

Remote sensing for detecting and tracking damage on municipal infrastructure systems: A review of recent trends

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Abstract—Ensuring safety, serviceability and resilience of infrastructure components and systems are key considerations for asset owners and engineers. However, realisation of these performance objectives is often hindered by ageing infrastructure and exposure to both natural and anthropogenic hazards. Furthermore, much of a nation’s infrastructure may be located in extreme or remote environments where access for inspection and maintenance is costly, dangerous or even impossible. Remote sensing is increasingly being used by civil engineers to inspect and monitor infrastructure assets and systems. Remote sensing systems can capture data across large geographical regions using e.g. satellite flyovers or surveys using camera and/or laser technology carried by drones. Remote sensing is also an important approach for inspections in post-disaster zones due to, for example, access limitations, safety concerns and the need for rapid data collection post-event to guide relief efforts. Monitoring infrastructure performance and tracking damage progress on fixed infrastructure assets can also be attempted using remote sensing systems. The increasing use of many types of SHM systems has in part been driven by the desire to supplant or at least enhance visual inspection regimes. This paper presents a concise review of recent literature on the use of remote sensing approaches in municipal engineering applications focussing on both assessment of individual infrastructure assets and distributed infrastructure systems. The synthesis of the results of the review aims to illustrate to what extent remote sensing approaches are actually replacing or supplementing visual inspection efforts across a range of scenarios e.g. pre- and post-disaster and during normal operation. The paper also discusses possible uses of artificial intelligence and machine learning to process the large quantities of data generated by some remote sensing systems. The paper concludes with recommendations for asset owners and operators considering increasing their use of remote sensing systems for infrastructure assessments.

Keywords—damage detection, infrastructure monitoring, municipal engineering, remote sensing, visual inspection

I. INTRODUCTION

ENSURING SAFETY, serviceability and resilience of infrastructure components and systems are key considerations for asset owners and engineers. However, realisation of these performance objectives is often hindered by ageing infrastructure and exposure to both natural and anthropogenic hazards. For example, the ageing stock of UK infrastructure has been described as an “asset time bomb” (Thurlby [1], Thurlby and Rimell [2]). This is arguably also the case for other nations where large amounts of infrastructure were built from the 1950s onwards (see e.g., Pfeiffer [3] and Blas [4] on the “Eisenhower” interstate highway system in the USA).

In this context, civil and municipal engineers need to appraise the state, or performance of infrastructure assets (or systems of assets) so that maintenance and upgrade activities can be planned and carried out. To achieve this Structural Health Monitoring (SHM) is often used. Webb et al. [5]’s review classified SHM systems into the following categories “Anomaly Detection”; “Sensor Deployment Studies”; “Model Validation”; “Threshold Check” and “Damage Detection”. In this paper many of the SHM systems that will be reviewed will focus mainly on the “Damage Detection” category of Webb et al. [5].

Furthermore, much of a nation’s infrastructure may be located in extreme or remote environments where access for inspection and maintenance is costly, dangerous or even impossible (cf. the case study on Ukrainian bridges by Koppika et al. [6]). Therefore, the ability to collect data on infrastructure without visiting the site is of value.

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A. Study Aims

This paper presents a concise review of recent literature on the use of remote sensing approaches in civil and municipal engineering (as distinct from military) applications focussing on both assessment of individual assets and distributed systems.

B. Paper Outline

The topics covered in this paper include: Brief History of Remote Sensing (Section II); Capabilities of Remote Sensing Technologies (Section III); Applications of Remote Sensing Technologies (Section IV); Remarks on Visual Inspection (Section V); and Uses of Artificial Intelligence (Section VI). The paper concludes with recommendations for asset owners and operators considering increasing their use of remote sensing systems for infrastructure assessments.

II. BRIEF HISTORY OF REMOTE SENSING

A. Definitions of Remote Sensing

Remote sensing (RS) is increasingly being used by civil engineers to inspect and monitor infrastructure assets and systems. However, this is not new (cf. Barr & James [7]) as the value in being able to achieve this has long been recognised "... since the late 19th century when new techniques in photography permitted the use of cameras from balloons" (Amos *et al.* [8], p. 119).

Barr & James ([7], p. 280) explained that "[t]he term remote sensing has evolved into a general descriptor of all technologies related to the detection, measurement, recording and utilization of emitted and reflected electromagnetic energy". More recently Almohsen ([9], p. 1) defined RS as "... the art and science of acquiring information about an object or a phenomenon from a distance above the ground by measuring emitted or reflected radiation from the object or phenomenon being observed". Kumari *et al.* ([10], p. 224) defined RS as "... the acquisition of information about objects or phenomena without physical contact". It could also be argued that transmissions (using wireless technology) from fixed sensors and/or sensor arrays (providing off-site access to data in real-time) (see e.g., Lynch & Loh [11], Hoult *et al.* [12], Stajano *et al.* [13], Webb *et al.* [5]) is also a form of RS (of sorts).

B. Evolution of Remote Sensing in Civil Engineering

Table I shows the key topics reviewed in the paper of Barr & James [7] on the uses of RS in civil engineering: arguably all are still applicable today. Since the writing of Barr & James's paper [7] there have been advances in available sensing platforms. Table II shows the progression of RS technologies presented in H.K *et al.* [14]. Table III summarises types of RS from the review of Prinari *et al.* [15].

Technological advance continues e.g., Roberts *et al.* ([16], p. 192) presented a review of developments of Global

TABLE I
APPLICATIONS OF REMOTE SENSING IN CIVIL ENGINEERING
(BARR & JAMES [7])

Application	Sub-topics
"Environmental and Sanitary Engineering"	"Water Quality"
	"Urban Runoff"
	"Sanitary Landfill"
"Water Resources"	"Atmospheric Quality"
	"Precipitation Runoff and Infiltration"
	"Ground-Water Hydrology"
	"Streamflow and Flooding"
"Transportation Engineering"	"Route Location"
	"Transportation System Surveillance and Maintenance"
	"Traffic Studies"
"Geological Engineering and Soil Mechanics"	"Soil Exploration and Classification"
	"Mass Wasting"
	"Site Evaluation and Selection"
	"Construction Material Location and Inventory"
	"Coastal Engineering"
	"Disaster Surveys"

TABLE II
ADVANCEMENT OF REMOTE SENSING PLATFORMS (H.K ET AL. [14])

Decade	RS Platform
1970s	"Launch of Landsat Satellites"
1990s	"High-Resolution Optical Imagery"
1990s	"Synthetic Aperture Radar (SAR)"
1999	"IKONOS Satellites High-Resolution Imagery"
2000s	"Interferometric Synthetic Aperture Radar (InSAR)"
2010s	"Unmanned Aerial Vehicles (UAVs)"
2010s	"Light Detection and Ranging (LiDAR)"

(See Figure 1 from [14] p. 4)

TABLE III
REMOTE SENSING TECHNOLOGY CLASSIFICATION (PRINARI *ET AL.* [15])

Type	RS Platform
I	"Sensors Attached to Subject"
II	"Sensors Attached to Robots"
III	"Remote Sensors, Passive RS" "Laser Distance Sensing" "Holography" "Radar"
IV	"Remote Sensors, Active RS" "Ultrasound RS Methods" "Laser RS Methods" "Combined Laser and Ultrasound RS Methods" "Radar RS Methods" "Electromagnetic Methods" "Acoustic Emission"

Navigation Satellite-positioning Systems (GNSS), concluding in part that “[t]he quality of the satellites’ signals, the GNSS receivers and the expected accuracies and precisions are also under improvement”.

While there have been advances in RS technologies, limitations remain such as those summarised in Table IV. Arguably the availability of less expensive drones means that RS approaches are now more accessible for practicing civil and municipal engineers and researchers (cf. Guan et al. [18]). Therefore, it is postulated that RS use will become more ubiquitous in civil and municipal engineering in the future and hence continual review of technological developments in this space is warranted. Tantele et al. ([19], p. 5) suggested “continuous learning and professional development” activities for practitioners for the industry to further realise the potential of RS technology. The next section briefly discusses the capabilities of various remote sensing platforms and the data that can be obtained.

III. CAPABILITIES OF REMOTE SENSING TECHNOLOGIES

A. Geographical coverage

O’Rourke ([20], p. 506 (Table 1)) explained the wide-ranging scales in geotechnical engineering noting that “region[al]” scale projects include the relevant municipal concerns of: “River, coastal and offshore systems” and “Water supplies”, “Transportation networks” and “Electric power and fuel systems”. Remote sensing systems can capture data across large geographical regions (e.g., Tantele et al. [19]) or along linear infrastructures such as road pavements (e.g., Schnebele et al. [21]) or for agricultural applications (e.g., Bolkas et al. [22]), using e.g., satellite flyovers or surveys using camera and/or laser technology carried by drones or other aircraft. Womble et al. ([23], p.4) note that “[a]erial platforms often offer the earliest remote-sensing imagery of disaster areas, though data acquisition spanning an entire affected area is typically slow compared to satellites.”

B. Drones

Recently the development of drone technology has increased in civil and construction engineering (e.g., Guan et al. [18]). Aerial robotic technology may one day even be an integral part of physical construction tasks especially in more extreme/difficult to access environments (cf. Kaya et al. [24]).

There have been many recent review papers on drones and their use in the civil and municipal engineering sectors (e.g., Albeanio et al. [25], Shakhathreh et al. [26] and Greenwood et al. [27]). In the review of Freeman et al. ([28], p.86 (Table 4)) on aerial robotics in civil engineering further review papers and other literature was reviewed and the following sub-categories of aerial robotic applications were classed as “Emerging”: “Inspection of civil infrastructure”; “Monitoring of civil infrastructure”; “Robotic construction and maintenance”; and

TABLE IV
CHALLENGES FOR REMOTE SENSING APPROACHES

Reference	Identified challenges
	Earthquake engineering context:
Rathje & Adams ([17], p. 483 (Table 1))	i. “Image Acquisition”
	ii. “Image Access”
	iii. “Data Quantity”
	iv. “Experience of Users”
	v. “Damage Level Resolution”
	vi. “Damage Scales”
Almohsen ([9], p. 11 (Figure 6))	Construction management context:
	i. “Temporal resolutions”
	ii. “Spatial resolution”
	iii. “Spatiotemporal resolution”
	iv. “Weather issues”
	v. “Atmospheric and cloud covering”
	vi. “Shadow issues”
	vii. “Logistical and regulation issues”
	viii. “Cost issues”
	ix. “Technical issues”
	x. “Standardization issues”
	xi. “Safety Issues”
Tantele et al. ([19], p. 5)	Civil engineering context:
	i. “Data accuracy”
	ii. “Data processing and interpretation challenges”
	iii. “Technological constraints”
	iv. “Cost considerations”
	v. “Ethical and legal implications”

“Postdisaster rapid damage assessment” while “Site management” and “Post disaster surveys” were classed as “Established”.

C. Satellites

Amos et al. ([8], p. 123) explained that cameras mounted/carried on Viking rockets and later Mercury space missions yielded “[h]igh altitude photographs of the Earth”. Later space stations and satellites (such as Landsat) would supply photographs of the Earth from space as well with improvements in resolution from satellites being realised (Amos et al. [8]) although often the openly accessible data is of lower resolution (cf. Koppika et al. [6]). In civil and municipal engineering work satellites are used in e.g., earthquake reconnaissance (e.g., Rathje & Adams [17] and Rathje & Franke [29]) as well as to study vegetation and water indices in municipal areas (e.g., Nýdrle [30]). Further applications using RS technologies carried by satellites (and drones) are briefly reviewed in the next section.

IV. APPLICATIONS OF REMOTE SENSING TECHNOLOGIES

This section briefly reviews some key applications of remote sensing technologies – many of the applications (as expected) briefly reviewed in the following sub-sections

are also covered in recent reviews on drone technologies in the civil engineering and allied sectors (see e.g., Albeanio *et al.* [25], Shakhathreh *et al.* [26], Greenwood *et al.* [27], Freeman *et al.* [28], Guan *et al.* [18] and Kim *et al.* [31]).

A. Data Collection & Modelling in Disaster-Prone Areas

Remote sensing is an important method for inspections in post-disaster zones due to, for example, access limitations, safety concerns and the need for rapid data collection post-event to guide relief efforts (e.g., Rathje & Adams [17], Foulser-Piggott *et al.* [32], Gupta & Nair [33], Selvakumaran *et al.* [34]). Womble *et al.* [23] reported on the use of RS data processed using various algorithms post-Hurricane Katrina in the USA. Mansouri & Nourjou [35] used SAR for detection of building signatures after the 2003 Bam (Iran) earthquake. Whitworth *et al.* [36] used open-source RS data to better understand the effects of the 2021 Haiti Earthquake as part of a hybrid Earthquake Engineering Field Investigation Team (EEFIT) mission (due to the covid-19 pandemic) (see also Giardina *et al.* [37]). Thermal RS techniques for studying anomalies have been reported (e.g., Avdan & Jovanovska [38], Zhao *et al.* [39]) as well as seismological studies (e.g., Tronin [40], Wright [41]).

B. Ground Movements

RS can be used to study ground movements as a result of earthquakes, rainfall or effects on mining. Earthquake induced landslides (and ground movements and liquefaction) can be studied using various remote sensing techniques (e.g., Rathje & Franke [29]). Zapata *et al.* [42] used drone surveys to create digital terrain models to carry out slope-stability modelling in landslide prone areas in Quito, Ecuador. Owczarz [43] presented a review of the use of RS techniques such as: “Aerial photogrammetry”, “Airborne LIDAR”, “GNSS” and “Satellite radar interferometry (InSAR)” for tracking mining subsidence.

C. Damage Detection on Infrastructure Assets

Monitoring infrastructure performance and tracking damage progress on fixed infrastructure assets or a network of assets can also be attempted using remote sensing systems (e.g., Stramondo *et al.* [44], Selvakumaran *et al.* [45], Selvakumaran *et al.* [46], Salem *et al.* [47], Casas *et al.* [48]). Three example applications are outlined in more detail in this sub-section.

1) Damage to bridges (Kopiika *et al.* [6])

Kopiika *et al.* [6] articulated the need to make assessments at “regional scale”, “asset scale” and “component scale”. Studying an area in Ukraine OpenStreetMap and GoogleMaps were used to make regional scale investigations while SAR was used to track damage on individual bridges (asset scale) (caution was advised when using low resolution satellite imagery) (Kopiika *et al.* [6]). Computer vision was used with other

available data to conduct component scale work (Kopiika *et al.* [6]).

2) Damage to buildings (Mele *et al.* [49])

Mele *et al.* [49] reported a multi-hazard study of a reinforced concrete building in the Campania Region in Italy. The building was being slowly damaged by a slow-moving landslide Differential Synthetic Aperture Radar Interferometry (DInSAR) analysis was used to study the landslide progression and evaluate the ground movements that lead to structural damage (Mele *et al.* [49]). Results of historical visual inspections were available to the researchers: see [49].

3) Damage to road pavements (Schnebele *et al.* [21])

Reconnaissance of pavement assets still often requires visual inspection which can be supplemented with cameras mounted on vehicles or drones (cf. Schnebele *et al.* [21]). The review also explains how sub-surface voids and other surface defects such as cracking or potholes can be detected with various RS technologies such as: ground penetrating radar (GPR), infrared thermography, LiDAR and terrestrial laser scanning and hyperspectral imagery – the aforementioned technologies have various advantages and limitations (see Schnebele *et al.* [21] for further details).

V. REMARKS ON VISUAL INSPECTION

The increasing use of many types of SHM systems has in part been driven by the desire to supplant or at least enhance visual inspection regimes (see e.g., the review of Nepomuceno *et al.* [50]). In RS work human interpretation of aerial photographs (see e.g., Amos *et al.* [8] in the context of civil engineering surveys and also Mintzer & Spragg [51]) or latterly satellite data (see e.g., Kazmi [52] in the context of a post-earthquake study) is often required.

Due to the distributed nature of many civil and municipal infrastructure assets (O'Rourke [20]), regional scale surveys are essentially only possible with forms or remote sensing and the change has been the technology available e.g., use of aerial photography collected from aircraft flyovers changing to photographs from satellite-systems. However, some application areas (identified by this review) where it would appear that RS approaches are replacing or reducing reliance on visual inspections would be in (i) pre or post-disaster reconnaissance (especially during the covid pandemic) (e.g., Whitworth *et al.* [36], Giardina *et al.* [37] Zapata *et al.* [42]); (ii) construction site management activities (e.g., Almohsen [9]) and (iii) pavement condition surveys (e.g., Schnebele *et al.* [21]).

In the aforementioned cases human interpretation of the collected data remains important. Use of Artificial Intelligence (AI) may reduce reliance on human-led data interpretation in the future. Uses of AI in RS are briefly reviewed in the next section.

VI. USES OF ARTIFICIAL INTELLIGENCE

Systems such as Synthetic Aperture Radar (SAR) and Light Detection And Ranging (LiDAR) produce large datasets (see e.g., the review of Ghaedi *et al.* [53]). Large datasets can lead to ‘data overload’. Therefore, algorithms that can assist with rapid data-processing and interpretation are of value when dealing with these large datasets. Artificial Intelligence and Machine Learning approaches may also be combined with data from social media when interpreting RS datasets (see Kumari *et al.* [10]). Nega & Gedafa ([54], p. 123) argued that “... the civil infrastructure industry is lagging to integrate AI, remote sensing (RS), and 3D printing (3DP) in the development of sustainability of civil infrastructure ...” with many potential productivity benefits on offer should this change (Nega & Gedafa [54]).

Adegun *et al.* ([55], p. 7) compared some “CNN-based deep learning architectures” (with CNN standing for Convolutional Neural Network) when they were applied to various RS datasets. The following factors were found to affect the performance: “Size of the dataset”; “Model Complexity” and “Computational resources” [55, p.19]. The study also explained that “[l]arger datasets require deeper and more complex models to capture the variety of features” (Adegun *et al.* [55], p. 20). Salem *et al.* [47] used a deep CNN method to detect building damage post the 2016 Kumamoto earthquakes. Malinowska *et al.* [56] used Multi-Temporal (MT)-InSAR data processed using an ML model to reduce processing times.

There are concerns on the use of AI and the impact on engineering judgement and ethical use of the technology. Vardanega *et al.* ([57], p. 3577) asked in the context of bridge management if practitioners “... will be able to safely overrule AI recommendations when they produce results that do not align with their own engineering judgement”. There should also be further studies on the ethics of the use of AI and drones (see e.g., the recent paper by Winfield *et al.* [58] proposing a “framework for the ethical governance of swarm robotic systems”). Tantele *et al.* [19, p. 5] explained that RS systems can “capture sensitive information” which may be subjected to different rules depending on jurisdictions. Finally, Ghamisi *et al.* [59] reviewed issues related to the ethical use of AI in the application area of earth observation (amongst other topics).

VII. CONCLUSION

This paper has presented a short review of recent literature on the use of RS approaches in civil and municipal engineering. This short review should also be expanded and built upon as part of a more extensive systematic review following a framework such as the “Preferred Reporting Items for Systematic reviews and Meta-Analyses” (PRISMA) (e.g. Moher *et al.* [60], Page *et al.* [61]) which was e.g. used in the review of Albeaino *et al.* [25].

The paper has reviewed definitions of RS systems; their capabilities and applications in modern civil and municipal engineering. RS is not a new approach but there has been considerable technological change recently. The main observation of this short review is the increased use of drone technology has arguably made RS more accessible to practicing engineers and researchers. The review tentatively indicates some recent increased use of RS in post-disaster work – possibly due to wider availability of drones and open-source satellite data.

Regarding the replacement of visual inspection, the review has tentatively shown that drones in particular can remove some of the need for site walkthroughs pre- or post-disaster. Also, RS technologies have been shown to remove the need for some on-site inspections and tracking in construction engineering or inspection of road pavements.

For asset owners and operators considering increasing their use of RS systems for infrastructure assessments the following areas for further reflection are recommended: (i) review the data-interpretation demand for any new sensing system: this may be mitigated in part with appropriate use of AI and (ii) decide how much human-interpretation and judgement should remain in the workflow. While use of RS technologies is expected to increase in the cities of the future, civil and municipal engineers should ensure that *understanding* is not replaced with simply *accepting* outputs from the technological systems reviewed in this paper.

DATA AVAILABILITY STATEMENT

This work has not generated new experimental data.

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