Institution: University of West London		
Unit of Assessment: UOA 12 - Engineering		
Title of case study: Applications of Non-destructive Technologies		
Period when the underpinning research was undertaken: 2017-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g., job title):**	**Period(s) employed by submitting HEI:**
Professor Morteza (Amir) Alani	Professor of Engineering and Director of the Faringdon Centre	Sept 2014 to date
Dr Fabio Tosti	Professor and Deputy Director of the Faringdon Centre	Feb 2016 to date
Dr Iraklis Giannakis	Research Fellow	Apr 2018 to March 2020
Dr Lilong Zou	Research Fellow	June 2019 to date
Period when the claimed impact occurred: 2017-2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact (indicative maximum 100 words)

This case study accounts for the impact created by the reported activities and outputs produced by a small team of researchers active at the Faringdon Centre (Non-Destructive Research and Testing Centre) at the University of West London. The case study concentrates specifically on the applications of the Ground Penetrating Radar (GPR) and the Interferometric Synthetic Aperture Radar (InSAR) satellite imaging techniques within the context of health monitoring and assessment of trees (early decay and trunk integrity), highways and airfield infrastructures (bridges, tunnels, pavements, taxiways and runways), railway tracks (foundation and ballast conditions) and archaeology (ancient structures and monuments). It reports on impact with communities and industries.

2. Underpinning research (indicative maximum 500 words)

In 2017 the University of West London embarked upon the development of the Faringdon Centre (Non-Destructive Research Centre) in collaboration with several philanthropic organisations and trusts including The Lord Faringdon Charitable Trust, The Schroder Foundation, The Cazenove Charitable Trust, The Ernest Cook Trust and others. A significant University of West London investment, in terms of funding, expertise (researchers) and space, was provided. Parallel to this, external funding, and internal investment, of over £750,000 was obtained to support the multi-disciplinary research and development work of the Centre.

The main identified areas that brought academics, philanthropic and community organisations and industry stakeholders together was the effectiveness of the applications of the non-destructive testing methods in health monitoring and assessment of environmental and highways and public transport infrastructure assets.

The Centre's specific research initiatives revolves around the following development and application areas:

- Advanced signal/data processing and numerical modelling for non-destructive testing methods.
- Assessing the condition of railway ballast using GPR and InSAR satellite imaging technology – experimental, numerical and field project-based developments.
- Monitoring the health of ancient and mature trees, identifying early signs of decay and measuring the extent of defects in tree trunks.
- Investigating tree root and soil interactions, and tree roots mass density and architecture, using GPR.
- Monitoring the integrity and health of bridges, and other civil and engineering structures, using GPR and InSAR satellite imaging technology including the development of novel site operation and data acquisition methods, data processing and interpretation.

- Investigating archaeological sites and features of historical and cultural values using GPR and 3D-Laser scanner.

In summary, the Centre's main achievements through the underpinning research in these areas of endeavour have been:

- New numerical methods, fully automatic imaging algorithms for processing GPR data and numerical modelling with applications in assessment of the tree trunks and roots architecture (leading to estimating the root mass density) have been developed and tested successfully. [R1 & R2]
- Identifying parameters and elements for designing and developing a dedicated GPR antenna system for tree assessment purposes, leading to the first design configuration and manufacture of new-generation GPR antenna systems (prototypes). [Publications have been withheld to date to protect intellectual property rights.]
- In collaboration with industry, developed a new computer-aided multi-stage methodology to control the integrity and monitoring of railway ballast (experimental, numerical, and modelling framework to identify location and scale of ballast fouling). [R3]
- In collaboration with industry stakeholders and the European Space Agency, developed a multi-source, multi-scale, and multi-temporal data system by integration of GPR and the InSAR techniques (satellite imaging) for the health monitoring and assessment of modern and historical bridges. The development included advanced data processing and data fusion between the adopted methodologies. [R4]
- In collaboration with NEDO (Japan's New Energy and Industrial Technology Development Organization), the Centre developed a new approach to detect the interlayer debonding phenomenon at early-stages using a multi-static GPR system. Also, the development of an advanced, accurate imaging method for a ground based synthetic aperture radar (GB-SAR) system. This development takes the advantage of the optimal transform of the spatial frequency changes under the fractional Fourier transform. [R5 & R6].

3. References to the research (indicative maximum of six references)

R1. Giannakis, I., Tosti, F. (Senior Member), Lantini L., and Alani, A. M. (2020). Diagnosing Emerging Infectious Diseases of Trees Using Ground Penetrating Radar, IEEE Transactions on Geoscience and Remote Sensing (TGRS), 58(2), 1146-1155. https://doi.org/10.1109/TGRS.2019.2944070.

R2. Alani, A. M., Soldovieri, F., Catapano, I., Giannakis, I., Gennarelli, G., Lantini, L., Lu, G., and Tosti, F. (2019). The Use of Ground Penetrating Radar and Microwave Tomography for the Detection of Decay and Cavities in Tree Trunks. Remote Sensing, 2019; 11(18):2073. https://doi.org/10.3390/rs11182073.

R3. Lantini, L., Tosti, F., Giannakis, I., Zou, L., Benedetto, A., and Alani, A.M. An Enhanced Data Processing Framework for Mapping Tree Root Systems Using Ground Penetrating Radar. Remote Sensing, 2020; 12(20):3417. https://doi.org/10.3390/rs12203417

R4. Alani, A. M., Tosti, F., Bianchini Ciampoli, L., Gagliardi, V., and Benedetto, A. (2020). An integrated investigative approach in health monitoring of masonry arch bridges using GPR and InSAR technologies, NDT & E International, 115, 102288. https://doi.org/10.1016/j.ndteint.2020.102288.

R5. Benedetto, A., Bianchini Ciampoli, L., Brancadoro, M.G., Alani, A. M. and Tosti, F. (2017). A computer-aided model for the simulation of railway ballast by random sequential adsorption process, Computer-Aided Civil and Infrastructure Engineering - An International Journal, 33(3), 243-257. https://doi.org/10.1111/mice.12342

R6. Zou, L., Yi, L. and Sato, M. (2020). On the Use of Lateral Wave for the Interlayer Debonding Detecting in an Asphalt Airport Pavement using a Multi-Static GPR System, IEEE Transactions on Geoscience and Remote Sensing (TGRS), 58 (6), 4215-4224. https://doi.org/10.1109/TGRS.2019.2961772.

Quality statement: All listed outputs have been published in peer reviewed journals. R1, R2, R5 and R6 have been submitted by the University to this unit of assessment in REF 2021.

4. Details of the impact (indicative maximum 750 words)

Research by the Faringdon Centre has been used to understand the condition of both natural and built structures through applying a range of non-destructive technologies – ground penetrating and airborne radars, satellite imaging and 3D laser scanner – to achieve pioneering results. This has led to novel applications with commercial and economic benefits, as well as benefits for the management of the natural environment. These benefits have been achieved through collaborations with leading international and national companies producing NDT technologies and tools, as well as with infrastructure operators.

Environmental and infrastructural impacts and benefits have been achieved on a regional, national and international basis through work with local authorities, arboriculturists, medium and large-scale enterprises in the UK and Europe by applying non-destructive technologies to the assessment of tree health, roads and highways, and railways infrastructures. In particular, the collaboration with international giants, such as IDS GeoRadar (Part of Hexagon), an Italian-based leading manufacturer of aerospace and NDT testing systems and equipment including GPR antenna systems and interferometric radar technologies, has been instrumental in widening the Centre's engagement with major projects. This has supported the development of novel data processing techniques, along with the design of a dedicated set of GPR antenna systems for health monitoring and assessment of tree trunks and tree roots. [S1]

Much of this impact flowed from the Centre's active role in the European COST project, TU1208. The main purpose of this multi-national project, part of the European Cooperation in Science and Technology programme, was to exchange and increase scientific-technical knowledge and experience of ground penetrating radar techniques in civil engineering, whilst promoting wider and more effective use of this safe and non-destructive method in the monitoring of structures. Alani was one of the two UK representatives on the management committee and together with Tosti had leading roles in several working groups, as well as on the coordination of activities, organisation of annual seminars and workshops associated with the Action. [S2]

Impact A – Railway infrastructure maintenance and management

The Centre's research findings on the health monitoring and assessment of railway tracks integrity [R5], have been applied by railway infrastructure managers in Italy to address limitations in the early-stage identification of structural decay in ballast foundations (ballast fouling) at the network level. This information is regarded as crucial because decay processes can compromise structural integrity, and maintenance must be prioritised based on actual risk levels.

In May 2017, the company – Ferrovie del Gargano srl – worked with the Centre to use advanced GPR technology and InSAR satellite techniques to undertake integrated health monitoring of two sections of their lines, covering inspection tasks including identifying areas of widespread ballast fouling and the monitoring of differential settlements on transition areas at the rail-bridges abutments.

Following these inspections, the company's manager responsible for the Infrastructure Division has written to confirm that: "*The novelty of the ground-based GPR inspections and the integrated approach with the InSAR technique and advances in terms of methodology applied for field surveying of railways are of great value to the maintenance agencies. This was clearly supported by the validation of the results, proving the effectiveness of the newly developed algorithms in data processing at mapping decay inside railway track-beds".* [S3]

Impact B – Health monitoring of trees and tree roots and soil interaction

Although ground penetrating radar is a relatively mature technology, the application and methodologies, processing, and interpretation of GPR data remains challenging and highly affected by noise and clutter, as well as by the competence of the user. In addition, a lack of automatic detection schemes results in subjective interpretations that are influenced by the biases of the user. The Centre's research findings, developments, and knowledge accumulation have included:

- Understanding the transmission of the electromagnetic waves in different trees species with varied moisture contents.
- Establishing existing GPR systems and their limitations with respect to the assessment of trees and tree roots integrity.
- Assessing the limitations of the commercially available software and data processing tools and techniques, and field survey and data collection methodologies.

These findings have led to a significant number of impactful cases in collaboration with local authorities, industries, and research communities.

The Centre has developed several enhanced imaging algorithms for detection of decay and cavities in trees. By applying a pioneering detection framework (tomographic migration), it has been able to produce new predictions to locate and show the scale of decay in tree trunks, with application in forestry management and arboriculture. The significance of the outcomes was received with interest by an audience of practitioners and experts at a London Tree Officers Association (LTOA) seminar in July 2019. This led to series of new collaborations with practitioners and stakeholders within the field. [R1 & R2] and [S6]

The Centre has developed an enhanced data processing framework for mapping tree root systems' architecture and mass density enabling it to identify tree root patterns up to a depth of 0.50m. This development had a great impact on the assessment of several well-established trees in two London boroughs [S6]. A paper on this pioneering work was awarded the "Best Paper Award" at 2020 IEEE 43rd international conference (TSP – IEEE Conference Record #49548). The Centre is currently engaged with the assessment of the oldest Lebanese cedar tree in the UK, located in the London Borough of Hounslow.

Impact C - Health monitoring of roads and highway infrastructures – GPR, Interferometric Radar and Satellite-based remote monitoring techniques

Roads and highway infrastructures, including bridges and tunnels, are major investments requiring viable and strategic maintenance and management. In recent years, the application of non-destructive testing techniques such as 3D laser scanners, ultrasound techniques, fibre optic sensors, and accelerometers, as well as ground penetrating radar technologies, have been developed for use in this area of endeavour. Faringdon Centre research has taken this forward by contributing significantly to supporting industry and stakeholders within the field.

The underpinning research on the health monitoring of highway infrastructures at the Centre has led to collaborations with several partners at national and international level. Since its inception the Centre has been engaged with several projects concerning the health monitoring of bridges and highway infrastructures using innovative approaches based on data integration between satellite imaging and ground-based non-destructive testing methods. To this end, the Centre has proactively collaborated with the Rochester Bridge Trust to use InSAR and GPR technologies for monitoring and assessment of bridges owned or associated with the Trust including, masonry arch bridges. [S7] Structural displacements of the "Old Bridge" at Aylesford, North Kent, UK – a 13th century bridge – was monitored using satellite data covering a period of 26 months in collaboration with the Italian Space Agency (ASI). GPR proved to be instrumental at providing the details of the inner structure of the bridge in terms of geometry and integrity of materials as well as in locating positions of the structural ties. Furthermore, InSAR identified measures of structural displacements caused by the seasonal variation of the water level in the river and the riverbed soil expansions. This pioneering work allowed the Aylesford Parish Council to carry out remedial work on the bridge.

The collaboration with the Rochester Bridge Trust, the ASI and Roma-Tre University in Italy, provided further opportunities for the Centre to develop and apply more advanced data processing algorithms for satellite imaging and GPR data (based on data fusion of multi-resolution datasets and data clustering for detailed and more accurate monitoring of the structural elements of bridges). This has been applied to the Rochester Bridge (a major bridge spanning the River Medway – an ongoing project) and a railway bridge in West London in 2019 (part of Network Rail).

It is important to report that the Centre's proposed multi-temporal InSAR technique was effective at detecting areas subject to an evolving subsidence and down-lifting displacements on the Rochester Bridge.

The Centre was also engaged with several major projects for monitoring runways and taxiways in different international airports. This included Runway 3 at the International Airport of "Leonardo Da Vinci" in Rome, Italy, in 2019, in collaboration with ASI and Roma-Tre University in Italy. The runway was subject to serious differential settlements due to consolidation of the foundation materials over time. The affected areas had previously been subject to successive remediation and repair works at significant financial cost. The scope of the project was to develop a new pavement management approach based on a systematic and integrated use of satellite data. The analysis of the medium and high-resolution data covered the period between January 2015 to April 2019 using the Persistent Scatterers Interferometry (PSI) technique. The reported results were conclusive in terms of accuracy and significance presenting a viable alternative to conventional time-consuming methods for pavement monitoring.

The significance of the outcome of Centre's work was well received by important industrial partners within the aerospace sector. Drawing on their research on the applications of aircraft-based SAR imaging technique in interaction with InSAR imaging, the Centre has collaborated with Umbria Aerospace Systems and Roma-Tre University in the development of innovative sensor systems synchronised with satellite remote sensing measurements for long-term non-destructive assessment and monitoring of transport infrastructure. [S3] A major R&D proposal has also been submitted to the European Space Agency (with support of ASI and UK Space Agency) on the same subject.

The Centre's further research impact with industry and communities has been witnessed in the work reported in section 3 of this document. [R6] Samples of the Centre's research work on the health monitoring of highway infrastructures has been reflected in several COST Action TU1208 proceedings within the context of guidelines in the applications of GPR in civil engineering infrastructure for European communities. [S2]

Impact D – Surveying archaeological and cultural heritage sites
The Centre has worked in conjunction with GEOSERVICE, an Athens-based geophysics services company, to demonstrate an improved approach in the application of NDT methods to archaeological investigations. This led to the demonstration of a use of multi-frequency GPR equipment, surveying methodology and newly developed data processing techniques on the mosaics of a Roman villa in Athens in conjunction with the Ministry of Culture. The tests carried out were used to verify the integrity and homogeneity of the structural layer underlying the mosaic using an integrated GPR surveying technique.

The CEO of GEOSERVICE endorsed this work and has reported that: *"...the integrated surveying methodologies, the GPR equipment and the algorithms developed by the Faringdon Centre team are now currently used by professionals and practitioners in this area of endeavour"*. [S5].

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. Letter from R&D Director, IDS GeoRadar (Part of Hexagon), dated 1/7/20.
S2. https://www.cost.eu/actions/TU1208/#tabs|Name:overview & https://gpradar.eu/index.html
S3. Letter from Consigliere Delagato, Ferrovie del Gargano srl, dated 27/7/20.
S4. Letter from Chairman and Commercial & Technical Manager, Umbria Aerospace Systems, dated 11/11/20.
S5. Letter from CEO, GEOSERVICE, dated 23/6/20.
S6. Corroboration available from the Tree Service Manager, London Borough of Ealing, and in a letter supplied by him, dated 27/11/19.
S7. Corroboration available from the CEO and from a Service Manager, Rochester Bridge Trust.