanning allows users to measure or extract geometric and semantic information as required (Gabara and Sawicki, 2018) to facilitate structural integrity inspections and identify defects using a rigorous method with a high degree of precision. For example, TLS can be used to measure deflections in bridge deck thickness regenerated from a point cloud dataset (Cha *et al.*, 2019).

However, the application of TLS is still dependent on environmental factors such as the distance to the target surface and weather conditions (Rashidi *et al.*, 2020). This calls into focus the process of planning to minimise the time on-site and maximise the integrity (i.e. quality and quantity) of the datasets (Aryan *et al.*, 2021). Additional processing is also required to translate the unstructured point clouds into structured models using third-party applications to increase the value of the dataset.

Infrared thermography

Infrared thermography (IRT) is a remote sensing technology used for the rapid inspection and visualisation of thermal images. IRT is known to be accurate and reliable that can produce both qualitative and quantitative indicators of a bridge condition. It can be utilised for measuring the thermal diffusivity of bricks and moisture mapping (Janků *et al.*, 2017).

There are two approaches of IRT, namely active and passive, depending on the presence or absence of an artificial and external mechanism of thermal excitation in the object (Omar *et al.*, 2018). Passive IRT means that there is a natural thermal excitation source, while active IRT means that artificial heat sources are used. With passive IRT, the analysis is carried out under natural conditions, and then the thermal behaviour of the object is assessed. When an artificial heat source is used for the active IRT, the heating or cooling processes of the object is monitored during and after the thermal excitation (Meola, 2007).

Moreover, depending on the purpose of the inspection, the thermographic analysis can be performed either qualitatively or quantitatively (Janků *et al.*, 2017, Birgonul, 2021). Qualitative IRT is applied when the focus is on the relative pixel values or the temperature distribution, and the exact measurement of temperature in the thermal images is not needed. This technique is particularly useful when the main objective is to identify thermal pathologies regardless of the thermal properties of the object and the severity of the identified defects (Garrido *et al.*, 2018). On the other hand, quantitative IRT is applied when the focus is on acquiring precise temperature values. This technique is used when possible thermal pathologies were detected through qualitative IRT in order to assess the severity or measure thermophysical properties of the identified anomalies (e.g., depth of cracks detected in the objects) (Bhatla *et al.*, 2012, Bulut *et al.*, 2021).

Most of the previous research studies performing thermographic testing are based on specimens prepared in the laboratory environment with stimulated defects (Raja *et al.*, 2020). Many algorithms have been developed based on the temperature of the pre-determined defects' locations and sizes with regards to the temperature of the surrounding materials (Lagüela *et al.*, 2014). Nevertheless, when applying thermographic testing in the context of a bridge, the characteristics of the defects are not known, and even quantitative IRT still heavily relies on the interpretation of the images. In other words, using IRT tests in a laboratory environment might not be consistent with when using in field studies.

Unmanned Aerial Vehicles

Current methods of inspection and producing as-built information are criticised for being labour-intensive and unsafe to be used at height (Elghaish *et al.*, 2020). The conventional air-or-space borne technologies depend on the terrain and the size of the area surveyed (Oskouie *et al.*, 2016) and their application is known to be costly, time-consuming, laborious with high measurement errors (Tang *et al.*, 2010). The utilisation of UAV technology for various applications, including surveying built assets, is increasing, especially because the accuracy of collected data by this technology is improving (Elghaish *et al.*, 2020, Elghaish *et al.*, 2021). A recent study reveals that the geometric accuracy of a 3D model generated by UAV images is less than 4 cm (Shazali and Tahar, 2019, Mahmoudi *et al.*, 2021).

UAV-based photogrammetry can generate 3D models, which are found to be useful for the condition monitoring of structures. For example, Puppala *et al.* (2018) use a visual range camera mounted on the UAV to analyse the health conditions of structures and also Marmo *et al.* (2019) explore the feasibility of utilising UAV to create as-built models and carry out inspections. Moreover, it is possible to integrate data collected by UAV with other datasets in order to create more comprehensive 3D models for inspection purposes. For example, in a study undertaken by (Park *et al.*, 2019), a framework is developed to automate the integration of images taken by UAV with point cloud data using 2D local feature points.

Despite the recent advancements of using UAV, little literature on the utilisation of UAV technology in practice exists, while most of the literature is focused on technical aspects (Elghaish *et al.*, 2020). In particular, there is scarce literature that explores the use of UAVs for the inspection of bridges, while the UAV technology is expected to transform the bridge inspection practices due to its unique data collection capabilities (Asadi *et al.*, 2020). This has resulted in the lack of experience among railway authorities and inspectors when it comes to the use of UAV technology.

Research Gap

Masonry bridges are of prime importance for the railway network in the UK. Some researchers have demonstrated the application of optical methods to tackle the challenges that inspectors currently encounter. Evidence in the literature acknowledges that those methods should be considered as the alternative to conventional methods (Raja *et al.*, 2020, Sokolović *et al.*, 2021, Artus and Koch, 2020, Dabous and Feroz, 2020). However, the available research studies on the topic often (a) have not gone beyond carrying out tests in a laboratory environment, (b) only focus on a specific optical method rather than the complementary application of those methods, and/or (c) focus on the technical aspect of such methods rather than practical recommendations to facilitate their implementation by railway agencies.

Optical methods are rarely accepted by railway agencies (Abdallah *et al.*, 2022). The reason behind this low acceptance can be traced back to the above gap, as concurred by (Sánchez-Aparicio *et al.*, 2019). This study's outcome is intended to provide a practical framework whereby pertinent optical methods can be utilised together to improve the current inspection procedures of masonry railway bridges. The applicability and practicality of the method are also demonstrated in a real-life case study.

2 Method

This research aims to propose a practical and feasible solution for the digital inspection of masonry railway bridges. In particular, this study examines the applicability and validity of optical methods derived from the literature within a real-world setting. An exploratory case study is selected for accomplishing such an objective. This method is adopted when explaining, describing and exploring a contemporary phenomenon within a real-world context and when the research study answers "how" questions (Yin, 2013). The exploratory case study in this research aims to answer how optical methods can be used in the context of masonry railway bridges to identify specific types of defects. The real-world setting is an essential part of the exploratory case study, in which many variables may affect the outcome (Ghauri and Grønhaug, 2005). Evaluating the impacts of any proposed framework in a real-world setting may be affected by many variables that can be refined through the case study to produce reliable outcomes for research endeavours (Zellmer-Bruhn *et al.*, 2016). Figure 1 presents the research design and method.

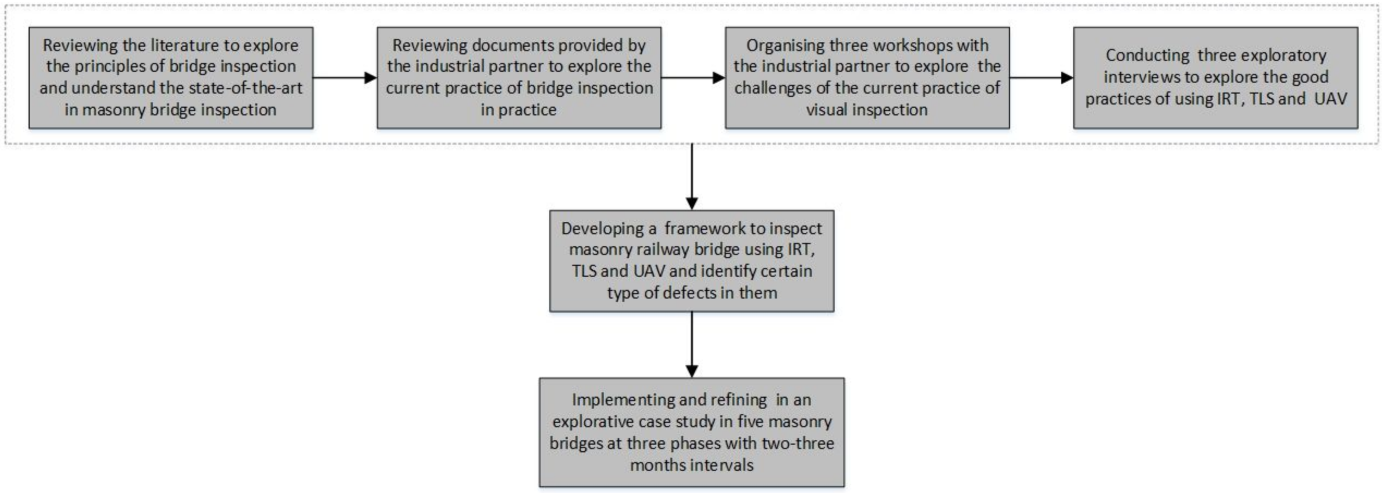


Figure 1. Research method

More specifically, the following steps have been undertaken together with an exploratory case study to address the gap in the current state of knowledge for the inspection of masonry railway bridges in the UK:

- A literature review was carried out to better understand the underlying concepts and principles of bridge inspection as well as to identify state-of-the-art for improving the inspection of masonry railway bridges. Key findings of the literature review are summarised in the Background section of the present paper.

- Document reviews were used to corroborate information collected from literature and to understand the current practice of bridge inspection carried out by the industry. Documents providing guidance on the examination of bridges and examination reports were reviewed. An important finding at this stage was the information about the prevailing defects in masonry bridges that must be detected (Table 2).

- Three exploratory workshops were conducted with experts within the industrial partner's organisation in order to capture the opinions of the industry practitioners concerning the challenges of the current practice of visual inspection as well as expectations from the digitalisation of bridge inspection. These exploratory workshops helped to define the problem and gained an understanding of how the potential solution should be devised. Moreover, three exploratory interviews with experts in IRT, TLS and UAV were carried out during the workshops. Through these interviews, the good practices of using these methods were explored. The findings captured helped ensure that the developing framework is pragmatic and relevant to the current industry practice.

- A masonry bridge inspection framework was developed based on a synthesis of the findings from the literature review as well as the collected information from the industry partner and semi-structured interviews.

- The proposed framework was implemented and refined in an explorative case study in five masonry bridges as part of the UK railway infrastructure. 360-degree imaging, TLS and UAV were utilised at three phases with two-three months intervals. IRT was utilised only in phase 3 for Bridge 5 and Bridge 6. The framework is presented in the Proposed Framework section. The findings from the implementation of this framework can be found in the Case Study section.

Table 2. List of common defects in masonry railway bridges, their descriptions and corresponding examples (Network Rail, 2010)

Bulging	Crack	Spalling
		
Refers to a local "blistering" type movement of the element, possibly associated with hollowness or loose masonry, or ring separation in an arch	Refers to cracks, possibly caused by ground movements and live loads	Refers to crumbling, peeling or flaking of masonry work caused by water entering
Joints defect	Loss of section	Water penetration
		
Refers to gaps in the joints between bricks. Such joint defects are possibly caused by ground movements and live loads	Refers to sections of bricks missing. The loss of section is caused by ground movements, live loads, impact damage and weathering conditions.	Refers to leakage in bridges

3 Result - Proposed Framework

This section presents the proposed framework (Figure 2) for the digital inspection of masonry railway bridges and shows the framework is compatible with the requirements of Superficial Inspection and General Inspection. This framework is composed of four general steps: (1) preparation for data collection, (2) data acquisition, (3) data processing, and (4) data analysing and reporting. The application of the proposed framework facilitates the digitalisation of the inspection of masonry railway bridges. The next subsections explain the details of each step.

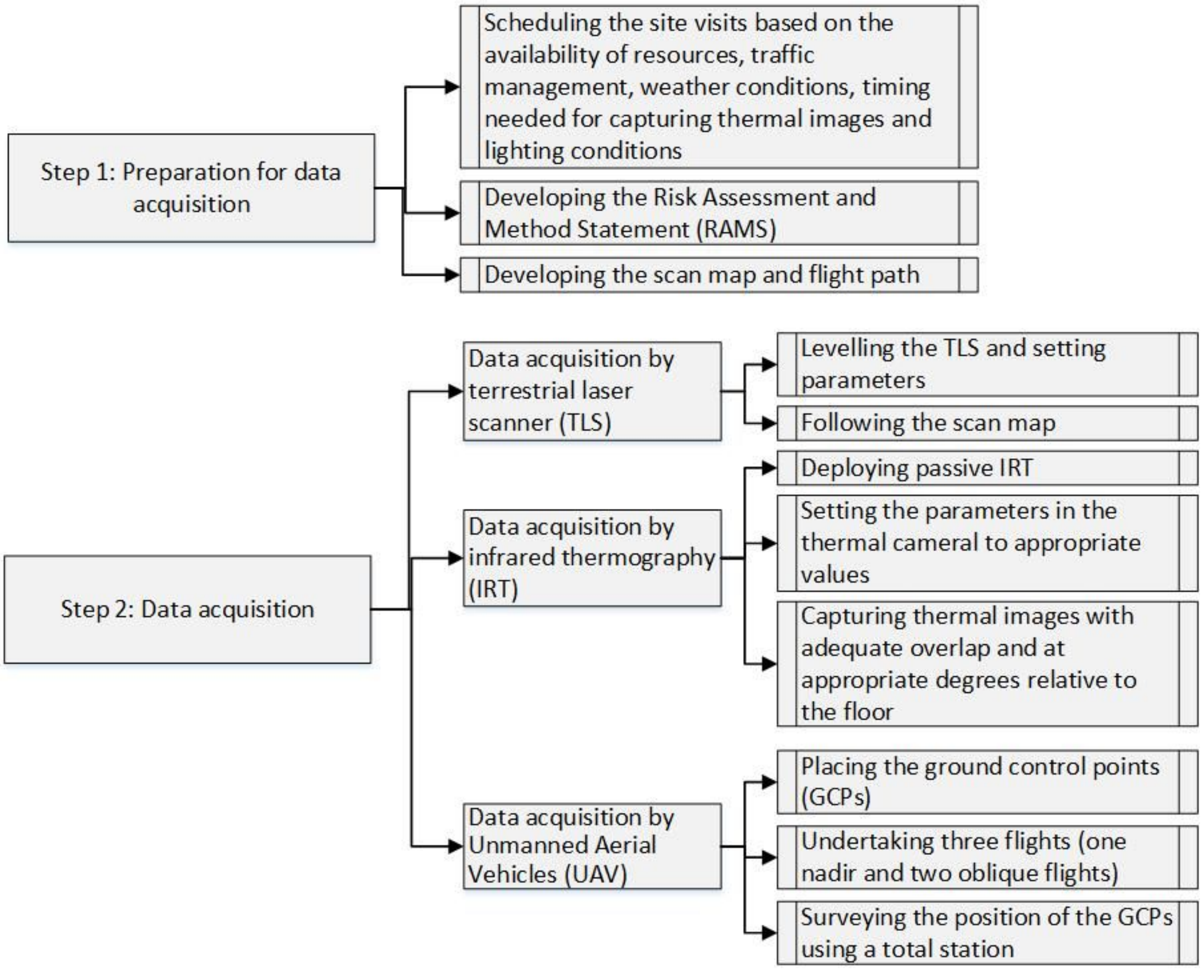


Figure 2. Proposed framework for the digital inspection of masonry railway bridges.

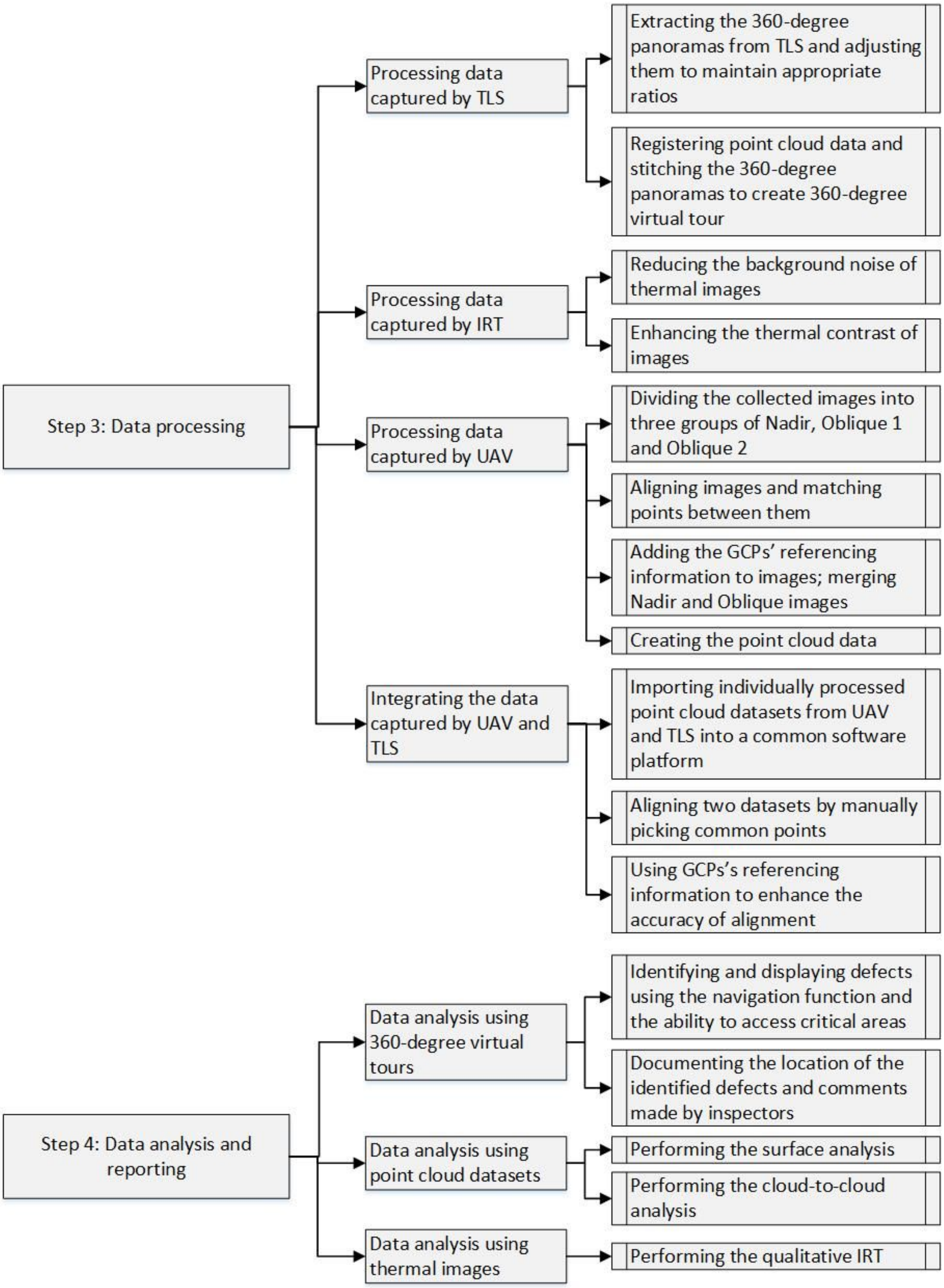


Figure 2. Proposed framework for the digital inspection of masonry railway bridges (continued).

Step 1: Preparation for data acquisition

The preparation for the data acquisition should be based on the availability of resources, traffic management and weather conditions. Prior to arrival on-site, the operators should familiarise themselves with the type and layout of the bridge. The Risk Assessment and Method Statement (RAMS) then needs to be prepared. RAMS includes a summary of the details of all the activities to be performed on-site, specifically any safety procedures and details of traffic management. After arriving on-site, a careful check is performed to confirm the information in RAMS, for example, to ensure it is safe to undertake the flights for UAV.

The environmental conditions, especially solar gain, wind speed and rain, should be taken into account before undertaking the measurements. The adversarial impacts of absorption of thermal energy during the day and wind on the thermographic survey can be mitigated by capturing thermal images nearly 2 hours after the sunset and avoiding days when the wind speed is over 5m/s. Rain may cause undesired noise in the scanned point cloud and may interfere with the thermographic survey. Wind and rain may also disturb the UAV flight.

A scan map should be prepared, which consists of a schematic drawing of the asset and demonstrates the scan positions of TLS with the corresponding scan numbers in the field. The scan positions should be marked along the way on the drawing. The scan map is useful to help plan the scan path in an optimum pattern (i.e. zigzag pattern) and optimum distances between scan positions. In other words, using this method will allow the operator to realise which scans have overlapping and common data, which is useful when processing the acquired point clouds. Furthermore, the scan positions can be recorded for future surveys. In addition to the scan map, a flight path should be created for UAV operation.

Step 2: Data acquisition

The acquisition of point cloud data, 360-degree imaging and thermographic data can be performed in parallel. 360-degree imaging can be captured by two means, namely using the TLS and using a specialised 360-degree imaging camera, such as iStar. The TLS has a camera that can produce high-quality 360-degree imaging while capturing point cloud data. Such 360-degree imagings are mainly used to colourise the point cloud but can also be used for other purposes, such as creating 360-degree virtual tours.

The TLS is attached to the tripod stand and should be levelled using tribrach or the sensors in the scanner. Successful registration of 3D data sets with a high accuracy largely depends on the position of scans and targets in the field. It is also important to consider the 'connector scans' and 'transition scans'. The connector scan is positioned in the border of the outside and inside of the asset to avoid deteriorated scans due to the difference in lighting; the transition scan is positioned between two spans in multi-span bridges.

UAV is used to produce a 3D model of the exterior of the asset (topside) for visual inspection purposes. Prior to starting the UAV survey, the ground control points (GCPs), which are a mixture of A3 sized black and white crosses, are placed on the ground at locations around the structure. In a UAV survey, three flights are undertaken. The flight path should be planned and set up so that the images are captured with 80% overlap forward and 75% overlap side to side. These parameters result in images being collected with a Ground Sample Distance of 4mm. Once the UAV survey is completed and data is collected, the position of the GCPs should be recorded.

For thermographic data acquisition, the passive approach is usually deployed. Thermographic cameras with resolutions of 320x240 pixels (i.e. a more basic camera) or 640x480 pixels (a current high-end camera) are recommended. General settings such as 'object distance', 'relative humidity', 'atmospheric temperature', and 'relative temperature' are set to appropriate values. The attenuation of the radiation due to the atmosphere will increase linearly with distance. Setting the 'object distance' on the camera allows the camera to take this attenuation into account. The thermographic data is collected with adequate overlap and at a known data acquisition path as well as at 60 – 90 degrees relative to the floor.

Step 3: Data processing

The captured point cloud data usually consists of multiple scans of the same asset from different positions. The registration process (target-based or target-less), a multi-step process aligning multiple, overlapping point clouds to form a detailed and accurate representation of the asset, is required. Target-based processing, which relies on targets, is used as opposed to target-less registration, which relies on vertical planes (e.g., walls, arches) in order to achieve a higher level of accuracy. The process is undertaken using native software supplied for the equipment, such as FARO SCENE (FARO, 2021) or other available commercial software packages.

The images captured by UAV are usually divided into three groups, namely Nadir, Oblique 1 and Oblique 2. The Nadir, Oblique 1 and Oblique 2 images are aligned, and points are matched between them and referenced with GCP data to create point cloud data using a photogrammetric process. The resultant point cloud data from UAV can be integrated with the data from TLS to form a 3D model, which provides a comprehensive overview of the structure with no areas of occlusion.

For the 360 images, a variety of tools, such as 3D Vista (3D Vista, 2021), can be used to create an interactive 360-degree virtual tour. The panoramic imagery from TLS may have different ratios. Ratios of 1:1 cube faces or 2:1 spheres can be maintained by adjusting those images.

The captured thermal images should be enhanced utilising software such as ResearchIR (Flir, 2021) to perform surface temperature distribution analysis.

Step 4: Data analysis and reporting

For point cloud datasets, two types of analysis methods can be applied, namely surface analysis and cloud-to-cloud comparison. The surface analysis is used to identify any changes in the primitive surface of assets to identify defects, such as cracks, joint deterioration, spalling. Specialised software packages such as VisionLidar (Geo-Plus, 2021) can be used for this purpose. The cloud-to-cloud analysis is to compare multiple scans of the same area captured at a different time to detect any changes, such as displacement, bulging, etc. Open-source software packages like CloudCompare (CloudCompare, 2021) can be used for cloud-to-cloud comparison.

The 360-degree virtual tours developed from the imaging images can be used as an asset inspection platform for asset inspectors to identify and record defects as well as document any additional supporting comments.

For the thermal images, the qualitative analysis can be applied because this approach does not require evaluation of the captured thermographic data, and it is a fast methodology compared to quantitative analysis. This common type of analysis for condition monitoring of infrastructure investigates the difference in temperature of the area of interest and provides quick decisions. For example, when a material is penetrated by water, the specific heat capacity and thermal conductivity are affected. In other words, the energy needed to raise the temperature of a moist area is higher than an area that is unaffected by water. Therefore, the surface temperature difference occurs.

4.0 Case Study

The case study demonstrated how the proposed framework could be applied to real-world masonry bridges when digital inspection methods were implemented. The data were acquired from five railway bridges in the UK. In Table 3, details of those bridges are presented.

Table 3. Details of bridges in the case study.

Bridge 1	Bridge 2	Bridge 3
		
Underline bridge, masonry, brick arch, single span	Underline bridge, masonry, brick arch, single span	Underline bridge, masonry, brick arch, single span

Bridge 4	Bridge 5
	
Underline bridge, masonry, brick arch with steel and timber deck, single span	Underline bridge, masonry, brick arch, viaduct, multi-span

The case study consists of four single-span underbridges and one multi-span viaduct. The width is an average of 4m, with end arches buried on firm ground. The height of the bridges averages over 8m. The bridge archways form part of the local traffic networks for both pedestrians and vehicles.

Three site visits were conducted for each bridge between September 2019 and July 2020, and data was collected through TLS (FARO X130x), two 360-degree imaging cameras (iSTAR and Matterport Pro) and a thermographic camera (FLIR T640). The topsides of the bridges were also captured by a UAV specialist (due to the commercial restrictions, the specific detailed UAV process are not included in the paper). Each examination included the underside of the bridge and substructure elements such as abutments and wing walls. A summary of the implementation of each step of the framework is presented in the following sections.

Step 1: Preparation for data acquisition

A careful and planned process of pre-inspection was carried out to organise the data acquisition from the field. The authors downloaded and reviewed the latest examination report available on the industry partner's Structures Dashboard, identifying the size, location and scope of survey required. This insight was used to complete an asset-specific RAMS, taking into account the location and environment of an asset. Google Earth and Google Street View imagery were utilised to gain the best possible insight into each bridge. Weather forecasts were monitored for rainfall intensity, humidity and wind to establish if capture could go ahead as scheduled without disruption to the data quality. The scan map for each bridge was created, and the scan positions were marked along the way on the drawings. Figure 3 shows an example of a scan map.

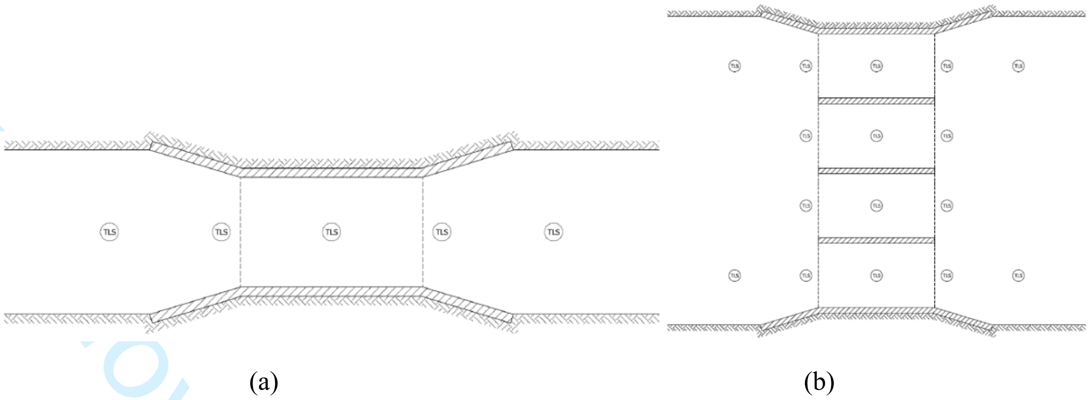
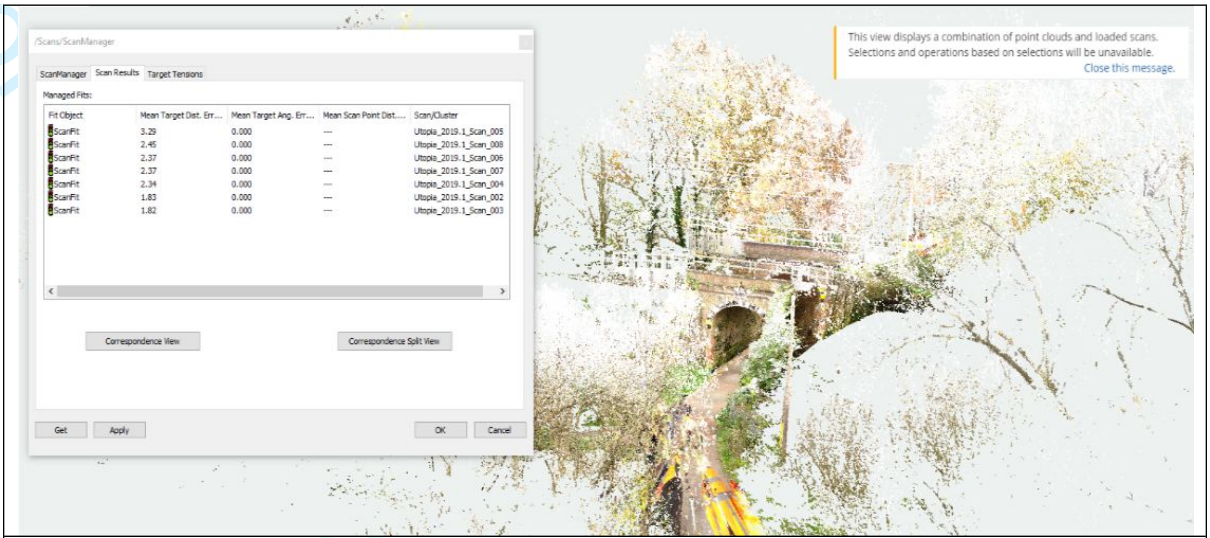


Figure 3. Example of the scan map for (a) a single-span bridge and (b) a viaduct

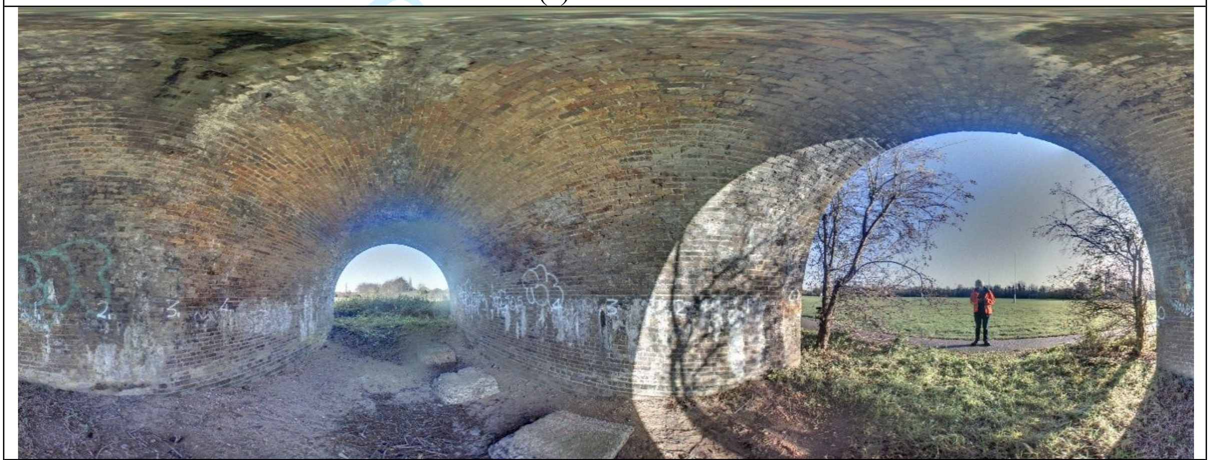
Step 2: Data acquisition

TLS was used to capture point cloud data and 360-degree imagings, and then the thermographic camera was used to capture thermographic data. During the case study, it was found that utilising the imagery taken with a TLS to produce the imagings is a possible solution to mitigate the need to take a separate 360-degree imaging camera on-site. Although TLS takes longer to capture a panoramic image, the quality and field of view of the image produced were considerably higher than the high-resolution 360-degree imaging camera (see Table 3). The resolution, Quality and Distance Range of TLS are set to 1/8, 2X and Normal, respectively. Table 4 shows an example of general settings in the thermographic camera for the FLIR T640.

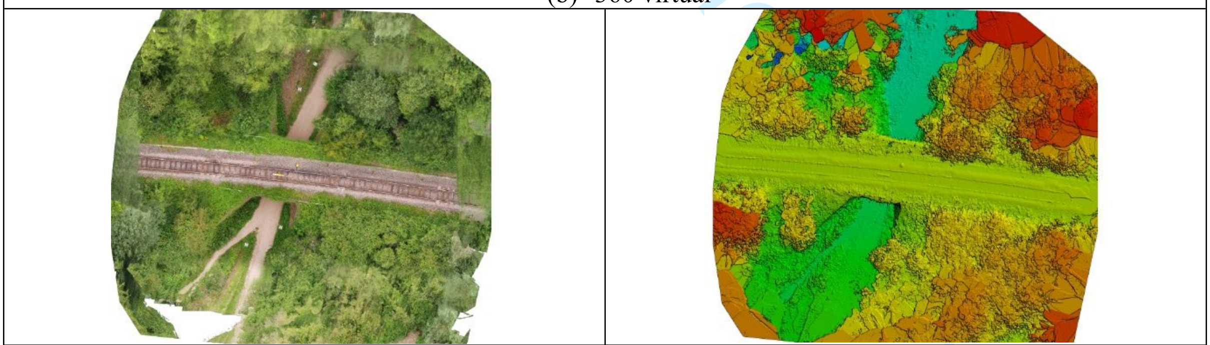
The UAV used in this project was DJI Matrice M210 Quadcopter fitted with a Zenmuse X5S RGB 20MP camera with a 45mm lens. Each survey takes around 30 minutes and the UAV flies at nearly 40m above ground level. In Figure 4, an example of a captured dataset is given.



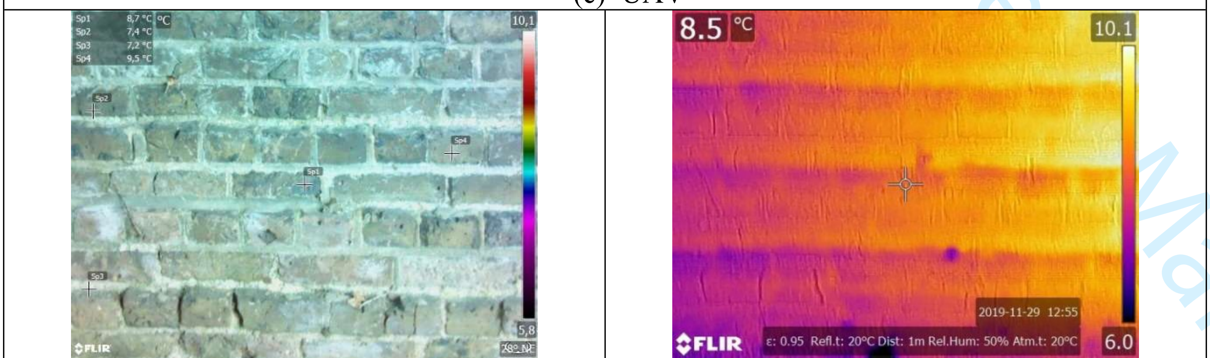
(a) Point cloud



(b) 360 virtual



(c) UAV



(d) Thermal image

Figure 4. Captured dataset for Bridge 3 in phase 2.

Table 3. Comparison between the imaging image taken by TLS and 360-degree imaging camera.

Equipment	Imaging capture time	Imaging quality	Field of view
TLS	3 minutes	165MP	360°x300°
360-degree imaging camera	1 minute	50MP	360x317.5

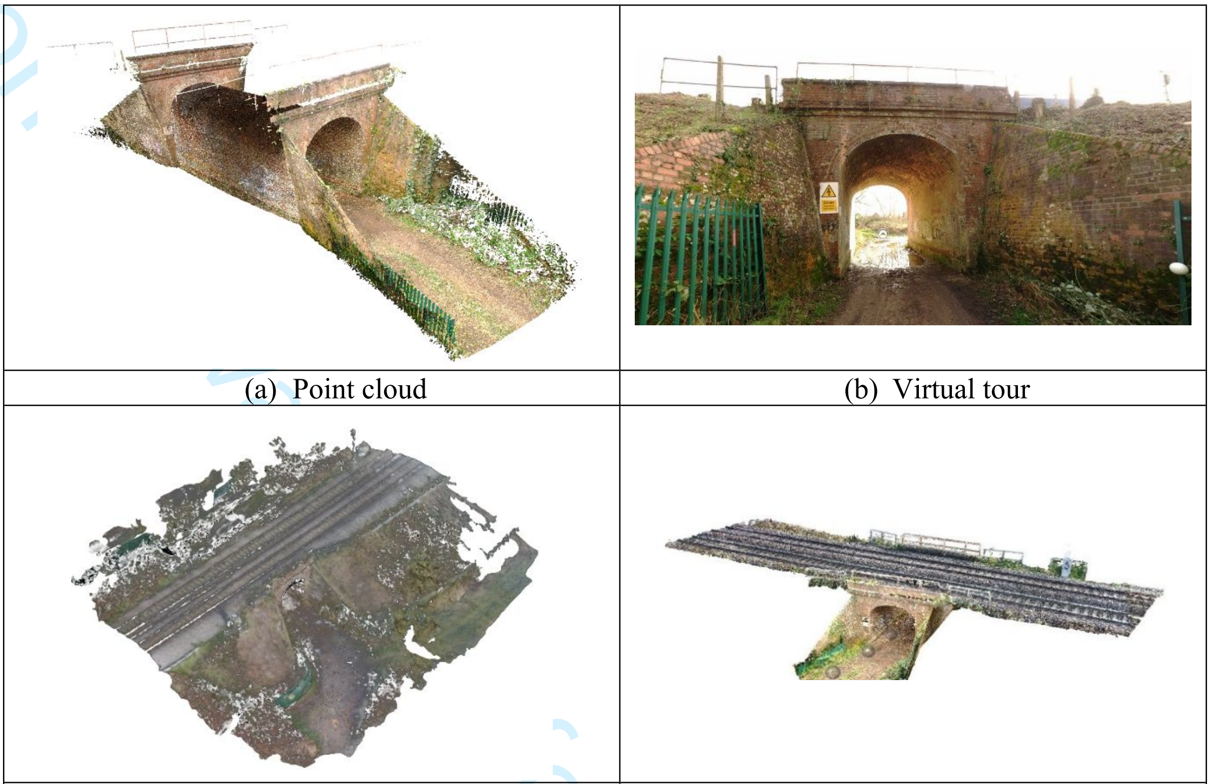
Table 4. Settings in the thermographic camera for FLIR T640

Settings	Values
Object distance	2 meters
Relative humidity	79
Atmospheric temperature	14
Relative temperature	23
Emissivity	0.91

Step 3: Data processing

The point cloud datasets from the FARO laser scanner were registered using FARO SCENE to generate a single 3D point cloud of the bridges. Colour information based on the 360 images was added that every point in the point cloud data was coloured with Red-Green-Blue (RGB) values. The UAV data was processed using the commercial software of Pix4Dsurvey (PIX4D, 2021), and it was then integrated with the data collected from TLS using Recap Pro (Autodesk, 2021) to form a holistic model cover top and underside of the bridge.

3D Vista is used to create an interactive panoramic virtual tour of the project, and thermal images were processed and tuned by ResearchIR MAX software. The Gaussian smoothing filter and the histogram equalisation function were applied to the thermal images. The former function is to minimise the background noise of images and facilitate the view of small objects, and the latter function is to distribute the intensities on the histogram, which results in enhancing the thermal contrast of images. Examples of processed datasets can be seen in Figure 5.



(a) Point cloud (b) Virtual tour (c) UAV (d) Integrated UAV and TLS

Figure 5. Examples of processed datasets for Bridge 2 and in phase 1

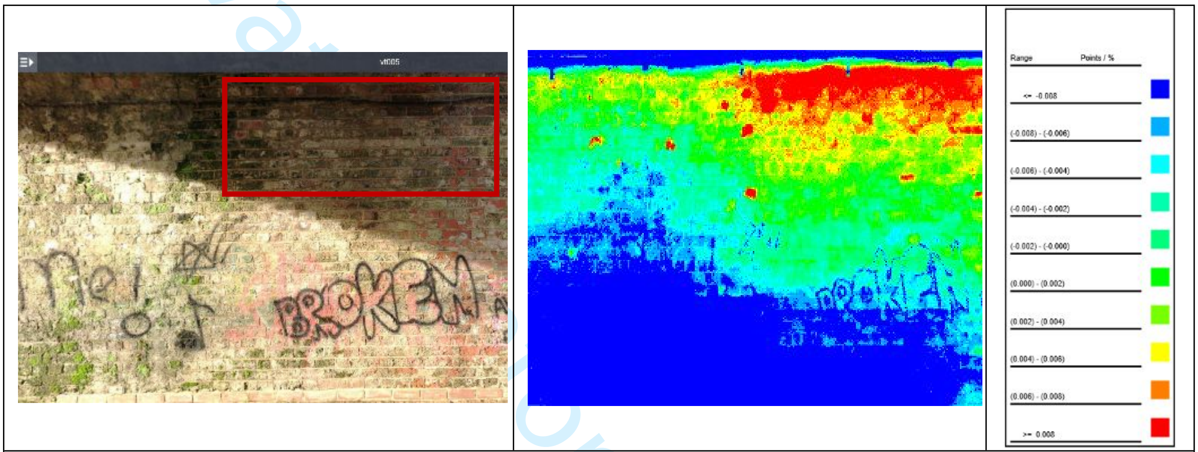
Step 4: Data analysis and reporting

The case study suggested that vegetation, spalling, cracks, loss of section and defective joints can be sufficiently identified and recorded in the 360-degree virtual tour by inspectors. Figure 6 shows examples of the identified defects highlighted by white circles. Assessing areas affected by bulging and spalling as well as identifying the cracks, loss of section, defective joints and deformation requires more detailed analysis through the point cloud data. Moreover, the presence of water penetration can be analysed through the IRT analysis. In Figure 7a and Figure 7b, examples of identified spalling in this research are presented. Figure 7c demonstrate the cloud to cloud analysis for Bridge 1 to investigate any deterioration between phase 1 and phase 3 of this study. However, the analysis delineates that no detectable changes have occurred in this timeframe. Figure 8 demonstrates the identified moisture in Bridge 5 and Bridge 6.

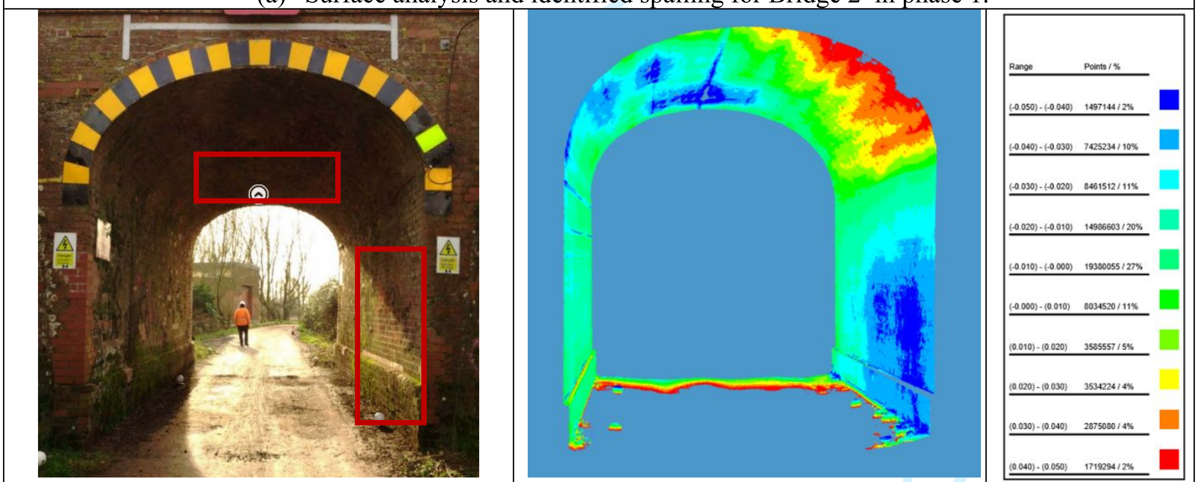
(a) Spalling | (b) Loss of section

Bridge 03

Figure 6. Example of identified defects in the 360-degree virtual tour for Bridge 3 in phase 3.



(a) Surface analysis and identified spalling for Bridge 2 in phase 1.



(b) Surface analysis and identified spalling for Bridge 1 in phase 1`.

(c) Cloud to cloud analysis for Bridge 1 in phase 1 and phase 3

Figure 7. Examples of identified defects by comparing heat maps with 360-degree virtual tours for Bridge 2.

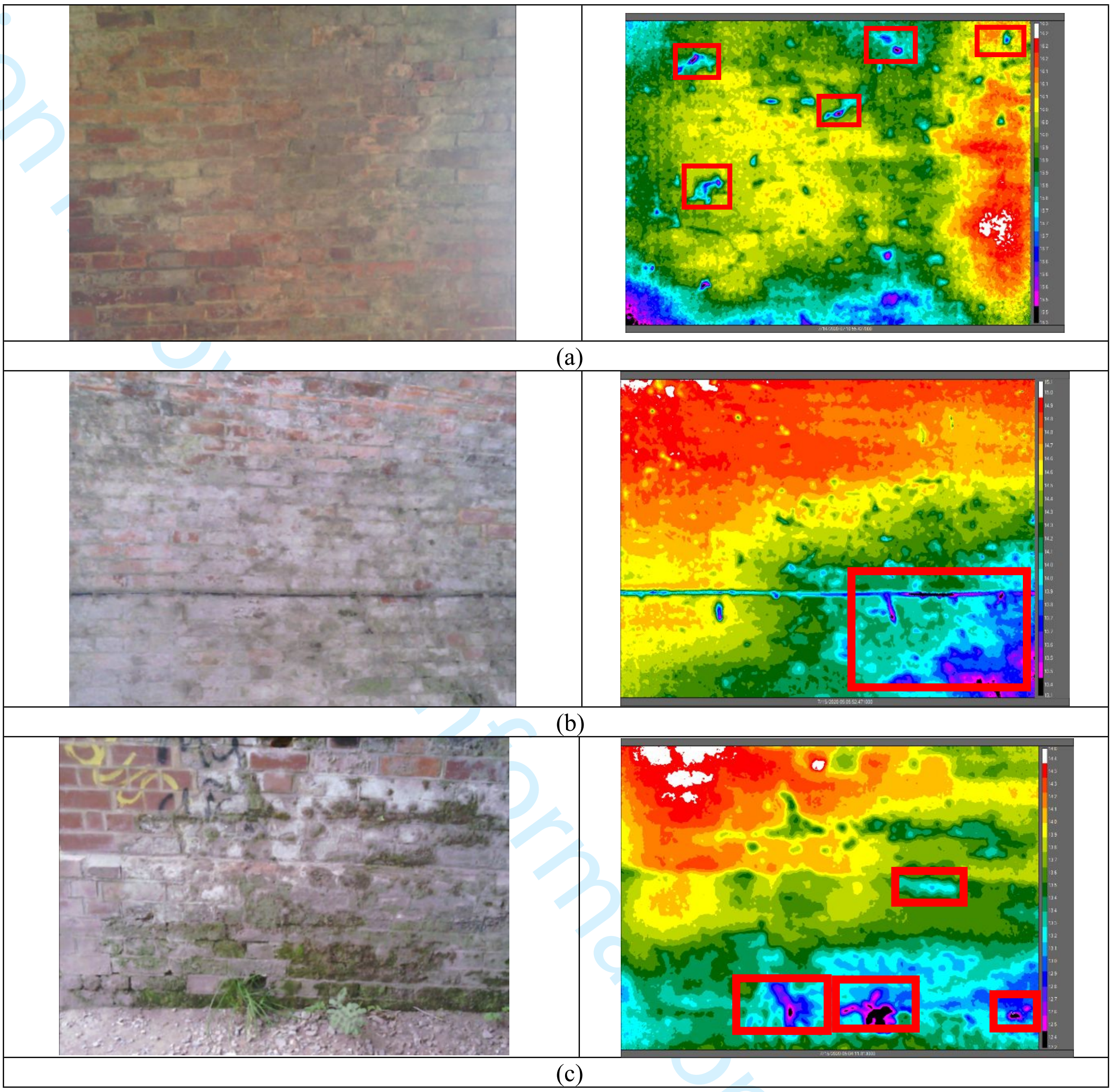


Figure 8. Examples of identified moisture in Bridge 5 and Bridge 6 in phase 3.

5 Discussion

The current masonry railway bridges inspection (i.e. Superficial Inspection and General Inspection) mainly depends on subjective assessments of inspectors, while any incomplete information collected during the inspection can easily result in inconsistency of assessment outcomes with potential disastrous consequences. The proposed framework offers a consistent approach and complete record of assets, and the proposed analysis methods require fewer needs of subjective interpretations due to the quantitative nature of the analysis outcome. The captured data can be shared with inspectors who have not even visited the asset, and their input can be used to analyse the findings while the conventional inspection is only limited to the inspectors on-site, and the knowledge transfer to successive inspectors is difficult. This is particularly important where transportation agencies globally have limited qualified inspectors (Omer *et al.*, 2019). The major novelty of the research is the establishment of the comprehensive and practical framework for the masonry bridge inspection that has been evaluated through field studies and offers a tangible contribution to the theory and practice of infrastructure asset management.

The reliability of documentation created by 360-degree imaging is important when it comes to the allocation of resources for maintenance and construction. The conventional reporting format is quite restrictive in terms of a full and detailed understanding of the wider environment and the overall context of the asset when reviewed by the asset management teams in offices. The focus of reports in conventional inspection is usually on the inside of the bridge, and they only provide a partial record of the bridge condition. However, the digital approach also includes the surrounding environment (including the topside), enabling the bridge to be understood within the context of its comprehensive settings. Compared to a current examination report, the 360-degree virtual tour offers an interactive and easy to understand format, especially for those who have not yet visited the bridge. The digital capture approach, including 360 imaging, TLS and UAV, can be deployed consistently over time to ensure thorough and consistent inspections. The additional data after each inspection can be easily integrated into the previous outputs to show the condition of a bridge over time and to allow for further analysis between inspections.

The quality of inspection will improve due to the high-level accuracy and resolution of point cloud datasets and 360-degree images of the asset. The cost of an inspection will fall when the data acquisition process is standardised and digital capture equipment becomes more affordable. Moreover, the site visit can be carried out by qualified digital operators instead of qualified Inspection Engineers. The actual inspection can be performed remotely by qualified engineers to improve overall efficiency and productivity. Furthermore, the captured data can be stored and revisited over time to inform more detailed levels of analysis, which presents a strong business case to adjust the interval of the current inspection regime, i.e. the reduced need for general inspection as the digital superficial inspection can meet the majority of the requirements of the general inspection.

The knowledge of the technical capabilities to tackle the challenges and limitations in the conventional inspection regimes obtained from the field studies is a significant contribution to practice.

Further technical recommendations are detailed below:

Preparation and data acquisition

The case study indicated that it is critical to take the following environmental conditions into account during the preparation and data acquisition.

Site condition

Although the digital approach allows inspecting the assets at height and distance without the need to deploy special cranes or scaffolding, access to bridges often requires a long walk on muddy side roads with heavy and expensive equipment. In some cases, the operator might need to stay days on sites for a large asset, e.g. a multi-span viaduct. Therefore, planning for transport and logistics is always required. Traffic management should also be considered to avoid constant interruptions during the capture.

Vegetation, obstructions (e.g., fences) are concerns for digital capture. Excessive vegetation obscures the bridge surface and prevents data acquisitions. Vegetation, such as overhanging trees, obscures many structural elements such as wing walls and parapets from UAV. By combining the UAV and TLS dataset, a comprehensive point cloud is still able to be created. However, it is recommended that vegetation needs to be routinely cleared before attending the site where time and cost permits to achieve a fully captured examination.

If the obstructions are permanent and unable to be removed or would cause a potential risk of trespass on the line, such as fence removal, Occlusions in data from obstructions can be mitigated by varying scanning locations to capture as much of each structure as possible.

Weather conditions

During daylight captures, there is a single source of bright light in an otherwise balanced scene (e.g., low sun or bright sunshine in the entrance to an unlit wide underbridge). Big differences between the light and dark values leave dark shadows or highlights. High Dynamic Range (HDR) images are recommended while using the TLS. For areas where the use of HDR alone are not sufficient, LED panels (output: 1100 Lumens with an average light intensity of 57 Lux) attached to individual tripod legs via specialist photography clamps are used to provide even lighting across the entire 360-degree scan field of view. Point cloud data and thermography images are not dependent on the lighting condition. The capture can take place in poor light conditions without the need for additional site lighting. The resulting point cloud, although not colourised, can still be utilised for further analysis.

Precipitation observed to be over the acceptable level of the TLS IP rating (IP54) was encountered at some structures, resulting in the deployment of a canopy to ensure capture could be completed. Although the canopy is visible in the dataset, it has no significant adverse effect on the point cloud datasets. In some visits, it appeared that the bridge was subject to flood, and the surveys were in very muddy and sometimes submerged conditions. Whilst the structure itself was successfully captured to the same level of detail as other assets, and the water obscured a large proportion of the surrounding land and base of underside walls. If the floodwaters had been clear, light refracting through the water would have made results unreliable. Where areas of ground were saturated/muddy but not flooded, light reflected off of the surface, reducing the number of points recorded.

Data processing, data analysis and reporting

All captured data has to be processed to create viewable results (point cloud registration, 360 virtual tours and thermal analysis). It can be done through the software provided by the device manufacturer or specialist suppliers. The data size is very large (Gigabytes for each bridge), and the processing time is in hours with a high-performance desktop workstation, which has to be taken into account in the workflow. UAV offers significant advantages to capture the topside (trackside) of the bridge; the resultant images can be integrated with TLS data to form a complete picture of a bridge asset. Despite the different accuracy levels between the UAV data and TLS data might reduce the overall precision of the integrated model. 360-degree images obtained from TLS while capturing point cloud data provide comprehensive and high-quality visual information of an asset and its surrounding for each inspection. The virtual tour offers an integrated environment to identify, record and visualise common masonry defects such as bulging, crack, spalling, joint defect, vegetation, and loss of section, as well as engineering comments as part of the inspection.

The point cloud analysis can detect small surface changes, such as bulging, together with high precision location data, it can also detect displacement /movement between multiple scans, and Thermal imaging is effective to detect certain defects related to moisture and water penetration. However, the images have to be captured at a particular time of the day (i.e. after sunset), which might not be suitable for a routine inspection.

6 Conclusion

The conventional visual inspection is time-consuming, lack consistency, prone to human errors and safety concerns. The aim of this research was to develop a framework whereby complementary NDT technologies are adopted to digitise the visual inspection of masonry railway bridges in the UK. An exploratory case study adopted in this research allowed to collect empirical data. The findings from the literature and empirical studies were used to develop a masonry bridge inspection framework. This framework has four steps: (1) preparation for data collection, (2) data acquisition, (3) data processing, and (4) data analysing and reporting. The proposed digitally enhanced visual inspection framework presents an entirely new approach by taking advantage of the existing digital capture technologies for the asset inspection process. The case study demonstrated a successful practical implementation of the framework on five bridges in the UK. The framework facilitates fast, easy and reliable inspection of bridges without the necessity of inspectors visiting the asset and the approach enables inspectors to understand the bridge within the context of its comprehensive setting. It offers a consistent and safe process supported by qualitative and quantitative analysis methods while it can be less costly in the long run than conventional visual inspection. The first objective of this study was addressed by exploring difficulties of conventional inspection regimes through the literature and empirical data collected from workshop and document review. The second objective of this research was achieved by implementing the proposed framework in a field study. The feasibility of utilising complementary optical methods to identify certain types of defects in masonry railway bridges was successfully demonstrated.

The main limitation of the study is the limited assets used in the case study. Most of the bridges in the case study are small single-span underbridges. It is envisaged that the framework will face challenges when applies to a large bridge at a significant height, and UAV is the primary method for data capture. The high accuracy point cloud data and 360 images might not be readily available, and different capture devices (UAV payload) might be required to overcome the problems. For future development, other emerging imaging devices, such as Matterport and Geoslam Zeb, offer rapid capture for 360 images and low-resolution point cloud, which might be suitable for the specific surveying tasks, should be investigated. A fully automated scan to BIM process can be developed to transform the point cloud model to fully-fledged BIM models. Computer vision-based machine learning techniques can be deployed to assist inspection engineers to identify the common defects.

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References

3D VISTA. 2021. *Virtual Tour Pro* [Online]. Available: https://www.3dvista.com/en/products/virtualtour [Accessed 3rd July 2021].

ABDALLAH, A. M., ATADERO, R. A. & OZBEK, M. E. 2022. A state-of-the-art review of bridge inspection planning: Current situation and future needs. *Journal of Bridge Engineering,* 27**,** 03121001.

ABDELKHALEK, S. & ZAYED, T. 2021. Performance assessment model of non-destructive technologies in inspecting concrete bridge decks. *Structure and Infrastructure Engineering***,** 1-22.

AGDAS, D., RICE, J. A., MARTINEZ, J. R. & LASA, I. R. 2016. Comparison of visual inspection and structural-health monitoring as bridge condition assessment methods. *Journal of Performance of Constructed Facilities,* 30**,** 04015049.

ARTUS, M. & KOCH, C. 2020. State of the art in damage information modeling for RC bridges–A literature review. *Advanced Engineering Informatics,* 46**,** 101171.

ARYAN, A., BOSCHÉ, F. & TANG, P. 2021. Planning for terrestrial laser scanning in construction: A review. *Automation in Construction,* 125**,** 103551.

ASADI, K., SURESH, A. K., ENDER, A., GOTAD, S., MANIYAR, S., ANAND, S., NOGHABAEI, M., HAN, K., LOBATON, E. & WU, T. 2020. An integrated UGV-UAV system for construction site data collection. *Automation in Construction,* 112**,** 103068.

BAKHSHI, S., CHENAGHLOU, M. R., RAHIMIAN, F. P., EDWARDS, D. J. & DAWOOD, N. 2022. Integrated BIM and DfMA parametric and algorithmic design based collaboration for supporting client engagement within offsite construction. *Automation in Construction,* 133**,** 104015.

BAQERSAD, J., POOZESH, P., NIEZRECKI, C. & AVITABILE, P. 2017. Photogrammetry and optical methods in structural dynamics–A review. *Mechanical Systems and Signal Processing,* 86**,** 17-34.

BERTOLA, N. J. & BRÜHWILER, E. 2021. Risk-based methodology to assess bridge condition based on visual inspection. *Structure and Infrastructure Engineering***,** 1-14.

BHATLA, A., CHOE, S. Y., FIERRO, O. & LEITE, F. 2012. Evaluation of accuracy of as-built 3D modeling from photos taken by handheld digital cameras. *Automation in Construction,* 28**,** 116-127.

BIRGONUL, Z. 2021. A receptive-responsive tool for customizing occupant's thermal comfort and maximizing energy efficiency by blending BIM data with real-time information. *Smart and sustainable built Environment*.

BRILAKIS, I., LOURAKIS, M., SACKS, R., SAVARESE, S., CHRISTODOULOU, S., TEIZER, J. & MAKHMALBAF, A. 2010. Toward automated generation of parametric BIMs based on hybrid video and laser scanning data. *Advanced Engineering Informatics,* 24**,** 456-465.

BULUT, M. B., WILKINSON, S., KHAN, A., JIN, X.-H. & LEE, C. L. 2021. Thermal performance of retrofitted secondary glazed windows in residential buildings–two cases from Australia. *Smart and sustainable built environment*.

CHA, G., PARK, S. & OH, T. 2019. A terrestrial lidar-based detection of shape deformation for maintenance of bridge structures. *Journal of Construction Engineering and Management,* 145**,** 04019075.

CHMIELEWSKI, R. & MUZOLF, P. 2021. Analysis of degradation process of a railway steel bridge in the final period of its operation. *Structure and Infrastructure Engineering***,** 1-17.

CLOUDCOMPARE. 2021. *CloudCompare: 3D point cloud and mesh processing software* [Online]. Available: https://www.danielgm.net/cc/ [Accessed 4th June 2021].

DABOUS, S. A. & FEROZ, S. 2020. Condition monitoring of bridges with non-contact testing technologies. *Automation in Construction,* 116**,** 103224.

EIRIS, R., GHEISARI, M. & ESMAEILI, B. 2018. PARS: Using augmented 360-degree panoramas of reality for construction safety training. *International journal of environmental research and public health,* 15**,** 2452.
ELGHAISH, F., HOSSEINI, M. R., MATARNEH, S., TALEBI, S., WU, S., MARTEK, I., POSHDAR, M. & GHODRATI, N. 2021. Blockchain and the 'Internet of Things' for the construction industry: research trends and opportunities. *Automation in Construction,* 132**,** 103942.
ELGHAISH, F., MATARNEH, S., TALEBI, S., KAGIOGLOU, M., HOSSEINI, M. R. & ABRISHAMI, S. 2020. Toward digitalization in the construction industry with immersive and drones technologies: a critical literature review. *Smart and sustainable built Environment*.
FARO. 2021. *FARO SCENE Software* [Online]. Available: https://www.faro.com/en/Products/Software/SCENE-Software [Accessed 3rd June 2021].
FLIR. 2021. *ResearchIR* [Online]. Available: https://www.flir.co.uk/support/products/researchir#Overview [Accessed 3rd June 2021].
GABARA, G. & SAWICKI, P. 2018. A new approach for inspection of selected geometric parameters of a railway track using image-based point clouds. *Sensors,* 18**,** 791.
GARRIDO, I., LAGÜELA, S. & ARIAS, P. 2018. Infrared thermography's application to infrastructure inspections. *Infrastructures,* 3**,** 35.
GEO-PLUS. 2021. *VisionLidar* [Online]. Available: https://www.geo-plus.com/point-cloud-software/ [Accessed 2nd June 2021].
GETULI, V., CAPONE, P., BRUTTINI, A. & RAHIMIAN, F. P. 2021. On-demand generation of as-built infrastructure information models for mechanised Tunnelling from TBM data: A computational design approach. *Automation in Construction,* 121**,** 103434.
GHAURI, P. N. & GRØNHAUG, K. 2005. *Research methods in business studies: A practical guide,* London, UK, Pearson Education.
HEARN, G. 2007. *Bridge inspection practices*, Transportation Research Board.
JANKŮ, M., BŘEZINA, I. & GROŠEK, J. 2017. Use of infrared thermography to detect defects on concrete bridges. *Procedia engineering,* 190**,** 62-69.
JO, B.-W., LEE, Y.-S., JO, J. H. & KHAN, R. M. A. 2018. Computer vision-based bridge displacement measurements using rotation-invariant image processing technique. *Sustainability,* 10**,** 1785.
JOHANSEN, K. W., NIELSEN, R., SCHULTZ, C. & TEIZER, J. 2021. Automated activity and progress analysis based on non-monotonic reasoning of construction operations. *Smart and sustainable built environment*.
KUZIN, A., VALKOV, V. & KAZANTSEV, A. 2018. Satellite-based techniques for monitoring of bridge deformations. *Journal of Physics: Conference Series,* 1118**,** 012022.
LAGÜELA, S., DÍAZ-VILARIÑO, L., ARMESTO, J. & ARIAS, P. 2014. Non-destructive approach for the generation and thermal characterization of an as-built BIM. *Construction and Building Materials,* 51**,** 55-61.
LIU, P., CHEN, A. Y., HUANG, Y.-N., HAN, J.-Y., LAI, J.-S., KANG, S.-C., WU, T.-H., WEN, M.-C. & TSAI, M.-H. 2014. A review of rotorcraft unmanned aerial vehicle (UAV) developments and applications in civil engineering. *Smart Structures and Systems,* 13**,** 1065-1094.
MAHMOUDI, E., STEPIEN, M. & KÖNIG, M. 2021. Optimisation of geotechnical surveys using a BIM-based geostatistical analysis. *Smart and sustainable built Environment*.
MARMO, F., DEMARTINO, C., CANDELA, G., SULPIZIO, C., BRISEGHELLA, B., SPAGNUOLO, R., XIAO, Y., VANZI, I. & ROSATI, L. 2019. On the form of the Musmeci's bridge over the Basento river. *Engineering Structures,* 191**,** 658-673.
MEOLA, C. 2007. Infrared thermography of masonry structures. *Infrared physics & technology,* 49**,** 228-233.
NETWORK RAIL 2010. Handbook for the examination of structures.
OMAR, T., NEHDI, M. L. & ZAYED, T. 2018. Infrared thermography model for automated detection of delamination in RC bridge decks. *Construction and Building Materials,* 168**,** 313-327.

OMER, M., MARGETTS, L., HADI MOSLEH, M., HEWITT, S. & PARWAIZ, M. 2019. Use of gaming technology to bring bridge inspection to the office. *Structure and Infrastructure Engineering,* 15**,** 1292-1307.
OSKOUIE, P., BECERIK-GERBER, B. & SOIBELMAN, L. 2016. Automated measurement of highway retaining wall displacements using terrestrial laser scanners. *Automation in Construction,* 65**,** 86-101.
PARK, J., KIM, P., CHO, Y. K. & KANG, J. 2019. Framework for automated registration of UAV and UGV point clouds using local features in images. *Automation in Construction,* 98**,** 175-182.
PHARES, B. M., WASHER, G. A., ROLANDER, D. D., GRAYBEAL, B. A. & MOORE, M. 2004. Routine highway bridge inspection condition documentation accuracy and reliability. *Journal of Bridge Engineering,* 9**,** 403-413.
POPESCU, C., TÄLJSTEN, B., BLANKSVÄRD, T. & ELFGREN, L. 2019. 3D reconstruction of existing concrete bridges using optical methods. *Structure and Infrastructure Engineering,* 15**,** 912-924.
PUPPALA, A. J., CONGRESS, S. S., BHEEMASETTI, T. V. & CABALLERO, S. R. 2018. Visualization of civil infrastructure emphasizing geomaterial characterization and performance. *Journal of Materials in Civil Engineering,* 30**,** 04018236.
RAJA, B. N. K., MIRAMINI, S., DUFFIELD, C., SOFI, M., MENDIS, P. & ZHANG, L. 2020. The influence of ambient environmental conditions in detecting bridge concrete deck delamination using infrared thermography (IRT). *Structural Control and Health Monitoring,* 27.
RASHIDI, M., MOHAMMADI, M., SADEGHLOU KIVI, S., ABDOLVAND, M. M., TRUONG-HONG, L. & SAMALI, B. 2020. A decade of modern bridge monitoring using terrestrial laser scanning: Review and future directions. *Remote Sensing,* 12**,** 3796.
REN, G., DING, R. & LI, H. 2019. Building an ontological knowledgebase for bridge maintenance. *Advances in Engineering Software,* 130**,** 24-40.
RIVEIRO, B., DEJONG, M. & CONDE, B. 2016. Automated processing of large point clouds for structural health monitoring of masonry arch bridges. *Automation in Construction,* 72**,** 258-268.
ROBERT, R. 2007. Traditional inspection techniques: The foundation of structural health monitoring. *Structural Health Monitoring,* 17**,** 1225–1244.
SACKS, R., KEDAR, A., BORRMANN, A., MA, L., BRILAKIS, I., HÜTHWOHL, P., DAUM, S., KATTEL, U., YOSEF, R. & LIEBICH, T. 2018. SeeBridge as next generation bridge inspection: overview, information delivery manual and model view definition. *Automation in Construction,* 90**,** 134-145.
SÁNCHEZ-APARICIO, L. J., BAUTISTA-DE CASTRO, Á., CONDE, B., CARRASCO, P. & RAMOS, L. F. 2019. Non-destructive means and methods for structural diagnosis of masonry arch bridges. *Automation in Construction,* 104**,** 360-382.
SELBESOGLU, M., BAKIRMAN, T. & GOKBAYRAK, O. 2016. Deformation measurement using terrestrial laser scanner for cultural heritage. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences,* 42.
SHAZALI, A. S. A. & TAHAR, K. N. 2019. Virtual 3D model of Canseleri building via close-range photogrammetry implementation. *International Journal of Building Pathology and Adaptation,* 38**,** 217-227.
SOKOLOVIĆ, N. M., PETROVIĆ, M., KONTIĆ, A., KOPRIVICA, S. & ŠEKULARAC, N. 2021. Inspection and assessment of masonry arch bridges: Ivanjica case study. *Sustainability,* 13**,** 13363.
TANG, P., HUBER, D. & AKINCI, B. 2010. Characterization of laser scanners and algorithms for detecting flatness defects on concrete surfaces. *Journal of Computing in Civil Engineering,* 25**,** 31-42.
YIN, R. K. 2013. *Case study research: Design and methods,* California, USA, SAGE Publications.
ZELLMER-BRUHN, M., CALIGIURI, P. & THOMAS, D. C. 2016. *From the editors: Experimental designs in international business research,* London, Springer.

Reviewers Comments to Author	Authors Response to Reviewers Comments
1. Originality: Does the paper contain new and/or significant information adequate to justify publication?: **Yes, just the author needs to highlight this in the introduction**	The reviewer's comment is well acknowledged and the authors are grateful for the insight. As per the reviewer's comment, we have added the following statement to the Introduction section "*This novel research is amongst very few studies that have utilised complementary optical methods in the field and have provided a comprehensive, practical framework by which other researchers and transportation agencies can tackle the limitations posed by conventional inspection regimes.*"
2. Relationship to Seminal Literature: Does the paper demonstrate an adequate understanding of the relevant literature in the field and cite an appropriate range of literature sources? Is any significant work ignored?: **Yes, but more recent papers should be added**	The researchers are grateful to the reviewer for providing the comment and appreciate the comment. As per the reviewer's suggestions, we have added the following references: ABDALLAH, A. M., ATADERO, R. A. & OZBEK, M. E. 2022. A state-of-the-art review of bridge inspection planning: Current situation and future needs. *Journal of Bridge Engineering,* 27**,** 03121001. CHMIELEWSKI, R. & MUZOLF, P. 2021. Analysis of degradation process of a railway steel bridge in the final period of its operation. Structure and Infrastructure Engineering, 1-17. SOKOLOVIĆ, N. M., PETROVIĆ, M., KONTIĆ, A., KOPRIVICA, S. & ŠEKULARAC, N. 2021. Inspection and assessment of masonry arch bridges: Ivanjica case study. *Sustainability,* 13**,** 13363. ELGHAISH, F., HOSSEINI, M. R., MATARNEH, S., TALEBI, S., WU, S., MARTEK, I., POSHDAR, M. & GHODRATI, N. 2021. Blockchain and the 'Internet of Things' for the construction

	industry: research trends and opportunities. *Automation in Construction*, 132, 103942.
3. Research Methodology: Is the paper's argument built on an appropriate base of theory, concepts, or other ideas? Has the research or equivalent intellectual work on which the paper is based been well designed? Are the methods employed, robust, defendable and appropriate?: **I advise that authors should present the research methods in a flowchart**	The authors are grateful for the reviewer's comment. Acknowledging the reviewer's comment, we have added Figure 1 to the Method section. The title of Figure 1 is "Research Method" and it presents the research design and method.
4. Results: Are results presented clearly and analysed appropriately? Do the conclusions adequately tie together all elements of the paper?: **Yes, but results should be presented against the proposed objective of the article**	The researchers are thankful to the reviewer for the comment. Acknowledging the comment, the authors have added a new statement to the Conclusion section. This is to make sure that the results are present against the proposed objectives of the article. The statement is as follows: "*The first objective of this study was persuaded by exploring difficulties of conventional inspection regimes through the literature and empirical data collected from workshops, interviews and document review. The second objective of this research was addressed by implementing the proposed framework in the field. Data was acquired from IRT, TLS, 360-degree imaging and UAV. The feasibility of utilising complementary optical methods to identify certain types of defects in masonry railway bridges was demonstrated.*"
5. Implications for research, practice and/or society: Does the paper identify clearly any implications for research, practice and/or society? Does the paper bridge the gap between theory and practice? How can the research be used in practice (economic and commercial impact), in teaching, to influence public policy, in research (contributing to the body of knowledge)? What is the impact upon society (influencing public attitudes, affecting quality of life)? Are these implications consistent with the findings and	The authors appreciate the reviewer's comment. The authors have added new statements to the Discussion section to make sure that the implications of this research are clearly communicated. More specifically, the following statements have been added: "*The major novelty of the research is the establishment of the comprehensive and practical framework for the masonry bridge inspection that has been evaluated through field studies and offers a tangible contribution to the theory and practice of*

conclusions of the paper?: **This should be highlighted in a separate section**	*infrastructure asset management*" "*The knowledge of the technical capabilities to tackle the challenges and limitations in the conventional inspection regimes obtained from the field studies is a significant contribution to practice.*"
6. Quality of Communication: Does the paper clearly express its case, measured against the technical language of the field and the expected knowledge of the journal's readership? Has attention been paid to the clarity of expression and readability, such as sentence structure, jargon use, acronyms, etc. Do the figures/tables aid the clarity of the paper?: **Good, some figures quality should be improved**	The researchers appreciate and acknowledge the reviewer's comment. We have now updated the figures to ensure they are in a good quality.

Reviewers Comments to Author	Authors Response to Reviewers Comments
I would like to congratulate the authors on their excellent work. I have read articles on similar subjects, but none were as clear or relevant as yours. I look forward to reading more from your research. Best wishes.	The authors are thankful for and appreciate the reviewer's comment.
1. Originality: Does the paper contain new and/or significant information adequate to justify publication?: **The paper contains new and significant information about the application of digital technology for bridge inspection purposes.**	The reviewer's comment is well acknowledged and the authors are grateful for the insight.
2. Relationship to Seminal Literature: Does the paper demonstrate an adequate understanding of the relevant literature in the field and cite an appropriate range of literature sources? Is any significant work ignored?: **To the best of my knowledge, the manuscript covers all important literature in the field.**	The researchers are grateful to the reviewer for providing the positive comment.
3. Research Methodology: Is the paper's argument built on an appropriate base of theory, concepts, or other ideas? Has the research or equivalent intellectual work on which the paper is based been well designed? Are the methods employed, robust, defendable and appropriate?: **The manuscript provides a detailed explanation of the adopted methods and their implementation.**	The authors are grateful for the reviewer's comment.
4. Results: Are results presented clearly and analysed appropriately? Do the conclusions adequately tie together all elements of the paper?: **The manuscript presents the results clearly.**	The researchers are thankful to the reviewer for the comment.
5. Implications for research, practice and/or society: Does the paper identify clearly any implications for research, practice and/or society? Does the paper bridge the gap between theory and practice? How can the research be used in practice (economic and commercial impact), in teaching, to influence public policy, in research	The authors appreciate the reviewer's comment.

(contributing to the body of knowledge)? What is the impact upon society (influencing public attitudes, affecting quality of life)? Are these implications consistent with the findings and conclusions of the paper?: **The manuscript clearly demonstrates the implication of the findings in practice.**	
6. Quality of Communication: Does the paper clearly express its case, measured against the technical language of the field and the expected knowledge of the journal's readership? Has attention been paid to the clarity of expression and readability, such as sentence structure, jargon use, acronyms, etc. Do the figures/tables aid the clarity of the paper?: **The communications are of high quality. The only point that the authors may consider is making the statements about the study contributions more consistent. In the abstract, consistency and safety are addressed as the focal points of the developed framework. In the introduction section, costs, unrealistic expectations, improper use and lack of practicality of the research in the past have been stated as the gaps in this area. Later on, the research objectives are presented as overcoming the difficulties and limitations of conventional inspection procedures and demonstrating the feasibility of deploying multiple optical methods for visual inspection purposes. The same reads in the research gap section on page 5.**	The authors are appreciative of the reviewer's insightful comment. The authors have attempted to comprehensively address this comment. Acknowledging the reviewer's comment, the authors have changed the Findings in the abstract as follows "*A digitally enhanced visual inspection framework is developed by utilising complementary optical methods. Compared to the conventional inspection regimes, the new approach requires fewer subjective interpretations due to containing both qualitative and quantitative analysis. Also, it is safer and needs fewer operators on site because the actual inspection can be carried out remotely and it allows inspecting the assets at height and distance.*" Moreover, the authors have made certain changes in the Discussion section to ensure that the contributions of this study are consistent. More specifically, the following statements have been added to the discussion section: "*The major novelty of the research is the establishment of the comprehensive and practical framework for the masonry bridge inspection that has been evaluated through field studies and offers a tangible contribution to the theory and practice of infrastructure asset management*" "*The knowledge of the technical capabilities to tackle the challenges and limitations in the conventional inspection regimes obtained from the field studies is a significant contribution to practice.*"

7. **This section also states that "the above gap is one of the issues behind the low acceptance of optical methods amongst railway agencies". The latter statement is a strong one that is supported neither by adding references nor explaining the reasons for such inference.**	The reviewer's comments are well acknowledged and the authors are grateful for this insightful comment. The authors have made changes to address this concern. The statement in question has changed as follows: "*Optical methods are rarely accepted by railway agencies (Abdallah et al., 2022). The reason behind this low acceptance can be traced back to the above gap, as concurred by (Sánchez-Aparicio et al., 2019)*." The authors have soften the statement and have added recent references to support the argument.

The authors would like to kindly thank the reviewer for the valuable comments. The authors tried their best to cover all the concerns raised by the reviewer.