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A review of recent research on visual inspection processes for bridges and the potential uses of AI

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ABSTRACT: Visual inspection remains an essential tool for assessing structural damage. Damage detection is a challenging task for those specifying, designing, and deploying SHM systems. Often only traditional visual inspection processes are available to determine the type and extent of structural damage. For bridge structures in the UK, a regime of general (every two years) and principal (every six years) inspections is often followed. Such visual inspections are time-consuming and costly in terms of both labour and financial resources. Therefore, the possibility of completing more of the bridge visual inspection process offsite has many potential benefits for bridge owners and managers during the service life of the asset. Recent research conducted at the University of Bristol in collaboration with industrial partners has examined how to make the best use of metrics derived from visual inspection data when assessing bridge condition and planning maintenance activities. Recent research into which aspects of the current visual inspection regime in the UK could potentially be moved offsite has also been carried out. This paper summarises these research efforts and discusses how AI may be used as part of future enhancements to visual inspection data capture and analysis.

1 INTRODUCTION

1.1 *Background*

The UK has aging infrastructure stock, often described as an 'asset time bomb' (Thurlby 2013, Thurlby & Rimell 2015). Therefore, assessing current asset condition and residual life is important for bridge managers. A key element of asset condition assessment is to be able to detect damage across the entire stock (in this case of bridges) and identify differences by region or asset type/class. 'Damage detection', although the most useful form of Structural Health Monitoring (SHM), is arguably the most difficult to realise in field conditions (see the SHM categories and discussion in Webb et al. 2015). The key method for damage detection in current practice remains visual inspection (VI) (e.g. Wallbank 1989, Moore et al. 2001, Lea & Middleton 2002, Middleton 2004, McRobbie et al. 2015, Bennetts 2019, Bennetts et al. 2016, 2020). In the UK, the following default visual inspection regime is often followed: principal visual inspections (conducted by inspectors operating within touching distance of the bridge) scheduled every six years and general inspections every two years (see HA 2007 and Bennetts et al. 2016). The aforementioned VI regime may be

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varied on a risk-basis (HE, 2021). Bennetts et al. (2023) conducted a study using VI data from 200 sample bridges from the UK highway network and concluded that 81% of the inspections were carried out in 'strict compliance' with BD63/07 (the standard at the time of the study; see HA 2007) and 93% were within 'the spirit' of the standard (see also Bennetts 2019).

1.2 *Paper outline*

This paper summarises recent research on the following topics: the use of VI data and metrics for asset management processes (section 2); how aspects of the VI process may be carried out offsite using new technologies, leading to a hybrid VI system (section 3) and ways in which recent advances in artificial intelligence (AI)/machine learning (ML) may influence aspects of VI processes in the future (section 4).

2 USING VI DATA AND METRICS FOR ASSET MANAGEMENT

2.1 *Importance Of VI in bridge engineering*

Bennetts et al. (2016, 2020) conducted a series of semi-structured interviews to elicit the use of VI and SHM in the UK bridge management community. The use of VI data and associated metrics is varied across the industry. The use of SHM was reported to be limited except in specific instances (Bennetts et al. 2020). Colford et al. (2022) note that SHM is not an alternative to inspections. Bennetts et al. (2021) argued that the inspection intervals used in UK practice (two years and six years) make detecting change difficult, especially at individual asset level. Bennetts et al. (2020) as part of hierarchical process modelling and their survey of bridge engineering professionals, identified the following high-level processes: 'understanding the stock', 'making decisions' and 'implementing interventions' (Bennetts et al. 2020, p. 214), shown in Figure 1.

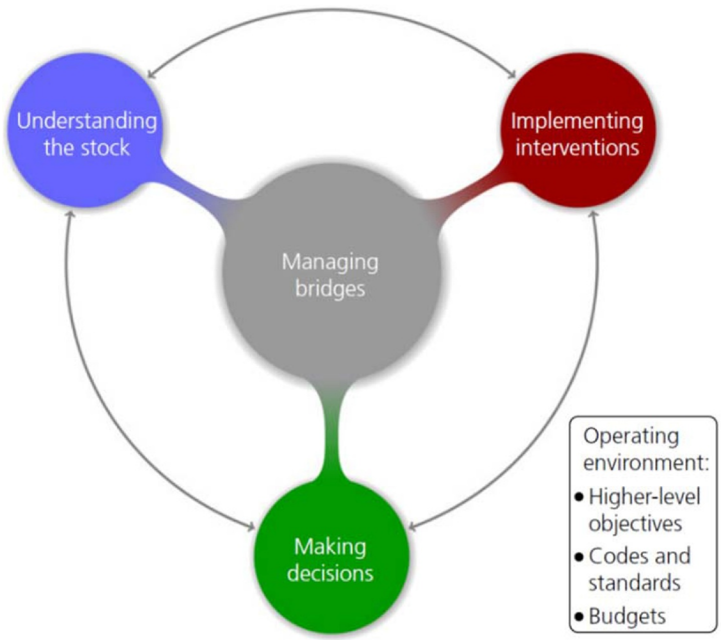

Figure 1. High-level model of the bridge management system (taken from Bennetts et al. 2020, used under the terms of the cc-by 4.0 licence).

2.2 *Bridge condition indicators*

VI data can be used to calculate Bridge Condition Indicator (BCI) metrics (defined in detail in Sterritt 2002). These metrics can be aggregated and analysed to study asset condition changes at stock/regional level (Bennetts et al. 2018a, 2018b). BCI metrics can be used to show varying asset deterioration across UK regions. For example, Figure 2 shows the reduction of BCI_{ave} and BCI_{crit} scores for a population of bridges (Bennetts et al. 2018b). As stated in Bennetts et al. (2018b, p. 26):

> "The average score, BCI_{ave} is calculated from the raw defect scores, taking the worst defects on each component type, weighted by the structural importance of each element. The critical score represents the worst defect on the most important structural components."

(See Sterritt (2002) for more details on the calculation of the aforementioned metrics.)

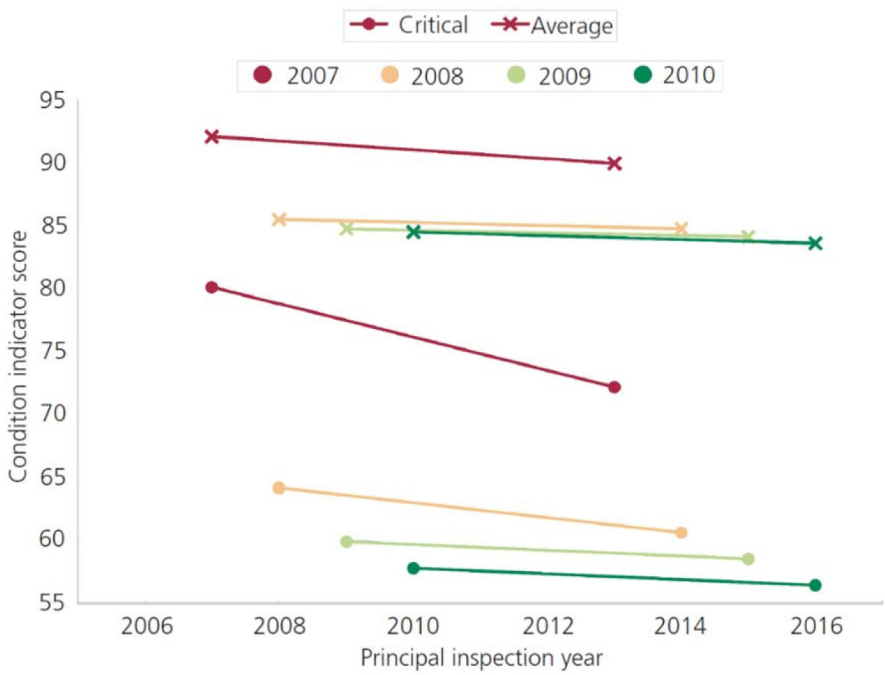

Figure 2. Change in condition between successive inspections for populations of structures that were inspected in the same year. The conditions of these populations of bridges are plotted as the average BCI_{crit} and BCI_{ave} scores for the population, weighted by deck area. A total of 2397 bridges are included in the plot (taken from Bennetts et al. 2018b, used under the terms of the cc-by 4.0 licence).

3 OFFSITE VISUAL INSPECTION PROCESSES

Visual inspection is a costly exercise for asset owners and managers (Bennetts 2019). Visual inspection requires human inspectors to work outside in varied weather conditions, often at night and frequently in high-traffic environments (e.g. Bennetts 2019). As an aside, in the case of assessing bridge scour, for VI to be carried out, divers are necessary to detect potential scour holes formed due to floods below the foundations of a bridge (cf. Selvakumaran et al. 2018, Pregnolato et al. 2021). The need for divers implies an increased safety risk which needs to be managed. Moreover, another issue of VI is the lack of skilled inspectors for which the UK has introduced the Bridge Inspector Training Scheme (BICS) (Lantra 2023). Therefore, efforts to move VI processes offsite have the potential to supplement/enhance existing VI/SHM efforts (McRobbie et al. 2015, Nepomuceno 2022, Nepomuceno et al. 2022a, 2022b).

Nepomuceno et al. (2022b) (Figure 3) have recently presented a possible schema for moving parts of the VI process offsite: future realisation of such efforts will require improved technologies for image capture (see the recent paper of Nepomuceno et al. 2022a for a detailed review of new technologies to assist VI processes and the best practice guide for bridge monitoring by Middleton et al. 2016). New technologies may include use of 360° cameras, precision drone-based camera

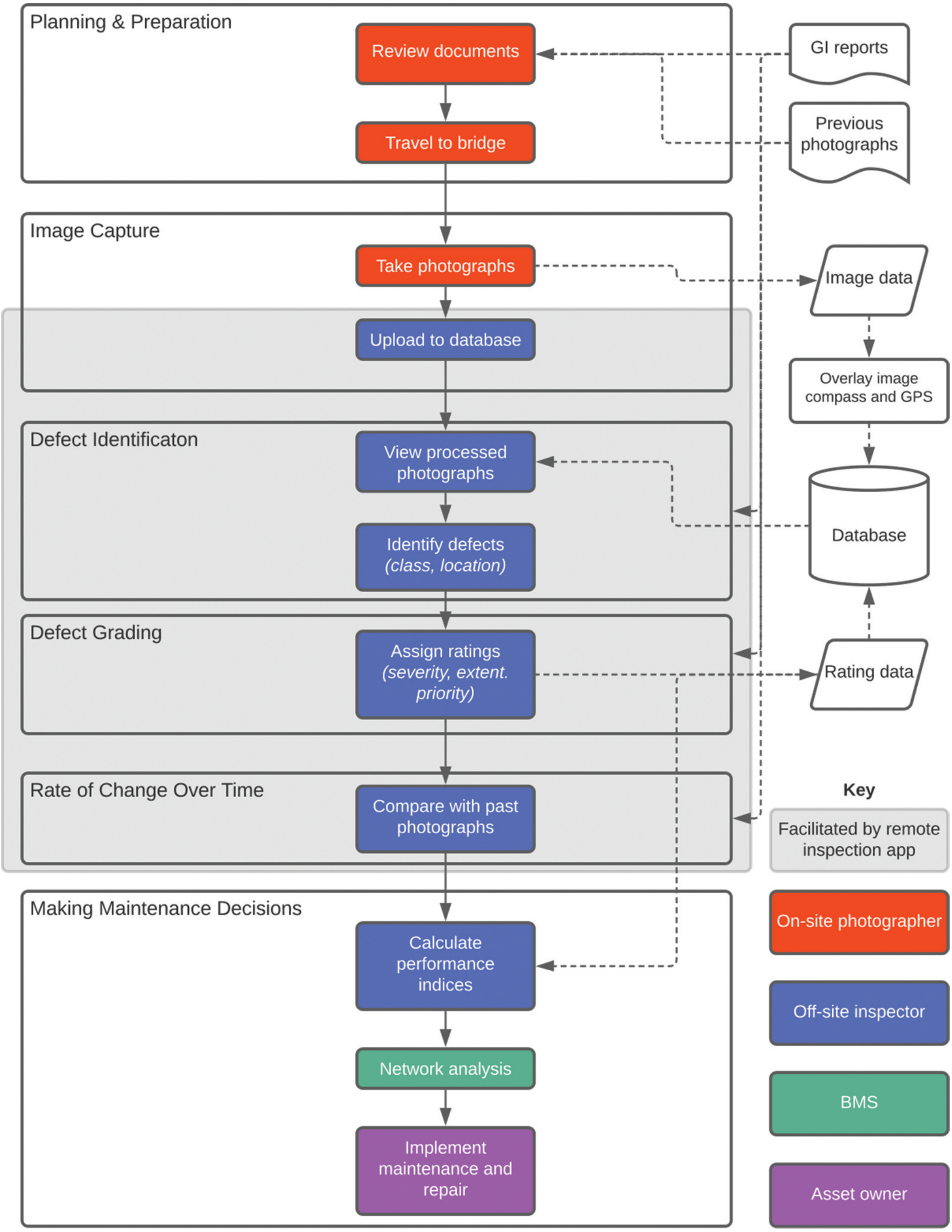

Figure 3. Workflow diagram of remote inspection schema (created in Lucidchart (2022)) (adapted from Nepomuceno et al. 2022b, used under the terms of the cc-by 4.0 licence).

systems, interferometric synthetic-aperture radar (InSAR) as well as virtual reality and computer vision (Nepomuceno et al. 2022a, 2022b). For the specific case of bridge scour, fibre optic installations, sonar and InSAR are devices that could potentially mitigate the need for divers in some instances (cf. Prendergast & Gavin 2014, Selvakumaran et al. 2018, Vardanega *et al.* 2021). Even if technological advances allow image capture to be done remotely with photographs and video, (i.e. assessed by human inspectors offsite) it is not guaranteed that the accuracy and precision of defect identification will be acceptable for those taking decisions based on this data.

Nepomuceno et al. (2021, 2023) presented preliminary survey data showing that the ratings from onsite and offsite inspectors tended to more closely agree for higher severity defects (see also Nepomuceno 2022). Further studies are needed to standardise off-site assessment of captured images. Regardless of whether the defect detection outcomes are the same offsite, decisions about maintenance and intervention still depend on the VI data and associated metrics. These considerations persist regardless on whether the process stays similar to current practices or shifts towards being more technologically driven and conducted partially remotely.

4 POTENTIAL FUTURE INFLUENCES OF AI IN VI WORKFLOW

4.1 *Recent AI uses in structural engineering*

Use of AI is expected to increase in many fields, including bridge engineering. Alexander et al. (2022) used deep learning methods for crack detection on structures. Munawar et al. (2022) used ML methods for crack detection processes. Luleci & Catbas (2023b) suggested population-based structural health monitoring (PBSHM) approaches for pre-stressed bridges. Luleci & Catbas (2023a) present a recent review of deep generative models (DGMs) in SHM. Luleci & Catbas (2023a) conclude that data scarcity remains a challenge in the field of bridge engineering (see also the review of Catbas & Avci 2023 which mentions in part the use of virtual reality in bridge SHM). Stacy (2023) notes that data alone is not sufficient for good decision making. Projects such as the Data Analytics Facility for National Infrastructure (DAFNI) may help with the analysis of future larger datasets (Matthews et al. 2023).

AI approaches may assist with data analysis and pattern recognition across large datasets. AI offers potential improvements across the VI process. For example, AI could potentially be used to evaluate trends from stock-level (regional) data sets of VI metrics, further enhancing what can be gleaned from 'manual' analysis of large structural data sets such as those reported in Bennetts et al. (2018a, 2018b).

There are potential concerns/limitations, such as the fact that semi-automated or fully automated processes may detect specific instances of bridge damage (i.e. the defect location). There are also concerns on how well severity will be assessed with AI methods compared to human inspectors. For instance, from an asset management perspective, if a bridge with a defect of a similar extent and severity is repaired and this is reflected in the data set the AI is applied to; would AI-based processes recommend repair in other similar cases and if so on what basis? Asset managers may not be able to deduce why AI prioritisation or recommendations have been made and hence the context for decisions/recommendations may become less clear and less able to be scrutinised by other stakeholders.

4.2 *Engineering judgement*

Bennetts et al. (2016) showed using data from semi-structured interviews that engineering judgement is very important in taking bridge management decisions. In the context of a potentially AI enhanced VI process, what is the fundamental role of the 'engineer'? Engineering judgement is needed to take decisions regarding assignment of design parameters and for catching errors in design processes (cf. Peck 1980, Petroski 1993, Vardanega & Bolton 2016). In the case of VI 'judgement' is exercised when assessing the 'extent' or 'severity' of the defect. Judgment is also needed when prioritising bridges for maintenance expenditure. A future question for bridge managers using AI processes will be how they will be able to safely overrule AI recommendations when they produce results that do not align with their own engineering judgement.

5 SUMMARY

This paper has reviewed recent research efforts on the use of VI data for associated bridge condition metrics – these data have the potential to be further analysed using AI tools. Use of VI data is still widely used for assessing structural condition and therefore there is a relevant question on how much of this time-consuming and expensive process can be conducted offsite. Survey data has shown some offsite evaluation of defect severity can be potentially considered, although more data is needed to confirm if off-site inspectors can replace on-site inspectors (assuming comprehensive image capture can be carried out using new and an emerging technological solutions). Finally, with the recent prominence of AI, further research of on the use of AI in VI should be undertaken.

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REFERENCES

Alexander, Q.G., Hoskere, V., Narazaki, Y., Maxwell, A. & Spencer Jr, B.F. 2022. Fusion of thermal and RGB images for automated deep learning based crack detection in civil infrastructure. *AI in Civil Engineering* 1: [3] https://doi.org/10.1007/s43503-022-00002-y

Bennetts, J. 2019. The Management of Bridges. *EngD thesis*, University of Bristol, Bristol, UK.

Bennetts, J., Denton, S.R., Webb, G.T., Nepomuceno, D.T. & Vardanega, P.J. 2021. Looking to the future of bridge inspection and management in the UK. In Yokota, H. & Frangopol, D.M. (eds.), *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations: Proceedings of the Tenth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2020), Sapporo, Japan, 11-15 April 2021*. CRC Press/Balkema Taylor & Francis Group, Leiden, The Netherlands, pp. 3858–3866 https://doi.org/10.1201/9780429279119-526

Bennetts, J., Vardanega, P.J., Taylor, C.A. & Denton, S.R. 2016. Bridge data – what do we collect and how do we use it? In: Mair, R.J., Soga, K., Jin, Y., Parlikad, A.K. & Schooling, J.M. (eds.), *Transforming the Future of Infrastructure through Smarter Information: Proceedings of the International Conference on Smart Infrastructure and Construction, 27-29 June 2016*. ICE Publishing, London, UK, pp. 531–536.

Bennetts, J., Vardanega, P.J., Taylor, C.A. & Denton, S.R. 2020. Survey of the use of data in UK bridge asset management. *Proceedings of the Institution of Civil Engineers – Bridge Engineering* 173(4): 211–222 https://doi.org/10.1680/jbren.18.00050.

Bennetts, J., Vardanega, P.J., Webb, G.T., Denton, S.R. & Loudon, N. 2023. Analysis of visual inspection data for a sample of highway bridges in the UK. *Proceedings of the Institution of Civil Engineers – Forensic Engineering* 176(3): 79–88 https://doi.org/10.1680/jfoen.21.00005.

Bennetts, J., Webb, G., Denton, S., Vardanega, P.J. & Loudon, N. 2018a. Quantifying Uncertainty in Visual Inspection Data. In: Powers, N., Frangopol, D.M., Al-Mahaidi, R. & Capriani, C. (eds.), *Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges: Proceedings of the Ninth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2018), 9-13 July 2018, Melbourne, Australia*. CRC Press/Balkema Taylor & Francis Group, Leiden, The Netherlands, pp. 2252–2259. https://doi.org/10.1201/9781315189390-306

Bennetts, J., Webb, G.T., Vardanega, P.J., Denton, S.R., & Loudon, N. 2018b. Using data to explore trends in bridge performance. *Proceedings of the Institution of Civil Engineers – Smart Infrastructure and Construction* 171(1): 14–28. https://doi.org/10.1680/jsmic.17.00022

Catbas, N, & Avci. O. 2023. A review of latest trends in bridge health monitoring. *Proceedings of the Institution of Civil Engineers – Bridge Engineering* 176(2): 76–91. https://doi.org/10.1680/jbren.21.00093.

Colford, B.R., Zhou, E. & Pape, T. 2022. Structural health monitoring – a risk-based approach. *Proceedings of the Institution of Civil Engineers – Bridge Engineering*, https://doi.org/10.1680/jbren.21.00073.

HA (Highways Agency) 2007. Inspection Manual for Highway Structures. Volume 1: Reference Manual. The Stationary Office, London, UK.

HE (Highways England) 2021. CS 450 Inspection of highway structures. *Standards for Highways.* See: <https://www.standardsforhighways.co.uk/search/html/c5c2c3e5-f7f3-4c94-8254-184e41ccd1a0?standard=DMRB> (23/02/2024)

Lantra 2023. National Highway Sector Scheme 31 for the Bridge Inspector Certification Scheme: Scheme Manual. Lantra, Coventry, UK. See:<https://www.lantra.co.uk/media/fk0btwgs/bridge-inspector-certification-scheme-manual.docx>(12/03/2024).

Lea, F. & Middleton, C. 2002. Reliability of Visual Inspection of Highway Bridges. Department of Engineering, University of Cambridge, Cambridge, UK, Technical Report C*UED/D-STRUCT/TR.201*.

Lucidchart 2022. See:<www.lucidchart.com>. Lucid Software Inc., South Jordan, UT, USA (31/10/2022).

Luleci,F. & Catbas, F.N. 2023a. A brief introductory review to deep generative models for civil structural health monitoring. *AI in Civil Engineering* 2: [9] https://doi.org/10.1007/s43503-023-00017-z

Luleci, F. & Catbas, F.N. 2023b. Condition transfer between prestressed bridges using structural state translation for structural health monitoring. *AI in Civil Engineering* 2: [7] https://doi.org/10.1007/s43503-023-00016-0

Matthews, B., Hall, J., Batty, M., Blainey, S., Cassidy, N., Choudhary, R., Coca, D., Hallett, S., Harou, J.J., James, P., Lomax, N., Oliver, P., Sivakumar, A., Tryfonas, T., & Varga, L. (2023). DAFNI: a computational platform to support infrastructure systems research. *Proceedings of the Institution of Civil Engineers – Smart Infrastructure and Construction* 176(3): 108–116 https://doi.org/10.1680/jsmic.22.00007

McRobbie, S.G., Wright, M.A. & Chan, A. 2015. Can technology improve routine visual bridge inspections?. *Proceedings of the Institution of Civil Engineers – Bridge Engineering* 168(3): 197–207 https://doi.org/10.1680/jbren.12.00022

Middleton, C. 2004. Bridge management and assessment in the UK. Paper presented at: Fifth Austroads Bridge Conference, 19-21 May 2004, Hobart, Tasmania. Austroads, Sydney, Australia. See:<https://web.archive.org/web/20221024074022/http://www.bridgeforum.org/files/pub/2004/austroads5/Middleton%20keynote.pdf> (12/03/2024).

Middleton, C.R., Fidler, P.R.A. & Vardanega, P.J. 2016. *Bridge Monitoring: A Practical Guide*. ICE Publishing, London, UK.

Moore, M., Phares, B., Graybeal, B., Rolander, D. & Washer, G. 2001. Reliability of Visual Inspection for Highway Bridges, Volume 1. US DOT, Federal Highway Administration, Washington, DC, USA.

Munawar, H.S., Hammad, A.W.A., Waller, S.T. & Islam, M.R. 2022. Modern Crack Detection for Bridge Infrastructure Maintenance Using Machine Learning. *Human-Centric Intelligent Systems* 2 (3-4): 95–112 https://doi.org/10.1007/s44230-022-00009-9

Nepomuceno, D.D.T. 2022. Technology Innovation for Improving Bridge Management. *PhD thesis*, University of Bristol, Bristol, UK.

Nepomuceno, D.T, Vardanega, P.J., Tryfonas, T., Bennetts, J., Denton, S.R., Collard-Jenkins, S., Thackray, C., Green, J. & DiNiro, M. 2021. Viability of off-site inspections to determine bridge defect ratings. In: Yokota, H. & Frangopol, D.M. (eds.), *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations: Proceedings of the Tenth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2020), Sapporo, Japan, 11-15 April 2021*. CRC Press/Balkema Taylor & Francis Group, Leiden, The Netherlands, pp. 3688–3695 https://doi.org/10.1201/9780429279119-501

Nepomuceno, D.T., Bennetts, J., Pregnolato, M., Tryfonas, T. & Vardanega, P.J. 2022b. Development of a schema for the remote inspection of bridges. *Proceedings of the Institution of Civil Engineers – Bridge Engineering*, https://doi.org/10.1680/jbren.22.00027

Nepomuceno, D.T., Vardanega, P.J., Pregnolato, M. Tryfonas, T. & Bennetts, J. 2023. Viability of bridge inspectors determining defect ratings using photographic images. *Infrastructure Asset Management* 10(3): 144–156 https://doi.org/10.1680/jinam.23.00004

Nepomuceno, D.T., Vardanega, P.J., Tryfonas, T., Pregnolato, M., Bennetts, J. & Webb, G. 2022a. A survey of emerging technologies for the future of routine visual inspection of bridge structures. In Casas, J.R., Frangopol, D.M. & Turmo, J. (eds.), *Bridge Safety, Maintenance, Management, Life-Cycle, Resilience and Sustainability: Proceedings of the Eleventh International Conference on Bridge Maintenance, Safety and Management (IABMAS 2022), Barcelona, Spain, July 11-15, 2022*, CRC

Press/Balkema Taylor & Francis Group, London, UK, pp. 846–854 https://doi.org/10.1201/9781003322641-101
Peck, R.B. 1980. 'Where has all the judgment gone?' The fifth Laurits Bjerrum memorial lecture. *Canadian Geotechnical Journal* 17(4): 584–590. https://doi.org/10.1139/t80-065
Petroski, H. 1993. Failure as source of engineering judgment: Case of John Roebling. *Journal of Performance of Constructed Facilities* 7(1): 46-58 https://doi.org/10.1061/(ASCE)0887-3828(1993)7:1(46)
Pregnolato, M., Vardanega, P.J., Limongelli, M.P., Giordano, P.F. & Prendergast, L.J. 2021. Risk-based scour management: A survey. In: Yokota, H. & Frangopol, D.M. (eds.), *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations: Proceedings of the Tenth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2020), Sapporo, Japan, 11-15 April 2021*. CRC Press/Balkema Taylor & Francis Group, Leiden, The Netherlands, pp. 693-701 https://doi.org/10.1201/9780429279119-91
Prendergast, L.J. & Gavin, K. 2014. A review of bridge scour monitoring techniques. *Journal of Rock Mechanics and Geotechnical Engineering* 6(2): 138–149 https://doi.org/10.1016/j.jrmge.2014.01.007.
Selvakumaran, S., Plank, S., Geiß, C., Rossi, C. & Middleton C. 2018. Remote monitoring to predict bridge scour failure using Interferometric Synthetic Aperture Radar (InSAR) stacking techniques. *International Journal of Applied Earth Observation and Geoinformation* 73: 463–470 https://doi.org/10.1016/j.jag.2018.07.004
Stacy, M. 2023. Data and decisions for bridge maintenance. *The Structural Engineer* 101(9): 38-39 https://doi.org/10.56330/KGIE8593
Sterritt, G. 2002. Bridge Condition Indicators. WS Atkins for CSS Bridges Group, London, UK, vol. 1.
Thurlby, R. 2013. Managing the asset time bomb: a system dynamics approach. *Proceedings of the Institution of Civil Engineers – Forensic Engineering* 166(3): 134–142 https://doi.org/10.1680/feng.12.00026
Thurlby, R. & Rimell, J. 2015. Discussion: Managing the asset time bomb: a systems dynamics approach. *Proceedings of the Institution of Civil Engineers - Forensic Engineering* 168(4): 181–182 https://doi.org/10.1680/feng.15.00007
Vardanega, P.J. & Bolton, M.D. 2016. Design of Geostructural Systems. *ASCE ASME Journal of Risk and Uncertainty in Engineering Systems. Part A: Civil Engineering* 2(1): [04015017]. https://doi.org/10.1061/AJRUA6.0000849
Vardanega, P.J., Gavriel, G. & Pregnolato, M. 2021. Assessing the suitability of bridge-scour-monitoring devices. *Proceedings of the Institution of Civil Engineers – Forensic Engineering* 174(4): 105–117 https://doi.org/10.1680/jfoen.20.00022
Wallbank, E.J. 1989. *The Performance of Concrete in Bridges: A Survey of 200 Highway Bridges*. Her Majesty's Stationery Office, London, UK.
Webb, G.T., Vardanega, P.J. & Middleton, C.R. 2015. Categories of SHM Deployments: Technologies and Capabilities. *Journal of Bridge Engineering (ASCE)* 20(11): [04014118] https://doi.org/10.1061/(ASCE)BE.1943-5592.0000735.