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A survey of emerging technologies for the future of routine visual inspection of bridge structures

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ABSTRACT: Bridges are important infrastructure assets that are vital for the connectivity of communities. Visual inspections remain a key method for bridge condition monitoring. However, visual inspections are often considered to be highly subjective and therefore alternative technologies are often proposed as a means of replacing or enhancing current visual inspection practices. This paper presents the results of a survey which aims to document the emerging trends for future visual inspection practice related to bridges. The implementation of new technological solutions has the potential to improve the quality of inspection data, reduce the safety risks posed to visual inspectors by moving more of the process off-site and improve the quantification of the rate of change in condition. The survey covers two key topics: (i) Emerging data capture methods and (ii) Emerging data analysis methods. Emerging data capture methods include: use of uncrewed vehicles, 360° cameras, photogrammetry, laser scanners, point cloud systems, and Interferometric Synthetic Aperture Radar (InSar). Emerging data analysis methods include: remote inspection, augmented reality and virtual reality, digital image correlation, artificial intelligence, Big Data and the Internet of Things. The survey concludes with a detailed discussion on the opportunities and barriers to implementation of the reviewed technologies and approaches.

1 INTRODUCTION

1.1 *Research motivation*

Bridges are important components of transportation infrastructure systems. Deterioration of bridge assets due to environmental actions and ageing of the stock, combined with increasing loads, is of concern to those seeking to maintain and manage these structures. Deteriorating condition can have a significant impact on structural capacity, and analysis carried out by the RAC Foundation found that over 3,000 council-managed road bridges were deemed ‘substandard’ across Great Britain (RAC 2020). Meanwhile, in the United States, the average age of bridges is approaching 50 years and 7.5% percent are deemed to be in poor condition (ASCE 2021).

Determining the condition of bridge assets remains highly reliant on visual inspection which itself is highly reliant on the judgement and experience of inspectors (e.g. see Moore et al. 2001, Lea & Middleton 2002, Graybeal et al. 2002, Middleton 2004, Bennetts 2019, Bennetts et al. 2016, Bennetts et al. 2020). The metrics which result from visual inspections can be used to assess the change of condition at stock or regional level but such processes can be unreliable for detecting the change of condition for an individual structure (cf. Bennetts et al. 2018, Bennetts et al. 2021). Undertaking visual inspections can cause network disruption and put inspectors at risk, especially on highways that have been converted to ‘all lane running’ and therefore always require lane closures even for short duration inspections. Therefore, developing processes to reduce the time spent on-site by human inspectors would be beneficial and reduce health and safety risk.

Visual inspection can be broken down into the following six fundamental stages: (1) ‘planning and preparation’, (2) ‘image/data capture’, (3) ‘defect identification’, (4) ‘defect grading’, (5) ‘interpretation of change over time’, and (6) ‘maintenance decision-making’ (cf. Bennetts 2019 and Nepomuceno et al. 2021). A further distinction can be made between ‘data capture’ (which consists of Stage 2), and the latter four stages which could be categorised as ‘data processing’. Data capture is primarily concerned with collecting the relevant sensory information pertinent to bridge condition. Data processing

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relates to how the captured data is analysed to obtain meaningful qualitative and quantitative information and, in some cases, visualise the state of the bridge. These stages were proposed by Bennetts (2019) and supplemented by Nepomuceno et al. (2021). If visual inspections are restructured into such a workflow, and explicitly separated, then adopting technological innovation at each stage would be more achievable.

Increasingly, new technologies are being deployed to augment or replace aspects of these visual inspection stages (e.g. McRobbie et al. 2015). This paper gives an overview of emerging technology trends that may supplement and enhance bridge visual inspection practice. The associated benefits and barriers to implementation are considered. A similar review on emerging digital technologies for climate-resilient infrastructure can be found in Argyroudis et al (2022). In this paper, technologies are divided into two broad groups: (1) 'emerging data capture methods' and (2) 'emerging data analysis methods'. 'Emerging data capture methods' refer to systems or physical devices that can primarily support 'Image capture'. Many of these technologies enable inspectors to collect data more easily and rapidly. It can be argued that with some adaptation, many of the systems in this group are readily available and commercially viable systems and could be adopted for industry practice in the short to medium-term. 'Emerging data analysis methods' refer to promising systems and processes that have the potential to enhance 'data processing' stages.

2 EMERGING DATA CAPTURE METHODS

2.1 *Unmanned Aerial Vehicles (UAVs)*

With rapid technology developments, the performance of UAVs has substantially improved with regards to size, agility and in-flight stability. As UAVs equipped with high-resolution cameras become cheaper and more widely accessible, their application in civil engineering continues to increase (cf. Liu et al. 2014, Ham et al. 2016, Dorafshan & Maguire 2018, Duque et al. 2018, Albeaino et al. 2019, Greenwood et al. 2019, Carrillo-Zapata et al. 2020, Freeman et al. 2021). In the area of bridge inspection, they can primarily help inspectors view inaccessible or hard-to-access places with minimal disturbance. This can potentially reduce safety-related issues for manual inspectors, particularly for large bridges. Various papers have investigated using UAVs for bridge inspection, where they are used in conjunction with other technologies such as 360° cameras (Humpe 2020), thermal imaging (Omar & Nehdi 2017), machine vision (Perry et al. 2020) and laser scanners (Chen et al. 2019).

The ease of utilising a UAV for inspections is greatly dependent on the governing aviation legislation of the jurisdiction where the bridge is located. For example, in the UK, commercial operations involving UAVs are only allowed to be flown by those who have acquired a license, which can be a costly and lengthy process. Furthermore, due to regulatory restrictions, obtaining permission from the Civil Aviation Authority (CAA) to fly a remote-control UAV close to live traffic is difficult; separation distances from 'uninvolved people' are 150 m horizontally, with a vertical 'no fly zone' in place (CAA 2019) (see also the review of Freeman et al. 2021). As a result, the use of UAVs in bridge inspection has mostly been limited to image acquisition at specific locations on a structure (e.g. Seo et al. 2018), or structures such as large rail viaducts where line blockades can be applied and the UAVs bring considerable benefit in being able to review a large area quickly to enable targetted tactile inspection by e.g. roped access teams.

According to an AASHTO survey conducted in 2018, 20 of the 44 responding state Departments of Transportation (DOTs) have integrated UAVs into their daily operations (WTKN 2018). Another 15 DOTs stated that they were testing UAVs to see how they could be used in practice. The Federal Aviation Administration (FAA) granted the NCDOT a waiver in October 2020 to operate UAVs beyond the pilot's visual line of sight while undertaking bridge inspections (NCDOT 2020). Utilisation of UAV technology may allow inspectors to collect high-resolution images in difficult-to-access areas, which may encourage legislative changes regarding their use for inspections.

2.2 *360° cameras*

A 360° camera can simultaneously capture an image in all directions to give a literal 360° view around a certain point. Such cameras are often comprised of multiple wide-angle lenses, with the image from each lens being automatically stitched together to create one spherical image (Huang et al. 2017). The resulting image can be used in a virtual reality (VR) setting by inspectors, enabling convenient inspection of recorded areas by 'looking around' the spherical image (Tan et al. 2018). This provides an alternative to the traditional 'point-and-shoot' method of standard cameras, which can simplify optimal inspection paths around a structure. For example, a high-resolution 360° camera unit mounted on a moving vehicle would have the potential to efficiently gather high-quality image data from the underside of a bridge. 360° cameras are readily accessible, but their use for bridge management is relatively unexplored, with only a few studies reported (e.g. Nishimura et al. 2012, Hada et al. 2017, Humpe 2020).

2.3 *Robotics*

The field of robotics involves physical robots or machines that can autonomously carry out a series of tasks usually performed by humans. Robots are programmed to use sensors and actuators to interact with the physical world. Inspection robots, when properly employed, can further improve inspection techniques by giving more quantitative inspection data than is generally obtained from traditional visual inspection methods (Jo et al. 2018).

In an extensive review of robot inspection systems, Lattanzi & Miller (2017) state that robotic systems must consider three principal challenges: (1) 'mobility', (2) 'autonomy', and (3) 'sensing'. In this regard, robotic systems tend to combine many of the technologies outlined in this paper.

Mobility is concerned with the mechanism that enables the robot to move around the inspection site - these can be air-based (Bolourian & Hammad 2020), ground-based (Phillips & Narasimhan 2019) and crawling or climbing systems (La et al. 2018). Autonomy aims to enable comprehensive and repeatable inspection through the use of planning algorithms. Much of the research in this area involves the development of these path-planning algorithms that aim to reduce the time and energy needed to ensure a complete observation (e.g. Hallerman & Morgenthal 2014, Bolourian & Hammad 2020).

The development of robotics technology is arguably key to automating parts of the visual inspection process with a view to increasing efficiency and reliability. Whilst research is promising, the inspection environment itself may be the most significant hurdle to widespread adoption of inspection robots. Bridges (and their surrounding environment) are rarely uniform in scale, shape and design, and they are typically exposed in outdoor settings.

2.4 *Interferometric synthetic aperture radar*

Synthetic Aperture Radar (SAR) satellites have the capability to provide radar images of the Earth's surface (Chan & Koo 2008). Interferometric SAR (InSAR) is an advanced processing technique applied to these images that can detect millimetre-scale movements of built infrastructure assets over time (Lu et al. 2007).

InSAR can be used to track various bridge behavioural characteristics, such as slope creep (Cusson et al. 2012) or thermal expansion (Fornaro et al. 2013, Cusson et al. 2018) and deformation (Milillo et al. 2019). As a result, InSAR may be employed to monitor signs of unusual behaviour that are not easily visible from an inspector on the ground or that occur between inspections. A study by Selvakumaran et al. (2020) found that bridge displacements measured through InSAR were comparable to traditional Automated Total Station measurements. The authors state that satellite monitoring is currently 'not a technique that could replace traditional monitoring methods' (Selvakumaran et al. 2020, pg. 7151); however, it is noted that it does have the potential to augment conventional inspection programmes.

2.5 *Capture of 3D representations*

2.5.1 *Photogrammetry*

Photogrammetric models utilize the principle of triangulation to identify key points between two different images and triangulate these back to a single viewpoint. This process can be undertaken to create 3D models from multiple 2D images of an object of interest, provided there is sufficient overlap between the images (Schenk 2005). The resulting 3D model will have a 'realistic' surface appearance composed from the images.

Photogrammetric models can be used to produce 3D models of a bridge which can be used for desktop inspection (e.g. Chan et al. 2017, Popescu et al. 2019). Additionally, they can be used in conjunction with laser scanners and 360° cameras to develop virtual reality environments. There is potential for photogrammetric models to be applied through consecutive inspections to create a historical build-up of the condition of the structure (e.g. Bush et al. 2021, Bush et al. 2022a, b). These successive models could then be reviewed throughout the structure's lifecycle to provide a more thorough understanding of deterioration (Zollini et al. 2020).

2.5.2 *Laser scanners and point cloud systems*

A 3D laser scanner uses a rapidly pulsing or continuous laser beam to systematically sweep an area, allowing spatial data points to be obtained. These points are calculated on surfaces on which the laser is reflected (Staiger 2003). The resulting scan of points is a detailed 3D depiction of an area called a 'point cloud'. Matching photographs can be integrated with the scan data to provide realistic texture or colour to these 3D scans. Additionally, scans can be georeferenced to local coordinate systems (Tang et al. 2010). Laser scanners are widely available commercially and are often used for infrastructure surveys. Farooq (2017) notes that they are time efficient at creating spatial data points compared to traditional equipment and require less labour. In the context of bridge inspection, they can be used to generate 3D bridge models for desktop and virtual reality inspection (e.g. Tang et al. 2007, Omer et al. 2019), which can enable remote inspections to take place.

3 EMERGING DATA ANALYSIS METHODS

3.1 *Remote inspections*

Several of the technologies outlined in the previous section have the potential to enable 'remote' inspections, where a structure is inspected by a human off-site using high-quality image data. If bridges can be accurately inspected for defects 'remotely', there would be cost savings on labour, reduction in travel time and less disruption to the transport network (Nepomuceno et al. 2021). However, the factors affecting the accuracy with which human inspectors obtain defect ratings remain somewhat unexplored.

McRobbie et al. (2007) found that it was possible to perform a visual assessment of a bridge structure using images alone. An on-site inspection of a bridge in the UK was conducted which comprised of: (1) a general assessment of the overall bridge condition and its external and internal walls, and (2) a detailed assessment on the unique defects observed. An image-based procedure was also set-up for the same bridge, which followed the same assessment guidelines as the on-site inspection, but employed image display software to present appropriate photos on a 15-inch monitor (McRobbie et al. 2007).

3.2 *Digital image correlation*

Digital image correlation (DIC) employs image analysis to obtain displacement measurements of surfaces (Yoneyama & Murasawa 2009). Following that, these displacement measurements can be utilised to generate 3D strain fields (Pan et al. 2009). DIC can be used in conjunction with a sequence of images obtained during loading to compare the images to determine relative displacement and strain. DIC is often used in structural health monitoring (SHM) systems (e.g. Nonis et al. 2013) and is considered viable for short-term bridge assessment (Murray et al. 2015, Reagan et al. 2018) and can be used for specific load tests which can be repeated periodically (Al-Salih et al. 2019).

3.3 *Augmented reality and virtual reality*

Virtual information can be superimposed onto the real world via Augmented Reality (AR) technology and viewed through a camera or digital lens. AR presents a novel way for inspectors to interact with a structure, allowing them to visualise features such as crack measurements (Moreu et al. 2017) and the positioning of internal reinforcement (Salamak & Januszka 2015). Inspectors have the potential to use AR to collect, interact with, visualise, and analyse inspection data on-site and in the office. In a pilot study that developed a bridge inspection process using AR, Nguyen et al. (2020) concluded that 'information communication, visualization and collaboration in inspection work' (Nguyen et al. 2020, pg. 43) is improved by making data more naturally interactive through real-time modelling.

Virtual reality (VR) technology immerses a user into a virtual environment which is viewed through a screen or wearable headset. An early instance of this is presented in Jáuregui & White (2003) who strived to enhance bridge inspection by using QuickTime Virtual Reality to convert still images into a 3D environment. More recently, Omer et al. (2021) introduced an inspection technique which combines VR and Lidar. Using a bridge in Manchester (UK) as a case study, the results from their novel method indicate that it offers benefits over conventional inspection techniques, such as higher consistency of findings and improved inspector safety (Omer et al. 2021). In the virtual world, artificial lighting effects ensure that all locations are equally visible, which is not the case in reality (Omer et al. 2019).

3.4 *Artificial intelligence*

Artificial Intelligence (AI) is a field of study that seeks to emulate human intelligence via the use of physical or virtual machines (McCarthy 2007), often through neural networks (NN). A NN is essentially a data-modelling tool that can formulate complex relationships between inputs and outputs. A NN can be 'trained' to predict outcomes based on additional input data, given a set of input and output data associated with a particular problem (Gurney 1997). Within the bridge management research space, NNs have been widely studied. Research activities include predicting life-cycle cost (Asadi et al. 2011), detecting (Weinstein et al. 2018) and classifying (Aslan et al. 2019, Spencer et al. 2019) defects and recognising structural components (Koch et al. 2015).

3.5 *Big data and the internet of things*

Big Data (BD) is a term that refers to the process of acquiring, storing, and analysing vast and/or complex data sets through the use of computational techniques (Kapliński et al. 2016). Common data analysis methods for BD include statistics, machine learning, data and pattern recognition. Bridge asset owners often collect vast amounts of data on their bridge stock. There is potential for using BD techniques to transform asset data into actionable information that can help guide best bridge management practices (Liang et al. 2016, Xu et al. 2019, Sun et al. 2019).

The Internet of Things (IoT) is a network of physical sensor-equipped objects capable of communicating and sharing data with other devices over the Internet (Atzori et al. 2010). In a future vision of bridge management, this would envision all bridges in a network being fitted with information-sensing devices (such as those outlined in this paper) that cancommunicate with a BD computer to accurately assess the safety of each bridge in real-time.

Research studies have begun to emerge in this space with IoT processes being implemented to detect cracks (Zhang et al. 2018) and monitor bridge vibrations (Tong et al. 2019). In a study investigating the IoT adoption in asset management, Brous et al. (2019) state that a number of changes are still required for IoT to have a transformative effect such as: the need for standardisation, data governance and significant changes to organisational and business processes.

4 DISCUSSION

4.1 *Opportunities*

Technologies that enhance image capture capabilities for on-site visual inspections will present many opportunities. UAVs and 360° cameras can help save time spent on-site and, in some cases, reduce the safety risk posed to inspectors and the disruption to the traffic network. 360° cameras, for example, could rapidly capture images of the underside of highway bridges on a slower moving vehicle, removing the need to shut down traffic lanes.

Several technology trends would help enable the move to 'remote' inspections, which would have considerable implications on the inspection process. Along with the benefits mentioned previously, inspection would consume less time and financial resources as the inspector would not be required to be physically on-site. Theoretically, this division of labour would result in a more efficient use of the workforce.

Through successive image captures of a structure, an asset owner could theoretically amass a large database of reproducible, high-quality images for the structures under their management. This database would aid in better understanding how a structure deteriorates over time, by comparing successive images (cf. Bush et al. 2022a, b).

Regarding the cost-benefit aspects of an inspection programme, there may be a long-term business case where the savings on labour and travel would, over time, offset the high initial cost of implementing new technologies.

4.2 *Barriers to implementation*

The implementation of these technology systems is typically associated with a high short-term cost that may be hard to justify due to the systems not yet being widely trusted. Humans undertaking visual inspections possess exceptional perception abilities that are currently challenging for visual algorithms to replicate. Increased trust in these systems may develop as more successful use cases are reported.

Many of the algorithmic processes associated with AI can help with pertinent inspection activities such as defect classification and grading. Despite significant development in this field, improved accuracy in component recognition and damage detection is still required. Underrating a severe defect on an ageing bridge, could have fatal implications should vital parts of the structure fail.

With the capture and storage of data during inspections, thematic issues such as data ownership, governance, and security emerge. Who holds clear ownership of image data that was captured by a service provider, but depicts a bridge owner's stock? If the database increases in value to match the cost of current service contracts, increased security measures will have to be put in place to safeguard the data.

Budget constraints can also dictate the level of adoption which greatly varies by project and structure. For example, smaller-scale projects will generally have smaller budgets which simply do not allow for investment in innovative materials and methods. However, on large-scale projects, where a life-cycle approach is often taken, monitoring and management solutions can be seriously considered as part of the design process.

5 SUMMARY & CONCLUSIONS

Bridges are key links in transport networks and critical to the function of a modern society. As they age toward their design life, routine visual inspections remain highly important.

This paper presents a number of technology systems and trends that may supplement and enhance the bridge visual inspection process. These technologies are broadly divided into two groups: 'data capture' and 'data processing' technologies. The implementation of these trends can help make inspections remote and rapid, reducing the safety risk posed to inspectors, especially in hazard-prone areas. Whilst the potential impact is vast, there remains some barriers to adoption by the industry.

Based on this review, it is argued that increased adoption of emerging technologies for routine visual inspections may occur as a result of: (i) targeted development of these technologies with respect to specific visual inspection stages; (ii) increasing trust by encouraging more industrial use-cases; (iii) revising legislation where appropriate to ease implementation (e.g. UAV legislation) and (iv) developing a rigorous business case for such technologies where the long-term value of enriched decision-making can be demonstrated.

Finally, a suitable next step would be to assess the value of information (VoI) (Wilson 2015) associated with various technologies for certain use cases. Prior to implementation, VoI analysis can be an effective tool for quantifying the benefits of an inspection technique (e.g. Quirk et al. 2017, Abdallah et al. 2022). Representative and practical instances of how technologies might aid decision-making, such as for emergent inspections following hazardous incidents, may be offered. As Webb et al. (2015) argue, the value of a SHM system may vary according to the user of the information obtained. For instance, SHM consultants may be concerned with 'model validation', whereas asset owners may be concerned with 'damage detection'. Similarly, the ultimate value received from the technologies discussed in this article may vary depending on the bridge management stakeholder.

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DATA AVAILABILITY STATEMENT

This study has not generated new experimental data.

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