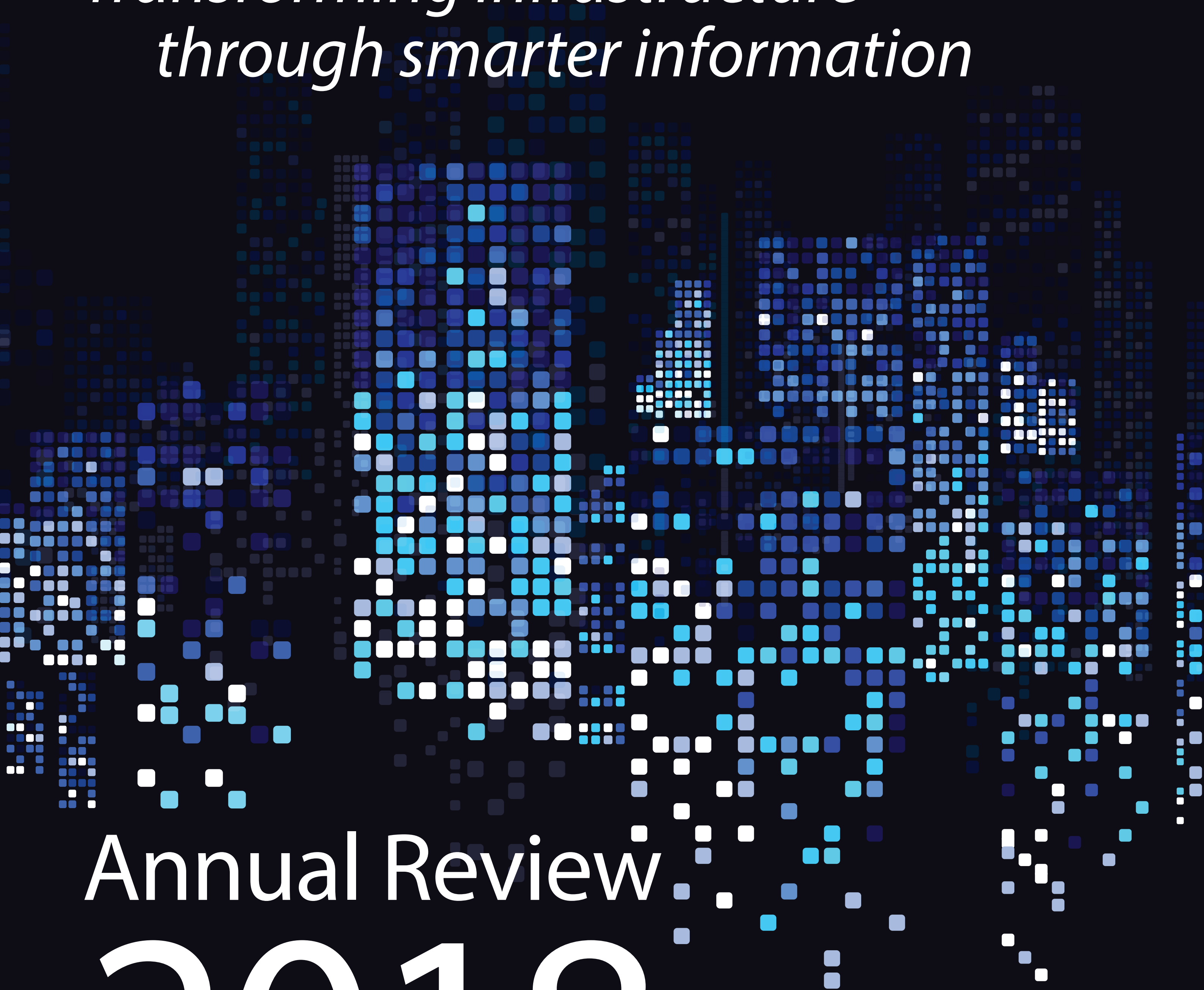
UNIVERSITY OF CAMBRIDGE

Transforming infrastructure through smarter information



Annual Review 2018

CSIC Cambridge Centre for Smart Infrastructure & Construction

CSIC Partners

Infrastructure clients
(owners and operators)

Consultants, contractors and
asset managers

Technology and information
supply chain

Contents

Foreword

Sarah Hayes
Senior Regulatory Advisor
National Infrastructure Commission

The UK National Infrastructure Commission is the non-ministerial government department responsible for providing independent, strategic thinking, analysis and advice to address the UK's long-term infrastructure needs.

Using technology in infrastructure can help us get more out of what we've already got.

CSIC are pioneers in this area and assisted the National Infrastructure Commission in the preparation of our recent report *Data for the Public Good*, which looked at how new technologies can increase the efficiency of our existing infrastructure. We found that data is now as much a critical component of our infrastructure as concrete and steel, and needs to be updated, housed and made secure in the same way as physical infrastructure.

But the value that new data technologies can provide will not be realised unless our infrastructure data can be shared and accessed easily and securely. Our report recommends the creation of a Digital Framework Task Group, which will provide a roadmap for standards and formats for collating and sharing infrastructure data. CSIC will play a central role in this group, and their expertise will be critical to the success of the programme.

We also recommend a national digital twin, which we believe is the culmination of data and artificial intelligence capabilities to build a bird's eye view of a city or the country to model how transport, water, energy and digital systems interact. The digital twin would model how, for example, we can make those systems run more efficiently so we can get to work more quickly or charge our electric vehicles at the cheapest rate possible. The key input to the digital twin is high quality, properly curated data.

This summer, we will publish the UK's first National Infrastructure Assessment, setting out our infrastructure needs for the next 30 years. For us, it is crucial that the resulting investment decisions are informed by high quality data to enable the best choices for future consumers. As a centre for excellence in infrastructure sensing, asset management, and smart city systems, CSIC has a major role to play in achieving this.

Introduction

Image courtesy of Paul Milsom on behalf of ICE

Professor Lord Robert Mair CBE
Head of CSIC
University of Cambridge

The principal aim of the Cambridge Centre for Smart Infrastructure and Construction (CSIC), funded by EPSRC, Innovate UK and industry, is to transform the future of infrastructure through smarter information informing better decision-making. Its key objective is to advance research in smart infrastructure and create impact in the infrastructure and construction industry. CSIC is developing cutting edge sensing and data analysis models, which will provide a powerful platform for delivering data to enable smarter and proactive asset decisions, both during construction of new infrastructure and for existing infrastructure. The underpinning theme of integrated data-driven solutions is the subject of this Annual Review, which highlights a range of innovative and timely projects delivered by CSIC.

The UK Government has published a number of key reports over the past year of direct relevance to integrated data-driven solutions and the work of CSIC.

A White Paper on the Industrial Strategy which included Construction as one of four new sector deals was published in November 2017. Key features of the Construction Sector Deal are 'Procuring for value' and 'Industry-led Innovation', the former emphasising whole-life value and the latter making a commitment to investing in a transformative programme bringing together construction and digital technology.

In December 2017 the Government also published *Transforming Infrastructure Performance* (TIP) by the Infrastructure and Projects Authority (IPA), *Transport Infrastructure Efficiency Strategy* (TIES) by the Department of Transport, and *Data for the Public Good* by the National Infrastructure Commission (NIC). The TIP report identified as immediate priorities digital technologies and innovation to improve the way we deliver and extract maximum whole-life value from infrastructure. It emphasised the importance of collection and use of data to improve maintenance efficiency and optimise asset life. The TIES report identified core challenges including a key one to 'exploit digital technologies and standardise our assets'.

As outlined by Jennifer Schooling in her article on page 4 of this Review, the *Data for the Public Good* report calls for making high-quality data more available to drive improved value for consumers and deliver a better experience for infrastructure users. It provides a call to arms for research and industry working at the cutting edge of new data-driven technology to help optimise the potential use of data to deliver benefits beyond individual sectors and for the good of the country.

A key theme of all of these recent Government reports is the power of integrated data-driven solutions, and the crucial roles of data and data-centric engineering. These will enable infrastructure and construction organisations to identify and extract valuable information from increasingly large data sets for better asset monitoring and management. Anne Kemp, in her article on page 6, highlights the value that we can draw from our digital assets – often referred to now as the digital twin.

Our Review presents a number of case studies demonstrating how CSIC works with partners to deliver effective solutions for industry. The importance of integrating sensors is illustrated on page 14 in a study describing the monitoring of the structural response of the Grade I listed St Mary Abchurch in London subjected to significant tunnelling-induced movement.

The value of integrating analytics is described on page 16 in an article about sensing for two new railway bridges (the Staffordshire Alliance) and a Victorian masonry viaduct. In each case vast amounts of data are being analysed by CSIC in collaboration with the Alan Turing Institute and Imperial College London.

This Review also brings focus to integrating infrastructure information for efficient whole-life asset management and to integrating cities – in the latter case, optimising space and resources from underground thermal heat sources to hot spots for growing plants.

These articles and case studies demonstrate CSIC's continuing commitment to providing leadership in the latest technical developments in infrastructure sensing, data analytics and asset management.

Transformation through collaboration

Dr Jennifer Schooling
Director of CSIC
University of Cambridge

Data science can help the nation increase the productivity of infrastructure by extracting information from data about infrastructure assets. This in turn can enable decision-makers to understand more about what infrastructure exists, where it is, how it interacts, how it is used and crucially how the system as a whole can be made more efficient.

Data for the Public Good, 2017, p17

In *Data for the Public Good* (December 2017) the National Infrastructure Commission (NIC) recognises the value of innovative technologies and quality data to transform the performance of the UK's infrastructure. Open collaboration between Government, industry practitioners and the wider community is crucial to realising the potential of smart infrastructure.

The report calls for making high-quality data more available to drive improved value for consumers and deliver a better experience for infrastructure users. It calls for research and industry to work together to maximise the potential benefits of data-driven technology to the advantage of all – from individual sectors to society as a whole.

CSIC has an established pedigree in employing world-leading research in sensing and data solutions to transform the future of infrastructure and construction. We work across policy, standards and industry adoption to effect transformative change and deliver benefits to all stakeholders.

Collaboration with partners in the infrastructure and construction industry and related organisations is key to success and it is through these collaborations that CSIC is able to initiate projects that harness new technologies and methodologies to provide solutions to real industry challenges.

Collaborating on data

Data for the Public Good recommends the creation of a 'National Framework for Infrastructure Data' to enable data about infrastructure assets to be shared, so that the benefits of coordination and collaboration across the infrastructure network operators, regulators and users, can be achieved from data and the application of data science. This is a critical enabler to overcome some of the barriers to the uptake of smart infrastructure solutions, caused by poor curation of infrastructure data within and between organisations. The NIC recommends that the newly established Centre for Digital Built Britain leads on this, with collaboration with a number of organisations including CSIC and the Alan Turing Institute.

Centre for Digital Built Britain

The prize from the digital agenda has grown from enhancing efficiency in construction to improving national productivity. This requires a next generation of Building Information Modelling that supports information throughout the whole asset lifecycle, in addition to making sure that the investment already made in enabling construction efficiency continues to grow to support new capabilities such as digital transactions, modular manufacturing and the provision of services through the life of the built assets.

The Centre for Digital Built Britain (CDBB) is a partnership between the Department of Business, Energy and Industrial Strategy (BEIS) and the University of Cambridge to deliver a smart digital economy for infrastructure and construction and transform the industry's approach to the way we plan, build, maintain and use our social and economic infrastructure. CSIC is working closely with CDBB to digitise the entire lifecycle of our built assets and find innovative ways of delivering more capacity from our existing infrastructure. This collaboration brings focus to developing standards and growing a culture of secure data sharing to dramatically improve decision-making, informing the design and maintenance of our assets. It will enable us to make better use of the infrastructure we already have and to enhance the performance of our cities and the communities they serve.

The Alan Turing Institute

CSIC researchers are joining data scientists at the Alan Turing Institute, the national institute for data science, to make sense of 'Big Data'. This data-centric engineering will enable infrastructure and construction organisations to identify and extract valuable information from increasingly large data sets for better asset monitoring and management. Real-time infrastructure data collected by monitoring systems will leverage advanced statistical and machine learning techniques to aid analysis and improve the interpretation of structural health monitoring data. In the longer term, this work will enable data and information to be fed into 'digital twins' of the instrumented assets, providing asset managers with a powerful tool for assessing performance and long-term risk.

Collaborating with our partners

As well as optimising the opportunity presented by the UK digital agenda, CSIC's programme is informed by the strategic needs of our partner organisations. The first annual CSIC Partner Strategy Day was held in November 2017, and was fully attended by our partners across the sector, including: infrastructure owners and operators; consultants, contractors and asset managers; and technology and information supply chain professionals. Presentations and discussions focussed on four key themes: infrastructure design, assessment and construction; asset management and operation; cities; and sensing and measurement. The strategy day resulted in the identification of a number of key areas where CSIC can bring expertise and support, future research opportunities and new collaborative proposals. The themes include data curation, risk monitoring and asset management, building the value case, and understanding city-scale transformation. CSIC is actively seeking to build these themes and opportunities into our strategy and projects moving forward.

Research direction

Over the last year, CSIC's investigators have won research funding totalling £3.4 million, bringing the total additional funding for Phase 2 (2016 onwards) to £4.9 million. This research is funded by a number of organisations, including EPSRC, Innovate UK, Horizon 2020, industry partners and charitable foundations.

Our research is focussed on data-driven decision making, including design verification (for example Principal Tower, see page 30), transforming construction through timely and accurate data (for example Integrating Sensors, see page 14), data-driven asset management (for example Integrating Analytics see page 16) and transformation at city scale (for example Integrating Cities see page 18). This approach to using world-leading research to address pressing industry challenges, in collaboration with partners, is key to CSIC's agenda.

Bringing benefits to all

This is a seminal moment: static and real-time capture, analysis, sharing and structured use of data (in a secure manner) should now be seen as fundamental to realising productivity gains. The digital age brings unprecedented opportunity for effective collaborative action.

The UK has the potential to lead one of the defining developments of the 21st century. The intelligent use of digital technologies will enable the country to capture not only the inherent value in our built assets, but also to create a digital and smart economy that will bring benefits to all.

Forward thinking for digital transformation brings opportunity and responsibility

Dr Anne Kemp
Director at Atkins – BIM Strategy and Development
Chair, UK BIM Alliance

The progress of the UK infrastructure and construction industry along the path of digital transformation has been profoundly influenced by the initiatives instigated by the UK Government BIM Task Group which first emerged in 2011. Significant effort has subsequently been spent on developing the strategy, leadership, standards and guidance to enable government departments in particular – and the wider industry in general – to take the fundamental steps towards digitally transforming the way infrastructure projects are delivered, and in the longer term, how our entire built environment is run. This leadership and drive has now passed to the Centre for Digital Built Britain (CDBB) and CSIC is working with CDBB to support the transformation to a smart digital economy for infrastructure and construction.

The principle that underpins the rationale for this transformation is the value that we can draw from our digital assets – often referred to now as the 'digital twin'. The digital twin will allow us to experiment, in an infinite number of ways, and to test, to the point of failure. It will enable off-site assembly in a safer and more controlled environment, and provide the tools to monitor and run, in real time, the assembly of physical assets within context of, and in response to, the wider environment and surrounding activities. Ultimately, there will be no value unless such 'virtual' simulation and control allows us to gain greater insight into how we can develop and improve the running of the built environment in a manner which benefits business, the environment and society.

This goes to the heart of the rationale behind BIM, much maligned as that term has become. The motivation for the UK initiative has always been about achieving better outcomes from infrastructure through better information management. And that has to be derived by 'beginning with the end in mind'.

This is why it is so important that we ensure that the principles developed around what has become labelled as BIM Level 2 are embedded across the UK industry as an essential component of the journey towards wider digital transformation.

The important point, which is so often missed, is that we are fundamentally looking for solutions to the challenges around the built environment – driven by data – and that data comes from multiple sources which need to be integrated. This is why the development of open standards, to support such integration in a dynamic way, is critical to progress. The work currently being delivered jointly by buildingSMART International and the Open Geospatial Consortium (OGC) through the Integrated Built Environment Working Group is a good example of the activity focusing on this challenge.

Our transformation to digital requires forward planning but we should not lose sight of the present and we must continue to focus on implementing the basic principles that underpin Level 2 and beyond at grassroots. Then we can afford to look into the future to ensure we are on the right trajectory and are addressing the relevant questions, and not be blind-sighted to changes and disruptions which are, no doubt, just around the corner. We need to ensure that we keep challenging our thinking by collaborating across industry sectors and across research communities to foster the required dynamic and rigour.

The responsibilities we hold for future generations is significant. Leadership, inspiration, curiosity and an open mind will be key to building our future.

The year in numbers

28
Total Phase 2 partners

59
Knowledge exchange events

£4.9m
Total Phase 2 funding

8
Industry secondments

14
Trade articles

£3.4m
New funding

40+
Current projects

12
New grants

21
Proof of concept and demonstrator projects

Work with us

CSIC works collaboratively with a range of infrastructure and construction organisations to catalyse the digital transformation that will help to establish the UK as a global leader in smart infrastructure. CSIC provides partner companies and organisations operating in the infrastructure and construction sectors with the tools, training and knowledge required to take advantage of the latest technical developments in data analysis and interpretation, asset management and sensor technology.

Sharing information, skills and knowledge is key to advancing industry adoption of innovative solutions to engineering challenges. CSIC's Business Development and Knowledge Transfer team work closely with industry to identify and understand key issues and barriers in order to design, develop and deliver effective and repeatable solutions. The following short case studies demonstrate how CSIC works with industry in four key areas of engagement: deployment of smart technologies, developing the value chain, delivering solutions and training and dissemination.

Developing the value chain

Industry collaborator: British Geological Survey (BGS)

CSIC and BGS collaborated on a six-month project to combine city information modelling with BGS's subsurface geological modelling to generate an integrated appraisal of land viability that takes into account above and below ground conditions in Greater London. A series of geospatial queries aligned to future city scenarios was identified, developed, and simulated using the integrated city model. The goal is to increase utilisation of underground space in a sustainable and efficient manner and to leverage underground space to yield city-wide energy efficient solutions.

> CSIC's knowledge of urban data sets and their expertise in processing such 'big data' was really important for understanding the linkages between the natural subsurface environment against the built environment. In particular, the influence of basement structures on geothermal potential, which was just one of a plethora of relationships that were explored. The capability provided by CSIC has been invaluable for enhancing the BGS's understanding of these types of data and the way in which they are interrogated, cultivating new ideas for CSIC and BGS to explore together in the future.

Ricky Terrington, Translucent Cities Project lead – British Geological Survey. Seconded to CSIC with colleagues Holger Kessler and Steve Thorpe between October 2017 and March 2018

Delivering solutions

Industry collaborator: Estate Management (University of Cambridge)

CSIC's Asset Management team is working with the Estate Management (EM) department at the University of Cambridge to assist in the development of their asset information requirements. EM is currently embarking on a project to embed asset management within the organisation and one of the key processes of this work is to develop asset information requirements that align to organisational objectives. A CSIC-developed framework is supporting this alignment which ensures only information that generates value for the orgnaisation is collected. The framework is also supporting the embedment of Building Information Model (BIM) within the EM.

> Estate Management has long procrastinated on the best approach to its asset information requirements. CSIC's Asset Management team is working with the department to agree a level of asset data that will help meet the objectives of the Estate Strategy. The work will ensure that the level of information is sufficient for safety and business purposes without creating unnecessary administrative burden.

Christine Leonard, Facilities Asset Strategy and Compliance Manager, University of Cambridge

Training and dissemination

Industry collaborator: Various

Sharing information and knowledge is key to advancing industry adoption of innovative solutions. CSIC provides training targeted to meet the needs of a particular monitoring application, from how to run specialised equipment to simply handling and installing fibre optic cables. Industry partner staff on the Principal Tower project (p. 20), the Bank Station monitoring project (p. 14) and the proof of concept project with Morgan Sindall (right) have received training from CSIC either on-site or in the CSIC labs in Cambridge.

> CSIC is keen to promote industry adoption and implementation of innovative monitoring techniques by providing knowledge and training directly to industry partners. Training in the use of new monitoring techniques allows industry collaborators to implement monitoring programmes without the need to rely on CSIC for regular monitoring activities. We look forward to expanding our training offering when the new UKCRIC-funded national sensing facility is completed in the summer of 2019.
>
> Dr Cedric Kechavarzi, CSIC Operations Manager

Deployment

Industry collaborator: Morgan Sindall Engineering Solutions Limited (MSES) (formerly UnPS Limited)

MSES collaborated with CSIC to develop a full-scale, proof-of-concept, real-time displacement control system using Fibre Optic Sensing (FOS) and expansive geopolymers to compensate for deep excavation induced displacements. A field trial was carried out at one of the main Tideway West Worksites at Carnwath Road, London. The FOS system was deployed to monitor subsurface displacements, interpret the soil-geopolymer interaction and enable displacement control.

> Without CSIC's expertise in providing a bespoke monitoring solution, specifically developed and adjusted to a project's needs, it would be impossible for my company to exploit our research in an optimal way. Working with CSIC means I am not limited to collaborating with geotechnical engineers, but work with several other disciplines. This enables me to gain a more holistic approach and view of the project challenges, which has led to more efficient solutions.
>
> Maggie Palaeologou, Senior Design Engineer at Morgan Sindall Engineering Solutions. Seconded to CSIC to lead the research project

Images show: a) The new civil engineering building under construction; b) The strong floor in the new civil engineering buildings with post tensioning cables exposed; c) Anchor tubes within the strong floor (before concrete)

CSIC collaboration with UKCRIC

The University of Cambridge is one of the founding members of UKCRIC (United Kingdom Collaboratorium for Research in Infrastructure and Cities). Construction of the UKCRIC-funded national centre for infrastructure sensing, a state of the art research facility available to researchers throughout the UK, is scheduled for completion in the summer of 2019. The new facility (pictured above), located on the University's West Cambridge Site, will build upon the success of CSIC and focus on research in the application and development of advanced sensor technologies for the monitoring of the UK's existing and future infrastructure, in order to improve resilience and extract maximum whole-life value.

CSIC Partnership – tailored to suit all sizes from individuals and start-ups to multinational corporations

Partnership agreements enable collaboration and open engagement to help companies and organisations working in infrastructure and construction to be well informed to stay ahead of the competition. By collaborating with partners, CSIC is able to accelerate the process of implementation of research outputs, delivering value to stakeholders by improving margins, reducing costs, enhancing returns and extending the productive life of assets. Partnership collaborations lead to new skills and techniques that deliver smarter and repeatable solutions to industry challenges and provide case study evidence to highlight where significant savings and value can be made to the benefit of all stakeholders, cities and communities. CSIC offers four types of partnership to best suit different types of organisations: Full Partners, SME Partners, Micro Partners (less than 10 employees), and Associate Partners which are typically non-commercial, non-profit-making organisations. Partner benefits include engagement in CSIC's strategic research themes, opportunities to second staff to CSIC, and access to partner events.

Get in touch

Working with CSIC creates a range of benefits that derive from a strategic collaboration between academia, industry and policy. This in turn can lead to step changes in delivering greater efficiency in design and performance, a low-carbon society, sustainable urban planning and management and improved health and productivity.

If you would like to learn more about the way we work or collaborate with us please contact:

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CSIC-Comms@eng.cam.ac.uk

Knowledge transfer and training
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Business development
Phil Keenen
ptk23@cam.ac.uk

Point cloud from 3D laser scan of St Mary Abchurch. Image created by Antonio Luciano

Integrating smart solutions

Advances in digital technology and outputs of world-leading innovative research at the University of Cambridge are enabling new integrated solutions to improve the whole-life performance of both new and existing infrastructure. The availability of large quantities of data presents opportunities to transform and optimise the sustainable, social, and economic functioning of our built environment and improve the resources, services and experiences delivered to infrastructure users.

The following four articles showcase a number of innovative integrated solutions to a range of timely challenges, providing tools and techniques that exploit synergies to deliver greater efficiencies and value. CSIC's collaborative and multidisciplinary research aims to secure the seamless optimisation of physical and digital infrastructure as a whole to provide smart solutions for the design, construction and management of our assets.

Integrating Sensors
Innovation in sensing to monitor the influence of tunnelling under heritage structures

Integrating Analytics
Tomorrow's world – developing data-centric engineering solutions for smarter infrastructure

Integrating Cities
Planning in 3D: Optimising space and resources in city settings – from underground thermal heat sources to hot spots for growing edible plants

Integrating Infrastructure Information
Integrating infrastructure information for efficient whole-life asset management

Innovation in sensing to monitor the influence of tunnelling under heritage structures

Introduction

CSIC is collaborating with the contractor Dragados and its monitoring arm, Geocisa, under the guidance of London Underground, to monitor the structural response of Christopher Wren's Grade I listed St Mary Abchurch and George Dance's Mansion House during major tunnelling work taking place under the buildings. The tunnelling is part of the Bank Station capacity upgrade taking place between 2016 and 2021.

Advanced engineering analysis had indicated only negligible impact is expected in each building. However, there are significant uncertainties regarding the behaviour of the ground and the buildings during the tunnelling making monitoring a necessary mitigation measure. Monitoring includes new generation sensing techniques – fibre optic strain sensing, photogrammetry, point cloud and satellite displacement monitoring. Data from these techniques are compared with data from traditional instrumentation to assess their reliability for these applications and to gain a better understanding of the response of the structures to inform future design.

Live monitoring with fibre optic sensing

Fibre Bragg Grating (FBG) strain measurement utilises a fibre optic cable with strain sensors present in-between cable attachments. For this project, FBG technology was used to measure horizontal strain and temperature at three elevations of the four external nave walls of St Mary Abchurch. This provided data at multiple points across the face and allowed monitoring of the development of building curvature during tunnelling. Another cable measured hoop strain of the painted dome in order to assess the influence of tunnelling works on this movement-sensitive heritage feature. Data was gathered from 80 sensors around the building every hour. FBG cables were also used to measure horizontal strains in the walls of the ballroom at Mansion House. In a first of a kind for CSIC, a single cable was used to measure both temperature and strain for external facades. The system has been live since July 2017 and has required minimal maintenance.

Advantages of fibre optics

Fibre optic (FO) sensing has been proven to be reliable, low-maintenance, and suitable for trigger alarm systems. It has a distinct advantage to traditional approaches for this application as it provides distributed strain measurements across the building, enough to ensure potential problems are identified in real time, and with relatively low cost and little visual impact. FO sensing measures damage directly via strain at a high enough resolution to avoid the assumptions typically required when inferring strain from sparse displacement data from traditional instrumentation, which can be unconservative. The fibre optic monitoring system installed at St Mary Abchurch allowed the project to take an informed observational approach and avoided traditional tunnel mitigation measures such as compensation grouting or temporary propping which would have been costly and disruptive (saving in excess of £1m).

3D Laser scanning

An innovative application of this technology has been employed to quantify existing damage in the buildings before tunnelling works by exploring distortions and rotations of the building facades with new algorithms. This is informing our estimations of the past settlement history of the building due to nearby excavations. Point clouds are also being used to measure deformations at the end of works, using techniques developed in earlier CSIC projects, to provide high quality deformation information on the facades and dome of the structure.

Training for Geocisa staff

CSIC provided training to the Geocisa survey team on how to use the fibre optic equipment hardware and software and familiarise them with the specific FO monitoring system of St Mary Abchurch and Mansion House so that sources of any problems could be identified quickly. Working together ensured effective maintenance of the system and the ability to identify anomalous readings.

Monitoring dashboard

Data from the FBG sensing was integrated into the monitoring dashboard system to complement the data from conventional sensors and has been used as part of the trigger alarm system. This is the first time fibre optic sensing data has been included in a monitoring dashboard for London Underground. It allows effective visualisation of the localisation of real-time strains, with digital 3D building models. This facilitates the communication of monitoring data to the construction teams and building owners.

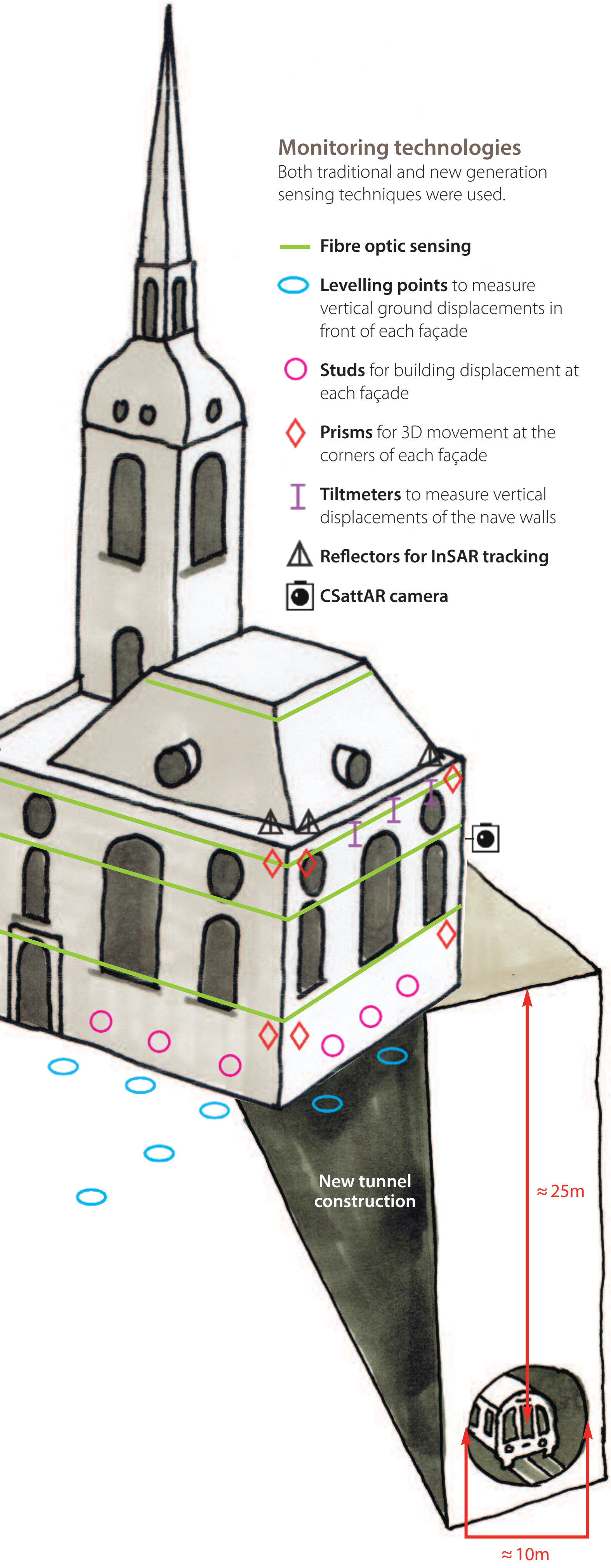
Understanding the response of the structures for future design: what the data and modelling revealed

- Advanced engineering assessments captured greenfield ground movements with remarkable accuracy. However, the building experienced higher strains than the greenfield. To find maximum strains it is necessary to model the building with its openings and existing damage.
- Inferred strains from measured displacements were significantly smaller than strains measured by fibre optics. This demonstrates the benefit of fibre optics to monitor building response during tunnelling.

Delivering value

This real-time monitoring project using state-of-the-art technology enabled savings in excess of £1m and led to an improved understanding of structural behaviour during tunnelling, which will enable further savings in future projects.

> “ The innovative monitoring system used on Grade I listed buildings has provided the client with extremely informative and useful data. By adopting this system, we were able to feel comfortable that we would be first to know about any unusual response, and I hope the data collated will also provide valuable input to any future building damage assessments.
>
> Mark Dewhirst, Senior Project Engineer, London Underground



Monitoring technologies

Both traditional and new generation sensing techniques were used.

- **Fibre optic sensing**
- **Levelling points** to measure vertical ground displacements in front of each façade
- **Studs** for building displacement at each façade
- **Prisms** for 3D movement at the corners of each façade
- **Tiltmeters** to measure vertical displacements of the nave walls
- **Reflectors for InSAR tracking**
- **CSattAR camera**

Relative displacement and strain deformation measurement using digital image correlation (DIC)

CSattAR, a photogrammetric monitoring system developed by former CSIC PhD student Mehdi Alhaddad which has proved successful in tunnel environments, has been used for monitoring the interior of St Mary Abchurch (including the painted dome) and the decorative plaster ceiling of Mansion House ballroom. Existing features in the painted dome and ceiling plaster were tracked by the low-cost, easily-installed CSattAR system which accurately measured real time relative deformations of structural elements at resolutions higher than 0.1 mm.

This CSattAR application is part of a larger project to provide a better understanding of the behaviour of the monitored assets when they are subjected to movements and also to validate and further explore the use of this new technology for monitoring purposes in varied environments and is funded by ARUP and CSIC. Contact: Dr Mehdi Alhaddad.

Relative displacement measurement using Interferometric Synthetic Aperture Radar (InSAR)

InSAR data from radar satellites are being compared with data from traditional measurement techniques at St Mary Abchurch and Mansion House to validate InSAR results and understand the opportunities and limitations of such measurements. The frequency and spatial resolution of satellite radar images has improved in recent years opening up the possibility of monitoring line of sight displacement as well as other phenomenon within infrastructure assets. However, the ability to identify specific monitoring points in densely developed areas such as the area around Bank Station is extremely challenging. In collaboration with the Satellite Applications Catapult with funding from Innovate UK, corner reflectors have been installed on St Mary Abchurch to allow the tracking of movement of very specific points on a structure and compare them with other monitoring data collected at the same points.

This work forms part of a larger University of Cambridge PhD research project investigating the advances in satellite measurement technologies to understand their relevance, utilisation, and limitations to civil engineering applications and is sponsored by the National Physical Laboratory with additional funding from Laing O'Rourke and support from the German Aerospace Centre (DLR). Contact: Sakthy Selvakumaran.

Benefit to

Heritage property asset owners, construction contractors, infrastructure designers

Impact and value

- real-time trigger assessments
- better understanding of the response of heritage structures to nearby tunnelling
- cost and time savings

Project contact

Dr Matthew DeJong, CSIC Investigator
Dr Sinan Açıkgöz, 1851 Brunel Fellow
Dr Andrea Franza, Research Assocaite

Tomorrow's world – developing data-centric engineering

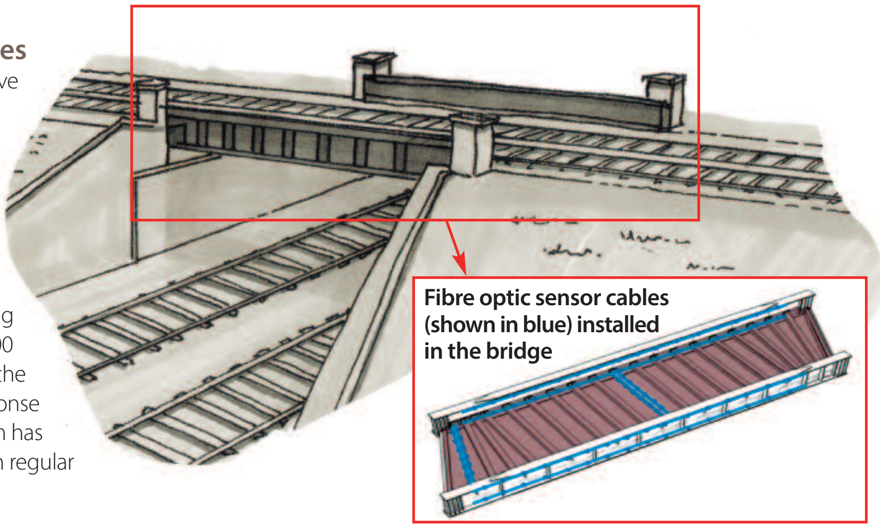
Introduction

Smart infrastructure delivers an abundance of data that offers new engineering insights, but how does an organisation identify valuable information from this data? In collaboration with the Lloyds Register Foundation, CSIC engineers, the Alan Turing Institute (ATI) data scientists and researchers from the Department of Mathematics at Imperial College London are working together to design and deploy long-term mixed-sensor monitoring systems to live stream data for high-level statistical analysis in real time.

This collaboration between structural engineers and big data analysts is being tested and developed on bridges at opposite ends of their service life: two new-build self-sensing bridges built as part of the award-winning £250m Stafford Area Improvements Programme on the West Coast Main Line near Crewe; and a Victorian masonry viaduct in Leeds. Both are owned and operated by Network Rail. These two data sets provide a rich resource of information, enabling engineers and statisticians to transform the current approach to structural health monitoring and optimise future design and asset management.

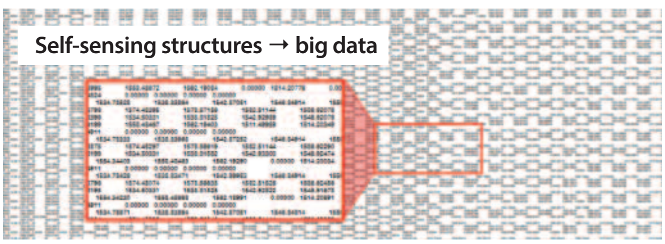
Sensing the Staffordshire Alliance Bridges

Two types of fibre optic sensor monitoring systems have been installed at the Staffordshire Alliance Bridges: a distributed system based on Brillouin Optical Time Domain Reflectometry (BOTDR); and a point-based system using fibre Bragg gratings (FBG) capable of measuring changes in strain in real time. Fibre optic sensor cables were installed into the main prestressed beams, steel girders and concrete sleepers off-site to allow faster installation of monitoring systems. More than 400 FBG sensors and more than 600 metres of BOTDR sensor cables have been installed in the two bridges to determine the static and dynamic response during whole-life performance. This monitoring system has already been generating vast amounts of data through regular data collection visits by CSIC researchers.



Integrating analytics to make sense of data

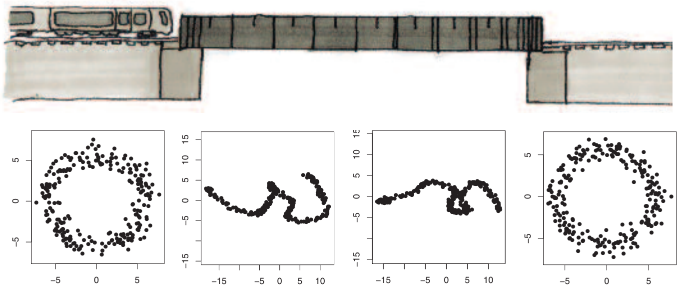
Provisions are currently being made in collaboration with Network Rail to enable real-time and live-streaming of data from the Staffordshire bridges. In collaboration with researchers from the Data-Centric Engineering programme, led by Prof Mark Girolami at the Alan Turing Institute, high-level integrated data analytics will be performed on the continuously collected data. Data will no longer be collected and then analysed separately, but will be streamlined to deliver analytics in real time using advanced statistical methods. These methods will be used to identify anomalies in the data patterns in order to alert asset managers to a change or an event in the structure which can then be investigated and addressed in real time. This system will allow for the identification of both time-sensitive data and long-term trends.



0.1 seconds of data from Staffordshire Alliance bridges

Doughnuts from data

Initial statistical analyses of data (based on principal component analysis) from the Staffordshire bridges have produced a doughnut-shaped plot which provides insight into how the sensor network data covaries over space and time. When a train passes over the structure, we see the shape of the plot change and then return to its original form after the train has passed. The aim is to use similar statistical techniques to track these plots and other parameters over time and correlate the changes to deterioration.



Statistical plots highlighting the covariation in sensor network data over space and time

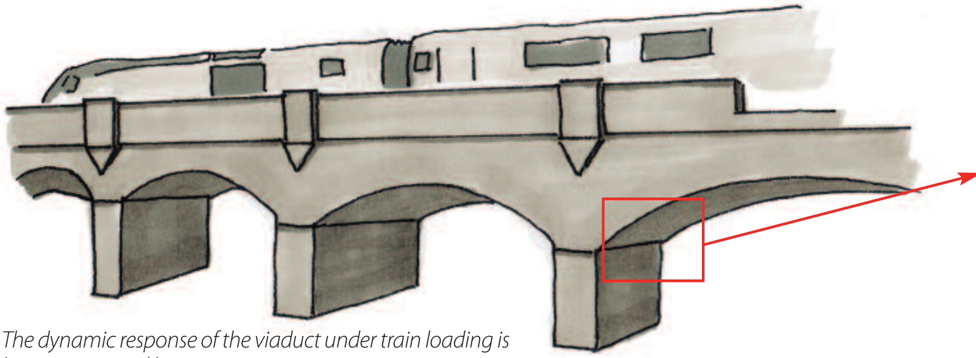
> Advanced statistical methods, including machine learning and artificial intelligence techniques, is the realm of data scientists and applying this to self-sensing infrastructure is an emerging area of research. Data is at the centre of the process, but it is not driving it alone. We want to see how we can create a model that is a synthesis of statistical and physics-based, or finite element, models.
>
> Dr Liam Butler, CSIC Research Associate and Group Leader within the Lloyd's Register Foundation Data-Centric Engineering programme at the Alan Turing Institute

Monitoring degradation of a Victorian viaduct

In September 2017 CSIC installed a long-term monitoring system at a viaduct in Leeds to evaluate deterioration of the structure and to determine the effectiveness of previous maintenance measures. This followed a short-term monitoring project that took place in July 2016 to understand the dynamic response of the viaduct under train loading, and to explain existing structural damage (see Figure 2 which shows data from 2016 and 2017).

The long-term monitoring system includes: a network of 80 FBG sensors to measure distributed deformation (at a sample rate of 1kHz) across three arch spans that exhibit a range of damage severity; acoustic emissions sensors (AES) at specific damaged locations, which are triggered by high frequency vibrations and capture the energy release when cracking occurs; high sensitivity accelerometers (HSA) to measure motion in the structure due to vibration caused by trains passing over the viaduct (see Figure 1).

Once the data acquisition system is fully operational, the sensing data will be sent remotely to the Alan Turing Institute and Imperial College for high level data analytics and statistical analyses. In short, the accelerometers aim to replace current methods of using deflection poles to measure displacements at critical locations, which require road closures and site visits for data collection and therefore are not useful for long-term deployment. The AE sensors aim to detect rates of cracking directly, and to see how these rates of cracking change with time and temperature. This is the first time these sensors will have been used with such extensive FO strain measurement, to be able to correlate local evidence of damage (AE) with both local and global changes in dynamic behaviour (FO). This will improve safety by allowing the development of effective alert systems.



The dynamic response of the viaduct under train loading is being monitored long term

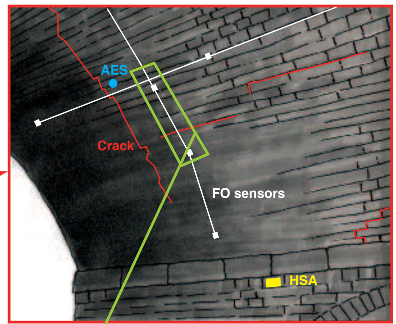
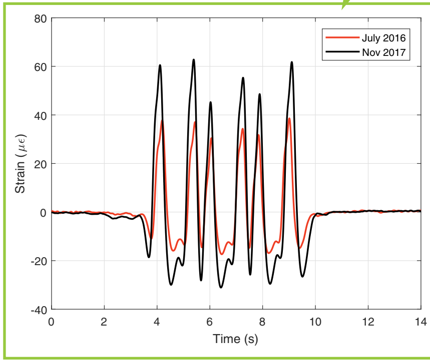


Figure 1: Snapshot of sensor location on bridge

CSIC data analysis

CSIC researchers have created software to identify and group specific types of trains, and to identify velocity, direction of travel, number of carriages and weight. Structural engineers aim to better interpret the behaviour through computational modelling of the masonry structure under simulated dynamic loading.

> Integrating the structural and data-centric engineering methods will form a clearer picture of the as-built performance of the new self-sensing bridges and the on-going degradation of the historical masonry viaduct, to improve both design practice and optimise maintenance intervention.
>
> Dr Haris Alexakis, CSIC Research Associate



Plot exemplifying the change in the dynamic response of the bridge (when a train passes over) between July 2016 and November 2017

Figure 2: Change in dynamic response of bridge

Looking to the future – the digital twin

Combining structural and data-driven engineering brings new opportunities to smart infrastructure. The structural engineer often works with a worst-case-estimate of what the actual load of a bridge may be, while the data-driven approach builds a statistical model from the data collected. Statistical models provide an effective tool to verify the physical models and confirm and measure best-guess estimates .Integrating these methods – a 'data centric' approach – delivers accurate and verified structural performance information to inform improved decision-making.

The next step is to combine advanced BIM modelling, advanced finite element models, and our data analytics to develop 'digital twin' bridge models (cyber-physical systems). The digital twin will exist alongside the physical asset and will be updated via a statistical process as new data is collected. These data-centric engineering-enabled models could potentially be used to perform 'what-if' scenarios providing asset managers with a powerful tool for improving resilience and assessing long-term risk.

Benefits to

Asset owners, asset managers, designers, end users

Impact and value

- design optimisation and cost efficiency
- better-informed, more effective maintenance
- reduction in disruption to travel
- structural alert systems to ensure asset and user safety

Project contact

Dr Haris Alexakis, Research Associate
Dr Liam Butler, Research Associate
Dr Matthew DeJong, CSIC Investigator (Leeds project)
Dr Mohammed Elshafie, CSIC Investigator (Stafford project)
Prof Campbell Middleton, CSIC Investigator (Stafford project)

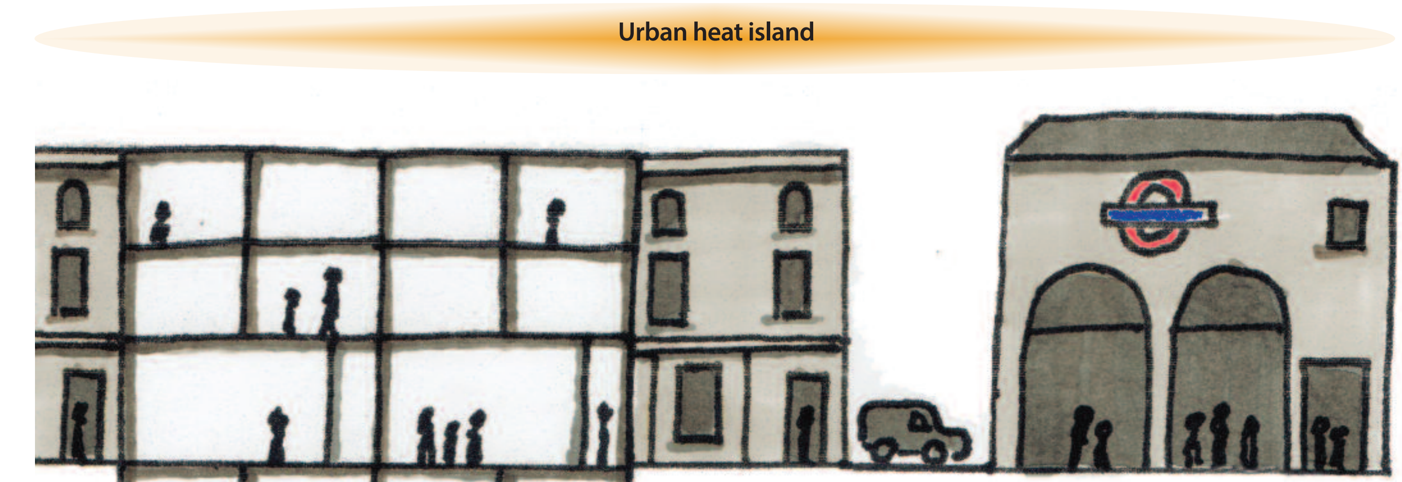
Planning in 3D: Optimising space and resources in city heat sources to hot spots for growing edible plants

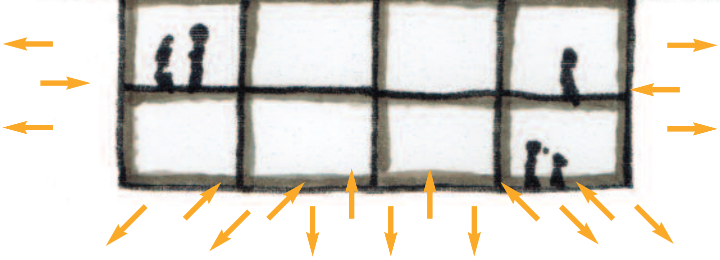
Introduction

With predictions of an additional 2.6 billion people living in cities by 2050 there is need for 3D planning of our urban areas to manage available space, energy, water and food resources optimally. Subsurface space in cities is already used for multiple purposes – infrastructure, transport and living – and will be further exploited in the future to help relieve land and energy shortages. The following two CSIC Cities projects, one above and one below ground, interact with the city's material and energy fluxes symbiotically to absorb and repurpose urban waste energy flows.

Below ground

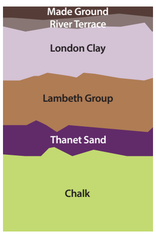
Geology is a significant consideration in the development of the cityscape. CSIC researchers are working to identify suitable areas for increased exploitation of underground spaces, and explore optimal locations across cities for harnessing the geothermal potential of the ground. The goal is to increase utilisation of underground space in a sustainable and efficient manner to deliver city-wide energy efficient solutions.





Transfer of heat between ground and basements

Geology



Dissimilar geologies of three distinct areas in London are being explored to consider how heated basements affect the surrounding ground temperature. This study combines British Geological Survey (BGS) data with numerical modelling. Constructing subterranean space creates changes in ground conditions: possible impact on water quality and structural mechanics of different soils.

Ground temperature

Undisturbed ground temperature in London at 5-6 metres is 12-14 degrees. The temperature of the ground just below the heated basements is warmer (18 degrees) and may be propagated as a free energy source and potential revenue stream.

3D geological mapping

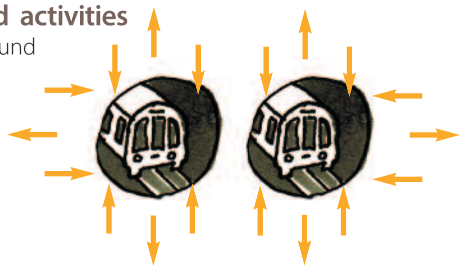
The British Geological Survey (BGS) has supplied 3D geological maps of Greater London. These are being incorporated into numerical models to create an integrated appraisal of land viability and to capture the effect of basement living on different geologies and hydrogeologies. Mapping the range of ground temperature will identify potential sources of geothermal energy to inform subterranean planning and development.

Effect of basements on ground temperature

CSIC is studying the effect of large increases in residential basements on the distribution of surrounding ground temperature. A pilot study of a few areas within central London was recently completed.

Effect of underground activities

Activities such as underground trains travelling through tunnels introduce additional heat which could be extracted and used elsewhere as 'smart' heat.



Mapping underground temperatures

The information from this CSIC and BGS research project is key to considering the suitability and sustainability of utilising the ground as a source of heat. Currently no complete database on ground temperature in London exists. This project will produce a map of indicative ground temperatures (including influence of additional underground activities such as train tunnels).

Efficient use of geo-energy

Combining different purposes (offices – empty at night and houses – empty during the day) to use geo-energy will allow ground temperature to recover and maintain balance and long-term sustainability.

Next step

A series of geospatial queries aligned to future city scenarios can be identified, developed, and simulated using the integrated city model. This model could be applied where relevant 3D geological maps and data sets exist.

settings – from underground thermal

Above ground

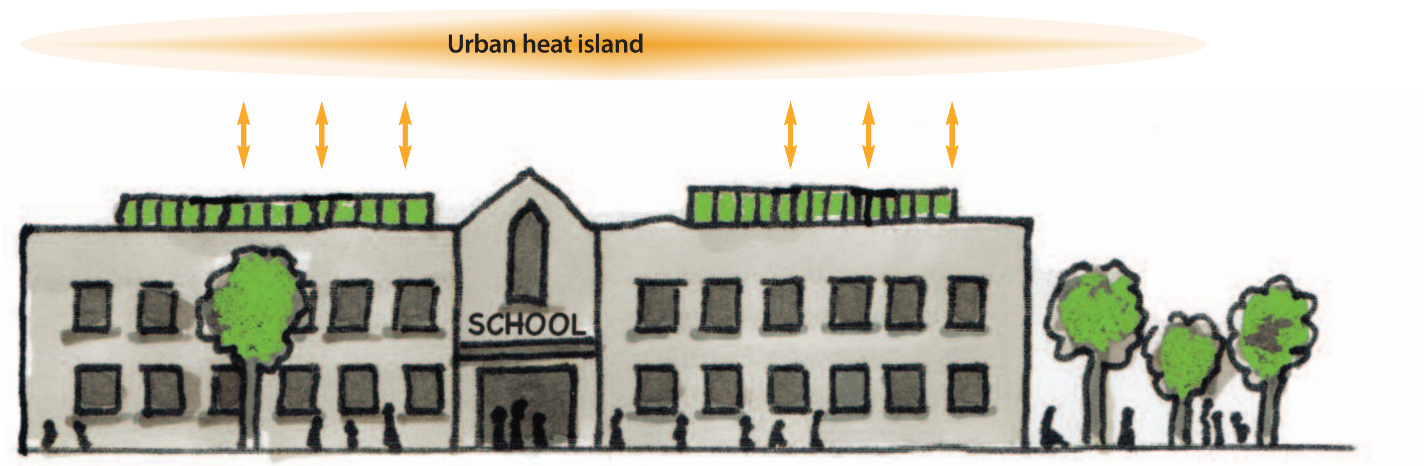
Energy demand for cooling in cities is set to rise by up to 30 per cent as cities get warmer. Cities create an 'urban heat island' effect where temperatures are higher than the surrounding rural areas. Increasing vegetation, for example, with green roofs, has been shown to reduce the urban heat island effect and, it follows, building energy consumption from cooling.

Urban planning to optimise a city's limited resources requires innovation above as well as below ground. London's high-cost land area is a barrier to urban farming. However empty rooftop space could be reused to grow edible plants, and also establish energy efficiencies within existing infrastructure. Researchers from the Energy Efficient Cities Initiative (EECi) and CSIC are exploring the potential for urban agriculture in schools where there is already an interest in growing edible plants. This project is developing a framework for integrating rooftop hydroponic greenhouses on schools to work in synergy with the buildings, essentially coupling the demands of a greenhouse (heat, water, CO_2), with the available resources in buildings (waste heat, rainwater, solar radiation, CO_2 from occupants).

Repurposing school rooftop space

Schools have regular occupation and resource consumption patterns. There is potential to reuse these resources for rooftop farms. Geospatial information is used to identify school buildings across the city that would benefit most from integrating a rooftop greenhouse. Repurposing flat rooftop space of London schools for hydroponic farms can have co-benefits between plants and building occupants.

> "It is important that we consider such city-wide synergistic planning solutions both for sustainability and utility. These are interlinked systems and therefore offer an amazingly rich multi-dimensional modelling exercise that requires 'out of the box' thinking.
>
> Dr Ruchi Choudhary, Head of Energy Efficient Cities Initiative and CSIC Investigator, University of Cambridge



To quantify the co-benefits between a rooftop farm and a building, both the effect of the surrounding area and the building energy use for heating and ventilation are being analysed by researchers. The aim would be to know how much food would be produced, how much waste resources from the building could be reused, and if it will improve the temperatures and air quality within the building.

Qualitative data input

CSIC researchers are designing a survey to identify the limitations and drivers for schools to adopt integrated rooftop greenhouses. Adding qualitative data to the quantitative model will help understand potential barriers or creative solutions in terms of benefits to the schools' students and teachers.

Next step

The quantitative potential impact and qualitative criteria inputs will guide the development of a geospatial (GIS) analysis tool to identify optimal locations for urban farming, and the outputs of its implementation city-wide.

Benefits to

City planners, asset owners, local authorities, citizens

Impact and value

- energy efficiency
- optimising sustainable utilisation of subterranean space
- potential air quality improvement
- positive impact on community, education, health and wellbeing

Project contact

Dr Ruchi Choudhary, Head of Energy Efficient Cities initiative and CSIC Investigator
Dr Asal Bidarmaghz, Research Associate (below ground)
Melanie Jans-Singh, PhD Researcher (above ground)

Integrating infrastructure information for efficient whole

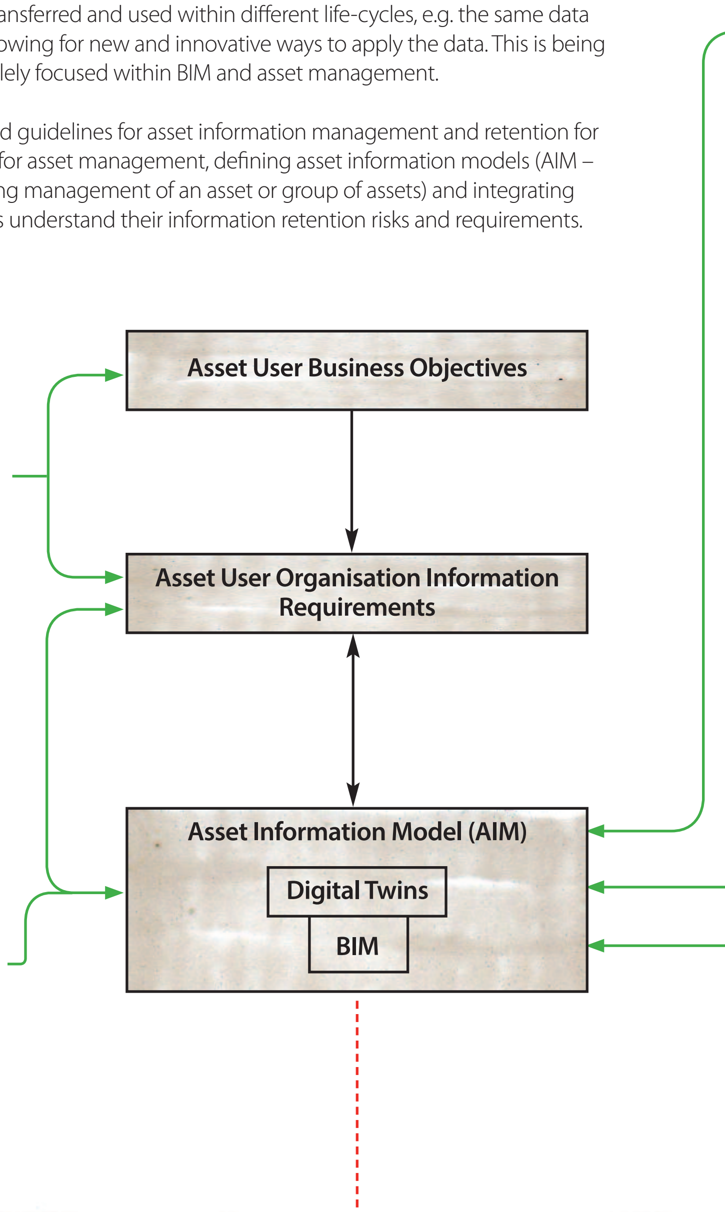
Introduction

Recognition of the critical importance of information management, processes and strategies is gaining momentum within the wider construction industry. As Building Information Modelling (BIM) adoption, implementation and development becomes more prolific in industry, asset owners are seeking to use the newly found information to improve decision making and achieve whole-lifecycle performance efficiencies from their physical assets. Information is no longer created and used for a single purpose; it can be transferred and used within different life-cycles, e.g. the same data sets used in the construction phase can be used within the operational phase, allowing for new and innovative ways to apply the data. This is being guided by novel and emerging technologies, supported by industry standards solely focused within BIM and asset management.

CSIC researchers are engaged in projects to develop generally applicable tools and guidelines for asset information management and retention for the whole life of infrastructure assets. This includes identifying data requirements for asset management, defining asset information models (AIM – the collated set of information gathered from all sources that supports the ongoing management of an asset or group of assets) and integrating such data with the BIM models, assessing BIM maturity, and helping organisations understand their information retention risks and requirements. Longer-term this activity will support the Centre for Digital Built Britain's agenda.

Data-driven asset management – a framework for linking ISO and BIM standards for whole-life value

BIM is being implemented for design and construction, but its use for asset management and maintenance is only beginning to be considered. Design data and asset information which would enable efficient management of built assets, although available, is not currently passed on to asset managers in a way that can be easily utilised. The aim of this project, in partnership with Costain, is to create a model based framework approach to aid in the development of whole-life asset information requirements (AIR) linking the PAS 1192 (BIM Level 2) standards with the ISO 55000 (Asset management) standards while validating the information model against the asset users' organisational requirements and objectives. A tool will be built that can automatically link AIR to Uniclass 2015 – a unified classification system for the construction industry. Uniclass 2015 contains consistent tables classifying items of all scales from a facility such as a railway through to products such as a CCTV camera in a railway station. Detailed industry case studies are being developed with English Heritage and University of Cambridge Estate Management to demonstrate the methodologies developed in this research.



Connecting information requirements to the information model

Infrastructure asset data sets are commonly held in disparate and incoherent platforms. Such data sets are generated with multiple enterprise software applications using an array of standards and format types. As a result, the optimum value from the information is often not fully realised.

The focus of this research is on developing tools for integrating different data sources to support whole-life asset management of infrastructure assets and systems. This project aims to develop multi-layered information platforms to integrate heterogeneous data sources, support intelligent data querying, and provide smarter decision-making processes in asset operations and maintenance.

Asset information futureproofing for whole-life value

The amount of information created and used in the infrastructure and construction sectors is vast and diverse by nature. In addition, the assets themselves are long-lived, and hence large amounts of information are generated during an asset's lifetime. Organisations need to understand the need for specific requirements for efficient information retention and management throughout the lifecycle of an asset. CSIC has developed a three-stage approach that helps organisations:

- understand their information retention requirements
- identify and assess risks of information losses in the long term
- identify and provide guidance on information futureproofing solutions to mitigate the risks of information loss.

The information futureproofing approach helps facilitate the process to select or identify technologies and services that would enable long term storage and retrieval of infrastructure information. To date the methodology has been successfully applied with two industry partners.

Investigating the role of the digital twin in optimising asset value

CSIC researchers at the Institute for Manufacturing (IfM) are collaborating on the flagship research project of the Centre for Digital Built Britain (CDBB) at the University of Cambridge with joint CSIC-CDBB industry partners, to develop a dynamic digital twin of the West Cambridge Site. The aim of the project is to demonstrate the impact of the digital twin on facilities management, wider productivity and wellbeing of the building users. A digital twin refers to a digital replica of physical assets, processes and systems. The long-term goals of this work are to demonstrate the impact of digital modelling and the analysis of infrastructure performance and use on organisational productivity. This will provide the foundation for integrating city-scale data to optimise city services such as power, waste and transport, and to understand the impact on wider social and economic outcomes. Additionally, CSIC researchers together with CDBB aim to establish a 'research capability platform' for researchers to understand and address the major challenges in implementing digital technologies across a range of scales and foster a research and development community interested in developing novel applications to improve the management and use of infrastructure systems. This project is funded by the Centre for Digital Built Britain at the University of Cambridge. (See case study on page 24)

BIM maturity assessment

Since 2016, all UK government-procured projects mandate Level 2 BIM. CSIC's BIM Maturity Assessment Tool (BMAT) is designed to support an organisation's implementation of BIM and delivers two significant areas of information – measurement of the organisation's BIM development maturity and measurement of the supporting processes. The tool provides a separate assessment of the different stakeholders (contractor, designer and employer), and is designed to be used as a continuous performance measurement tool that can be employed to track the evolution of BIM maturity throughout the construction phase through to handover. The Excel-based tool is designed to be user-friendly and adaptable to the needs of individual organisations and projects. (See case study on page 28)

Where will this lead?

This research will help industry in its journey to digitalisation through developing, and enabling adoption of, approaches to data curation and information management throughout the lifecycle of built assets. This includes frameworks for developing information models and assessing organisational maturity in the adoption of these approaches.

> "Research in this area is paving the way to releasing the true value of information across the whole lifecycle of infrastructure.
>
> Mark Enzer, Chief Technical Officer, Mott MacDonald

Benefit to

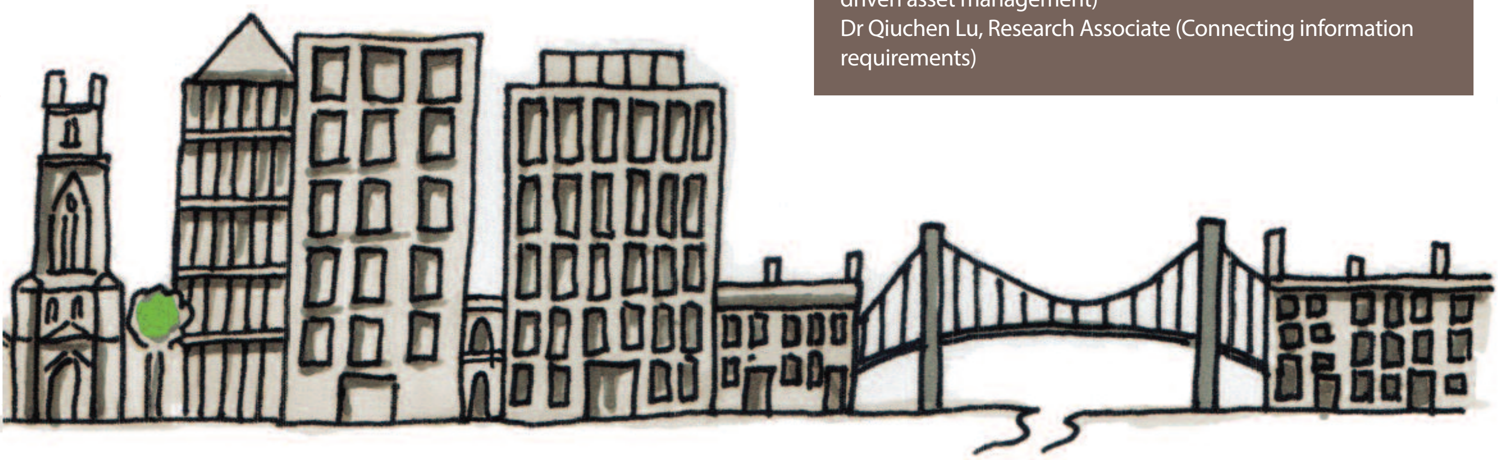
Asset managers, infrastructure owners and operators

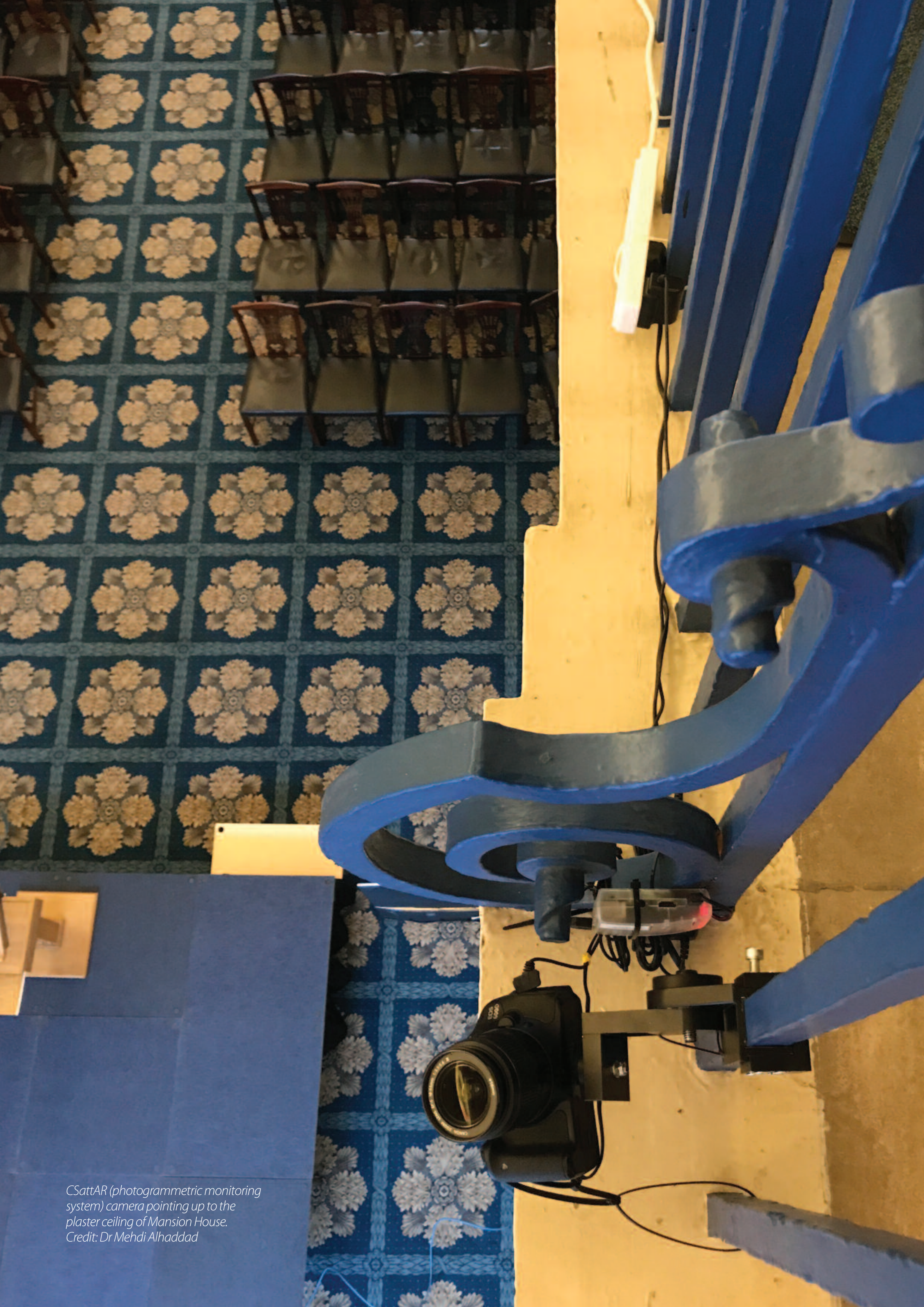
Impact and value

- new approaches to data curation and information management to enable better decision making

Project contact

Dr Ajith Parlikad, Senior Lecturer in Industrial Systems at the Institute for Manufacturing, CSIC and CDBB Investigator
James Heaton, PhD Researcher sponsored by Costain (Data-driven asset management)
Dr Qiuchen Lu, Research Associate (Connecting information requirements)





CSattAR (photogrammetric monitoring system) camera pointing up to the plaster ceiling of Mansion House. Credit: Dr Mehdi Alhaddad

Case studies

The case studies in this Annual Review highlight a number of ways in which CSIC collaborates with industry partners and organisations to advance research in smart infrastructure and create impact in the infrastructure and construction industry.

These studies represent part of the larger CSIC project portfolio that brings solutions to challenges faced by industry on a range of infrastructure projects featuring both new and existing assets. From early-stage research on the Centre for Digital Built Britain (CDBB) digital twin project, a test scale prototype of a bridge and tunnel strike prevention system, and industry-ready tools for assessing BIM maturity and prioritising bridge maintenance, to deployment of distributed fibre optic monitoring of axial compression, these case studies demonstrate CSIC's collaboration with industry at different stages of a project lifecycle.

Integrating digital technologies to capture and analyse data that leverages the whole-life value of our assets is key to CSIC's approach to transforming the future of infrastructure through smarter information. Collaboration with industry enables CSIC to deliver evidence for the benefits of investment in smart infrastructure that will increase efficiencies, reduce risk and cost, create economic growth and improve social wellbeing.

Case study 1
Investigating the role of the digital twin in optimising asset value

Case study 2
Autonomous vision-based bridge and tunnel strike prevention system for improved safety and more efficient asset management

Case study 3
Working with industry to co-develop industry-ready tools

Case study 4
On the rise: monitoring the axial shortening of a high-rise building under construction using embedded distributed fibre optic sensors

Investigating the role of the digital twin in optimising

Benefit to

Asset managers, infrastructure owners and operators, design engineers, contractors

Impact and value

- enabling adoption of data curation and information management approaches for the lifecycle of built assets

The digital age brings opportunities for optimising the use of our physical assets. A key component to realising the whole-life value of our built environment is the development of digital twins – digital replicas of physical assets, processes and systems. CSIC researchers at the Institute for Manufacturing (IfM) are collaborating on the flagship research project of the Centre for Digital Built Britain (CDBB) at the University of Cambridge with joint CSIC-CDBB industry partners (Bentley Systems, GeoSLAM, Topcon, and RedBite), to develop a dynamic digital twin of the University of Cambridge's West Cambridge Site. The aim of the project is to demonstrate the impact of the digital twin on facilities management, wider productivity and wellbeing.

Collaborations between industry and academia offer benefits and value to both parties as well as the wider infrastructure community. By sharing our combined expertise and skills we are able to test new technologies and tools on live projects, accelerating the timeframe for cutting edge innovation to become part of mainstream industry practice.

Digital twins

The vision for a digital twin is to integrate artificial intelligence, machine learning and data analytics to create a living digital simulation model which continuously learns and self-updates from multiple sources to represent near real-time status, working condition and/or position of the physical asset. Digital twin models will help organise data into interoperable formats and also share this data, with defined levels of access, to inform better policy, planning, and management decisions on the interaction between the built environment and the economy, society and the natural world.

Developing a digital twin of the IfM and the West Cambridge Site

The West Cambridge Site and the IfM, the offices of the CSIC/CDBB researchers, are the ideal location for the test bed for this ambitious and innovative project. The aim is to create a digital twin that will incorporate multi-layered information models to integrate heterogeneous data sources at asset, building and district scales. This will support intelligent data query and smarter decision-making for operation and maintenance management, as well as bridging the gap between people and the buildings they use via more intelligent and visual use and display of information. This dynamic digital twin will be supported by an as-is Industry Foundation Classes (IFC) Building Information Model (BIM) and data from the facilities management systems and Internet of Things (IoT) sensors and devices. Between December 2017 and May 2018 a platform has been established to build a geometry model of the West Cambridge Site, a BIM model of the IfM building with a medium level of detail, and BIM models of specific areas in the IfM with highly detailed information (Figure 1 and Figure 2). This work is being carried out through a joint effort between CSIC and CDBB researchers at the IfM, Bentley Systems, GeoSLAM, and Topcon.

Figure 1: Snapshot of BIM Model of IfM Plant Room from ContextCapture modelling software by Bentley Systems

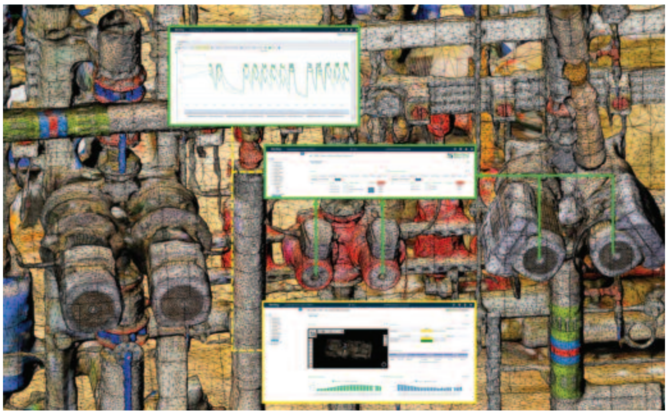


Figure 2: View of the BIM Model of IfM Plant Room with information about components displayed

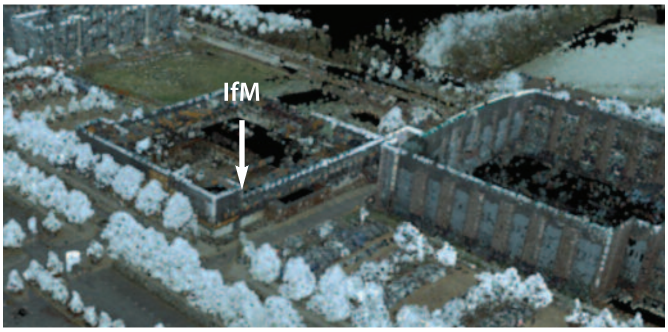


Figure 3: Snapshot of the mobile scan of the IfM and surrounding area performed by Topcon

Next stage – comprehensive, business-objective-led asset information management

A comprehensive high quality asset register will be generated by CSIC/CDBB researchers using itemit, RedBite's asset management solution. The itemit app will be used to provide asset users and stakeholders with relevant information and to incorporate input and feedback from users through the use of itemit QR and RFID asset identification tags on critical equipment. Asset maintenance and inspection schedules and records will also be built in to itemit. RedBite will develop APIs (application programming interfaces) that can be used to integrate the asset data with the 3D BIM model through Bentley's AssetWise operational analytics solution. In addition, the project team will explore potential ways in which the data collected through the Building Management System (BMS) and the Estate Management's work-order system (Planet) can be integrated with itemit and the BIM model.

Bentley Systems, working together with Topcon, and GeoSLAM expect to further advance the extent of data captured via a hybrid Reality Model of the whole West Cambridge Campus including external and internal building data. Focus will be upon continuous updates and automation of model generation. Focus then will be on the linking with time series data flows from sensors and data from the Building Management System (BMS). The data set will then be available for CSIC and CDBB researchers, together with application specialists from Bentley Systems, Topcon, GeoSLAM, and RedBite to test and validate workflows.

Working closely with University of Cambridge Estate Management, CSIC and CDBB researchers at the IfM will identify potential opportunities for, and test the feasibility of, deploying additional sensors that will help monitor the condition of critical assets in the IfM and the usage of the building. Other sensors may also be deployed across the site, subject to availability.

Future work

During 2018 -2019 the aims of the project are to:

- continue the work on integration of live data with BIM and expand this to include data captured from other buildings on the West Cambridge Site
- explore data integration from different sources using open standards to ensure that the digital twin development is vendor agnostic
- install and deploy additional sensors in key areas of the IfM
- develop novel applications (the 'APP STORE' in Figure 4) that exploit data capture through the digital twin including augmented reality support for maintenance and inspection, predictive data analytics to improve asset maintenance, improved asset tracking across the West Cambridge Site and improved equipment utilisation and management.

Long term vision – a dynamic digital twin

The long-term goals of this work are to demonstrate the impact of digital modelling and analysis of infrastructure performance and use on organisational productivity across an estate or district through development of a dynamic digital twin representing current conditions at any point in time. This will provide the foundation for integrating city-scale data to optimise city services such as power, waste, and transport and understanding the impact on wider social and economic outcomes. Additionally, CSIC together with CDBB aims to establish a 'research capability platform' for researchers to understand and address the major challenges in implementing digital technologies at scale and to foster a research community interested in developing novel applications to improve the management and use of infrastructure systems.

Further work (3-5 years)

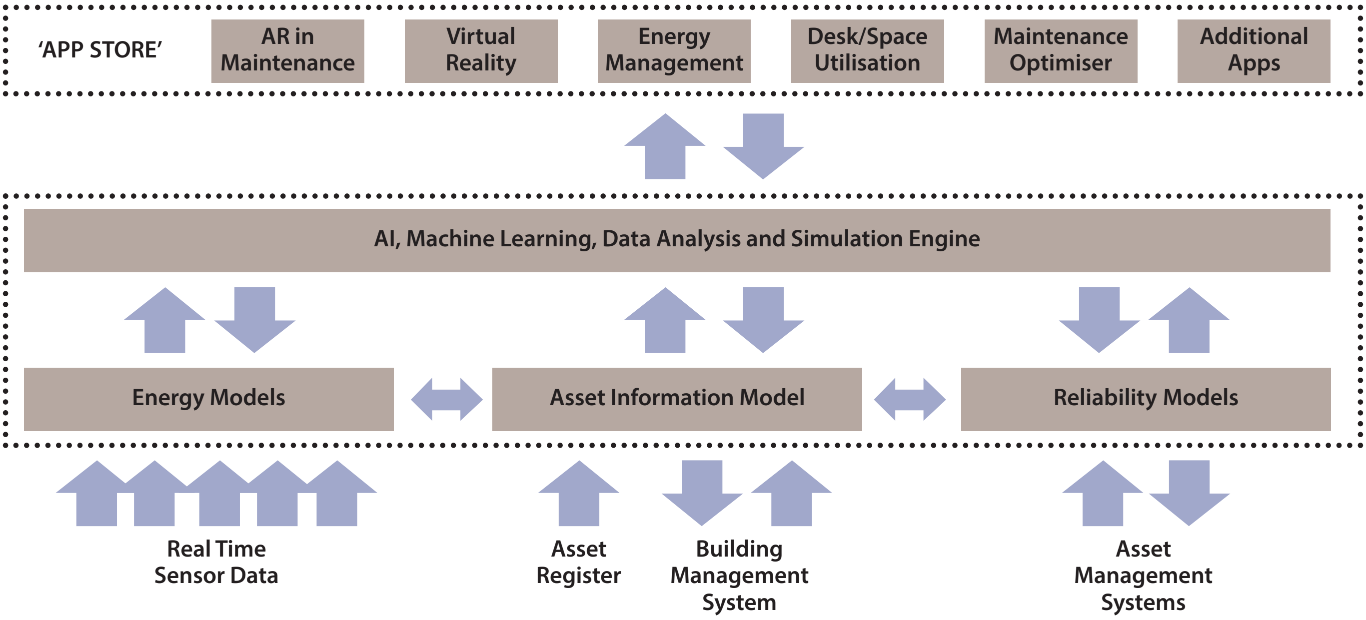


Figure 4: Digital Twin Vision

> Collaborating with leading experts in industry and academia is central to achieving the Centre's mission to deliver a digital built Britain. We are delighted to be partnering with academics from the University of Cambridge, and with Bentley Systems, Topcon, RedBite and GeoSLAM to deliver this flagship project.

Alexandra Bolton, Deputy Director,
Centre for Digital Built Britain

Project contact
Dr Ajith Parlikad, Senior Lecturer in Industrial Systems at the Institute for Manufacturing and CSIC and CDBB Investigator

Autonomous vision-based bridge and tunnel strike pre safety and more efficient asset management

Benefit to
Asset owners, travelling public

Impact and value
- improved safety
- cost savings for asset owner
- reduction in travel delays
- cost savings for public purse

Over-height vehicle strikes (OHVS) are a constant and costly problem for asset owners. An OHVS is caused by a vehicle attempting to pass under a bridge or tunnel that is lower than its height, leading to a collision with the structure. A common reason for such strikes is drivers not knowing the height of their vehicles and ignoring or missing warning signs despite a number of preventative methods installed in advance of low clearance bridges. OHVS can cause many problems including: impact to the wider travel networks; traffic delays; damage to bridge structures; bridge closures; and injuries. In the worst-cases, derailments, immediate collapse of bridge structures and fatalities may occur.

According to Network Rail[1] there are typically five bridge strikes every day nationally costing the organisation £12.7m per annum in compensation (2016/17). Each strike costs the asset owner around £13,000 and the financial burden to the UK taxpayer is calculated at £23m a year. Highways England, another major asset owner in the UK, has recently seen an increase in the number and severity of bridge strikes, at times resulting in significant delays on the strategic road network.

Autonomous vision-based bridge and tunnel strike prevention system

Researchers at the Laing O'Rourke Centre (LOR Centre) for Construction Information Technology (CIT) Laboratory at the University of Cambridge are working on a project, partially funded by CSIC, to create, test and deploy an OHVS system for the prevention of bridge and tunnel strikes. This innovative system uses a vision-based approach featuring a single calibrated video camera mounted on the side of the road at the height of the low bridge. The camera is strategically positioned to capture three main features using the same data feed: over-height (OH) vehicle, number plate of vehicle, and record of vehicle at the scene. The camera position and orientation are determined using a calibration process with a reference object.

Existing OHVS systems

Managing OHVS requires attention in three domains: prevention (discouraging strikes in the first place); detection (accurately recording strikes that do occur); and reporting (efficiently communicating OHVS details to the relevant authorities). The latter two aspects of OHVS management are effectively managed by existing systems. However, many of the OHVS technologies currently available are too expensive for asset owners to justify the upfront costs and very few systems are designed to mitigate OHVS impact.

Asset owners favour quick, affordable, and accessible passive methods such as signage, bridge markings, and flashing beacons as an initial attempt to warn drivers and prevent strikes. These passive interventions are readily available, easily installed and minimise further infrastructure installation. They prevent ~10–20 per cent of

strikes (Cawley 2002: Cawley, P. M, 2002. Evaluation of Overheight Vehicle Detection/Warning Systems. In Today's Transportation Challenge: Meeting Our Customer's Expectations (No. CD-016), but additional complementary systems are necessary for higher prevention rates.

Where strikes have persisted, asset owners have used sacrificial or active systems. Sacrificial systems (also known as rigid passive systems) are attractive for asset owners because post installation maintenance is minimal. These systems typically comprise crash beams, metal hanging chains and road-narrowing techniques that are protective rather than preventative. Active strike prevention systems – also known as early warning detection systems (EWDS) – detect and notify vehicle operators ahead of the presence of low structures. Current systems of this type consist of a transmitter receiver placed directly across the lane(s) of traffic (laser or infrared light warning systems have also been deployed) with an inductive loop to detect the presence of a vehicle in advance of the warning sign. There has not been widespread adoption of EWDS due to the high cost associated with the physical infrastructure requirements.

Framework for a relatively low cost EWDS solution for OHVS

The autonomous vision-based bridge and tunnel strike prevention system potentially provides a viable solution for OH vehicle detection that specifically addresses prevention. The objective is to develop a lower cost EWDS system by replacing the transmitter, receiver, and loop detectors with a single camera mounted upstream of the low bridge.

[1] www.networkrail.co.uk/communities/safety-in-the-community/safety-campaigns/check-it-dont-chance-it/

The proposed method is based on the following geometric principle: when a camera is properly mounted at the height of the bridge clearance relative to the road surface, the OH plane will appear as a line in the camera image. The method is suitable for various shapes and sizes of vehicles, numbers of laneways, and illumination conditions (day and night time). Camera stabilisation is crucial to minimise any potential captures of noisy motion that may contribute to triggering false positive alarms.

Detection of OH vehicles

Video footage is converted into image frames, which are then used as inputs for the OH detection process. When an OH vehicle is detected, cameras and accelerometers are activated; a message is issued on the display unit, warning the driver of the low bridge. The driver warning process may take one of two paths: (1) if the driver exits or stops, and no impact is detected, then video data are discarded and accelerometers are deactivated; and (2) if the driver continues and an impact is detected, then the vehicle license plate number is extracted from the recorded video and impact data from the accelerometer are stored. The collision report (video segment, license plate, and accelerometer data) is sent to the relevant authorities.

Testing the system

Testing of a small scale prototype has been carried out with London Underground and Redbridge Council to evaluate the height and detection accuracy of the system. The tests were conducted on two collector roadways with two and four lanes of traffic in sunny, cloudy, and rainy weather conditions.

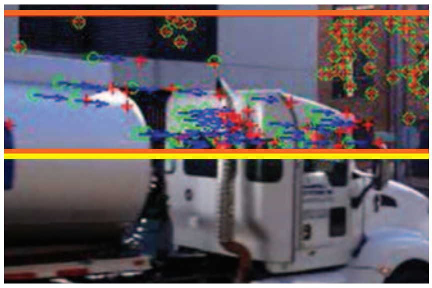
Results and benefits

Evaluation of the small-scale prototype system, which is jointly funded by Transport for London and CSIC, resulted in a height accuracy of ±2.875 mm; outperforming the target accuracy of ±50 mm. The algorithm performed with 100 per cent recall, greater than 80 per cent precision, a false positive rate of 0.2 per cent and a warning accuracy of greater than 90 per cent. Although its accuracy is comparable to existing EWDS laser beam systems, it outperforms them on cost which is an order of magnitude less because of eliminating the need for new permanent infrastructure. The proposed system is also applicable to low-deck parking garages and shipping barges with height restrictions. Additionally, components of the system are intended to minimise inspection, maintenance, and repair costs that fall to the asset owner.

Next step

Researchers plan to develop and test a larger scale prototype and are seeking potential investment from system providers that may be interested in the technology, either to diversify or to complement their existing product line. Commercialisation options with system providers to roll out the product as a service offering are at an early stage. Other asset owners have expressed interest in deploying the system.

(a)



(b)

Images show: (a) Camera system installed at Fairlop Station in London. The camera is installed at the same height as the bridge clearance; when calibrated, the camera behaves like a laser-beam and detects moving objects above the over-height plane; the over-height plane (3D), i.e., line in camera view (2D) and region of interest (ROI) are annotated in yellow and red, respectively; the ROI is optimally positioned above the over-height plane to minimise the amount of processing required; (b) zoomed in view – the moving over-height features are detected and tracked using Kanade–Lucas–Tomasi algorithm.

> “The autonomous vision-based bridge and tunnel strike prevention system may be of interest to asset owners who would benefit from the system and accompanying data services, including monthly reports, that enable inspection to be minimised and safety risks and maintenance and repair costs to be reduced.
>
> Ash Parmar, Project Manager, London Underground TfL

Project contact

Dr Ioannis Brilakis, CSIC Investigator
Dr Bella Nguyen, Senior Consultant, Arup and former PhD Researcher

Working with industry to co-develop industry-ready tools

Benefit to

Asset operators and managers, BIM managers

Impact and value

- user friendly and adaptable tool for BIM maturity assessment
- industry-ready tool for optimising bridge maintenance

Introduction

CSIC with industry partner, Mott MacDonald, jointly funded two six-month secondment projects for Mott MacDonald staff to join CSIC's asset management team to create industry-ready tools from existing CSIC research. These secondments are part of the CSIC Industry Secondment Programme, funded by Innovate UK and industry partners, which offers six to 12 month secondments, tailored to meet both the needs of the seconding organisation and CSIC's research, development and deployment programme. These two secondments took place from October 2017 through to March 2018 and resulted in two tools ready for industry uptake – *BIM maturity assessment tool* and *Bridge maintenance optimisation tool*.

Extending BIM maturity assessment tool to Digital Built Britain Level 2

CSIC's BIM Maturity Assessment Tool

Since 2016, all UK government procured projects require Level 2 BIM. CSIC's BIM Maturity Assessment Tool (BMAT), initially developed in 2017, uses established performance measurement practices, BIM literature, and other relevant standards, to build and expand on previous BIM assessment tools. Consisting of two major parts – measurement of the organisation's BIM development maturity and measurement of the supporting processes – the tool provides a separate assessment of the different stakeholders (contractor, designer and employer), and is designed to be used as a continuous performance measurement tool that can be employed to track the evolution of BIM maturity throughout the construction phase through to handover. The Excel-based tool is designed to be user-friendly and adaptable to the needs of individual organisations and projects. Limited testing of the tool was successful but more case studies were needed for validation.

Secondment project – BIM Maturity Assessment Tool

This aim of the secondment project was to ensure the tool complies with all of the applicable standards[1], to validate the tool through five additional cross-sector case studies and to ensure its appropriateness for Level 2 BIM maturity assessments. Also, the tool required future-proofing for extension beyond Level 2.

In order to develop the tool and make it effective and useful to industry, diverse case studies were identified from a range of sectors (water, railways, highways, and nuclear) and various stages in the project delivery cycle (design, construction and handover) as well as different contract types (e.g. traditional, and, design and build). The updated tool is structured to ask the right questions of the user depending on the stage of the Information Delivery Cycle (IDC) and which stakeholders are involved. The tool is designed to reveal how well the asset owner has defined the asset information requirements and how well the different project stakeholders have defined their approach to develop these requirements for both the BIM Execution Plan (BEP) and the Master Information Delivery Plan (MIDP). The tool enables clarity on who owns the data, who owns the common data environment, and who will take responsibility for the Asset Information Model (AIM) upon handover. Questions are asked about competency and information production, which standards have been applied, how to measure the quality of data used, and how the different stakeholders collaborate.

Next steps

The tool is designed to be extended further. Plans include testing additional case studies and improving the weighting system and interdependencies between the various BIM elements, as well as the development of a web-based version which will enable widely processing and disseminating maturity assessment results across the country.

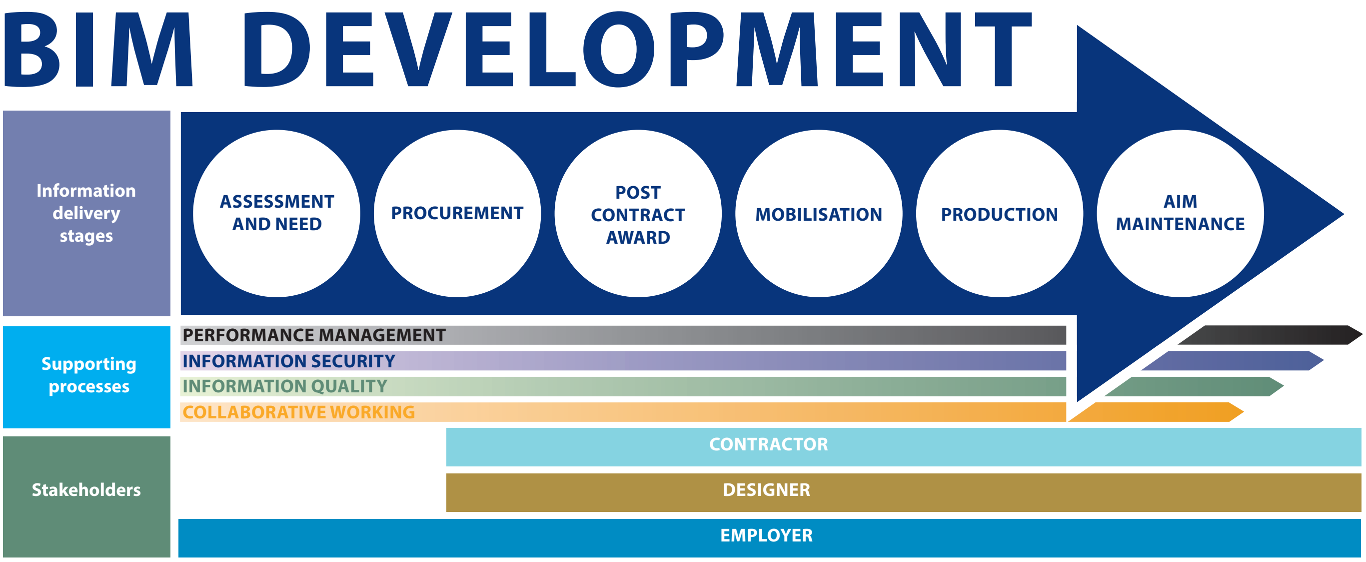


Figure 1: BIM maturity process

[1] PAS1192 series (information management), BS1192 (COBie), PAS91 (construction pre-qualification), ISO55001 (asset management), ISO27001 (information security), ISO8000 (information quality), ISO31000 (risk management), ISO44001 (collaboration)

An industry-ready tool for optimising maintenance activities across multiple bridges throughout their lifetime

CSIC 's Predictive Maintenance Model

CSIC researchers have developed a methodology to help asset managers to determine the most optimal timing for interventions on their bridge portfolio in a predictive manner. As maintenance budgets for bridge systems are squeezed, many necessary maintenance activities are delayed or cancelled. Retaining an appropriate level of service and safety for an infrastructure network has become a challenging issue and there is pressing need for a smart asset management approach for road bridges.

The structure of the overall approach is composed of five interconnected models: deterioration model; lifecycle cost model; predictive maintenance; group maintenance; and maintenance scheduling model (Figure 2). The deterioration model is formulated for each component of the bridges based on the information from the Structures Asset Management Planning Toolkit, general inspection, and other theoretical models. The predictability of the maintenance model enables proactive grouping of maintenance activities at different timings to reduce add-on costs such as the cost of preliminaries, traffic management and design. These add-on costs can be up to 80 per cent of the cost of repairs that are carried out at the same time. Finally, a

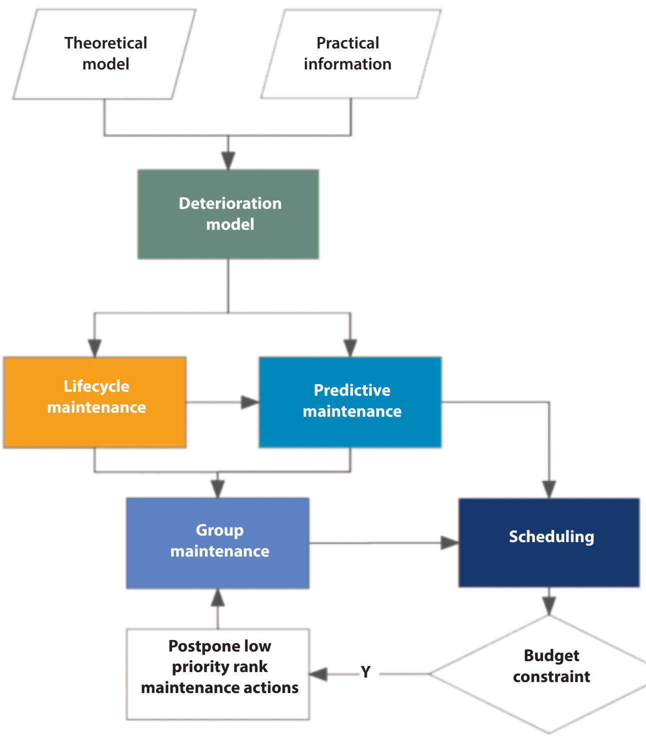


Figure 2: CSIC's sytematic approach integrating five interconnected models

genetic algorithm is developed to schedule the maintenance under the budget. The methodology was initially applied on a case study with Hertfordshire County Council on the Hailey Link and Stansted road bridges along the A10.

Secondment project – Bridges Asset Management Toolkit

Through this secondment an industry-ready tool has been developed based on the CSIC approach that provides industry focus to assist in making the tools practical and usable by the end user, e.g. the asset manager or consultant acting on their behalf. The output is designed to be meaningful and supports asset management planning and business case development for the asset owner, as well as the interface between the Structures Asset Management Toolkit and asset management systems to allow asset data input to be automated. The tool is designed to be used for any type of bridge from footbridges to motorway bridges. It has been tested and demonstrated using real industry data and dependencies and, constraints have been tested to enable scenario planning.

Next steps

To develop the CISC toolkit, data including deterioration rates and maintenance costs were extracted from the 2015 update of the Structures Asset Management Toolkit Documentation published by the Department for Transport. This data is different from the current version of the DfT Strcutures Asset Management Toolkit released in 2017. Therefore, it is difficult to compare the CSIC toolkit results against the DfT toolkit. The latest data are required in order to secure more accurate results and also validate the outcome of the CSIC toolkit.

The available tools in the market have a time-dependent strategy based on experience. The CSIC tool is the first to provide a strategy based on data using a mathematical model to reduce the maintenance costs and improve the safety of bridges at the same time; the CSIC tool introduces a cost and safety dependent maintenance strategy. The tool can be used for a wide range of applications within the infrastructure sector. The next step is to make the tool adaptable for different types of assets such as tunnels, retaining walls, and earthworks.

Secondment programme

Our secondment programme offers benefits to all stakeholders. Secondees bring new skills, projects and challenges to CSIC that help to develop emerging tools and technologies for industry use. The secondees gain a deep understanding of innovations which they can apply for the direct benefit of their own companies/organisations.

> I was seconded to CSIC to develop an industry-ready BIM maturity assessment tool and the experience exceeded my expectations. The digital expertise that CSIC has is second to none and I am pleased to bring the benefits of what I have learned during my secondment back to Mott MacDonald.
>
> Alex Gkiokas, Hydraulic Civil Engineer – Water Consultancy Division, Mott MacDonald

Project contact

Dr Ajith Parlikad, Senior Lecturer in Industrial Systems at the Institute for Manufacturing and CSIC Investigator
Dr Zhenglin Liang, Research Associate
Alex Gkiokas, Secondee – BIM Maturity Assessment Tool, Mott MacDonald
Dr Hooman Atefi, Secondee – Bridges Asset Management Toolkit, Mott MacDonald

On the rise: monitoring the axial shortening of a high-rise using embedded distributed fibre optic sensors

Benefit to
Design engineers, contractors

Impact and value
- verification of design assumptions, ability to adjust construction process
- improves understanding of built asset and construction techniques

Figure 1. Principal Tower under construction

Recent years have seen an increase in proposals, approval and construction of high-rise buildings in the UK, a trend which is set to continue driven by the demand for housing and increased urbanisation. An important factor in the design and construction of high-rise buildings is the axial shortening of vertical load-bearing elements, which is different for each column or wall. Contractors need to allow for the expected final shortening, particularly when setting slab levels and installing finishes and partitions in lower floors, while the building has not yet been completed. However, design predictions of the time-dependent shortening of concrete elements are notoriously inaccurate, as they try to account for the interaction between several parameters. Additionally, these predictions account for the permanent shortening of the members due to the superimposed load and material creep and shrinkage, but do not take into account transient thermal effects.

Conventional monitoring using surveying techniques is limited to measuring shortening at intervals, and at just a few levels. This cannot provide a measure of the local member shortening at un-instrumented levels, or of the global shortening of the whole building. CSIC has developed a novel application of distributed fibre optic sensors (DFOS) to continuously measure the progressive axial shortening of reinforced concrete columns and walls during the construction of high-rise buildings. This monitoring system was successfully trialed for the first time at Principal Tower, a 163 metre-tall, 50-storey residential building in central London, designed by celebrated architectural firm Foster + Partners (Figure 1). This trial was carried out in collaboration with the overall project contractor, Multiplex, the frame contractor, Careys, and the structural designers, WSP.

The tower was constructed using an automated jumpform that incorporated the whole building footprint, including the columns. CSIC's fibre optic (FO) strain and temperature sensing cables were continuously embedded inside two columns and two locations in the core walls of Principal Tower, as construction progressed. The FO cables were prepared in advance with sufficient length to extend all the way up to the top of the building, and wound on cable reels that were housed in the jumpform rig. This enabled the rig operatives to un-reel the cables as the construction progressed upwards. The FO cables were tied to the reinforcement of the instrumented elements during steel fixing, and subsequently embedded in the concrete (Figure 2). CSIC trained the contractor's operatives to install the FO cables, and CSIC researchers analysed the data and provided the required information to the contractor and design engineers.

Figure 2. The fibre optic cables tied to the reinforcement prior to concreting

Monitoring from the DFOS system started in September 2016, just before the ground floor of the tower was concreted. Since then, measurements have been taken at least twice every hour. Each measurement consists of strain and temperature readings from around 3,000 points along the height of the four instrumented locations. These data were used to calculate the axial shortening relative to the ground level, along the whole height of the completed elements, at any time during the construction. This enabled the engineers and contractors to verify their predictions and adjust their assumptions if necessary, thus benefiting the construction sequence.

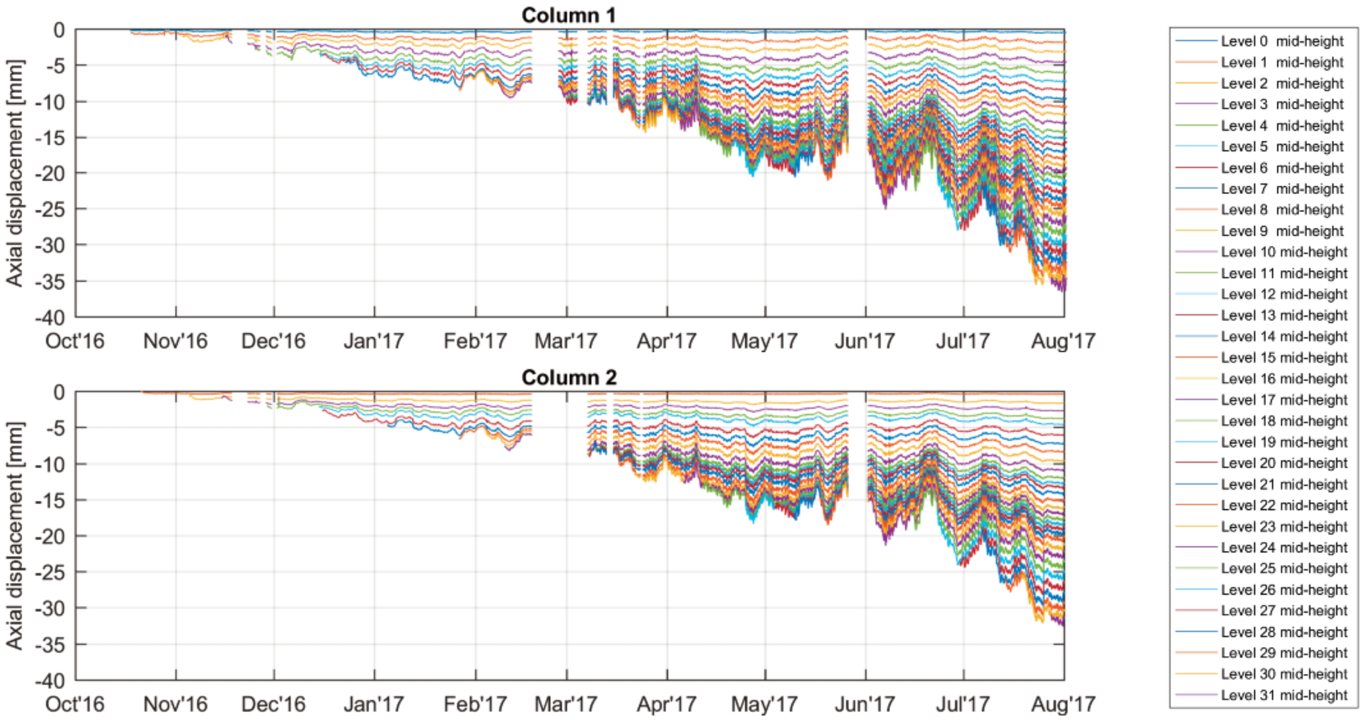


Figure 3. Axial shortening of the two instrumented columns obtained from the DFOS monitoring system during the first 10 months of construction. Negative displacement indicates shortening (L0 = ground floor etc).

Results

The axial shortening of the columns derived from the monitoring system during the first 10 months of construction are shown in Figure 3. Except for some periods where the monitoring was stopped to enable repairs or alterations to be made to the monitoring system, the data provide a continuous profile of the building's shortening over time. This has enabled the project team to make a number of observations.

Differential shortening

The four instrumented elements have deformed at different rates. Column 1, which has approximately half the cross-sectional area of column 2, has shortened around 15–25 per cent more than column 2, despite supporting approximately 12 per cent less dead load. Similarly, both columns have shortened significantly more than the core walls, as the walls have a larger cross-sectional area and are stiffer. This was expected, since an element's shortening is related to its cross-sectional area and surface area. This observation nevertheless highlights the importance of accounting for the differential shortening across the footprint of a tall building.

Thermal effects

The data show a strong thermal effect that gives rise to occasional fluctuations in the axial movement of each instrumented element, due to expansion and contraction of the building. One example is the decrease in shortening that happened due to expansion of the building during a warm period in mid-June 2017.

By estimating the expansion and contraction of the concrete elements, it is possible to derive the axial shortening due to mechanical effects alone. This showed that thermal effects accounted for as much as half of the total deformation during temperature extremes. Such thermal effects can have unexpected consequences when using shortening estimates to pre-set column heights, particularly when concreting during hot or cold periods, since these estimates do not normally account for transient thermal effects.

DFOS monitoring system offers unprecedented detail

The data acquired to date provide the shortening time histories of the instrumented elements with unprecedented detail and at an unprecedented temporal density. This information has been used to demonstrate how an element's shortening is affected by its profile and stiffness, with smaller and less stiff elements shortening more. The continuous data also show that transient thermal effects can play a significant role in axial shortening, at times accounting for as much as 50 per cent of the total deformation. This is particularly significant as shortening predictions prior to construction do not take into account such thermal effects. CSIC's FO monitoring system also makes it possible to observe the effects of occasional and unexpected events – such as an incident of abrupt loading – which could not be observed with periodic or occasional measurements.

Future prospects

This FO monitoring system provides continuous data throughout construction, enabling engineers and contractors to verify predictions and adjust assumptions if necessary. No other monitoring system is able to provide this information with such spatial and temporal density. Design engineers and contractors working on the construction of other tall buildings in the future would benefit from using this monitoring system, which provides valuable insight into a problematic phenomenon that is otherwise very difficult to quantify precisely. This knowledge can lead to more efficient and cost-effective construction of high-rise buildings.

The DFOS-based axial shortening monitoring system developed by CSIC can also be applied to other long and/or slender structures, where thermal effects, load and material properties can lead to significant axial movement, such as in bridges and large area concrete slabs.

Project contact
Dr Nicholas de Battista, Research Associate

Impact and outreach

Communicating the Centre's research and policy outputs to industry, academia and the public is a key part of our activity. CSIC works at a number of levels to engage with a range of audiences and invite interest in its work. Partner-focused events are held throughout the year which present the latest developments in selected topics to provide valuable and timely information to our partners. Working closely with our partners also helps to inform our future research programme that seeks to deliver solutions to real industry challenges. Events also provide an opportunity for partner networking which can lead to new projects and collaborations. As well as hosting workshops, lectures and events, CSIC experts are regularly asked to contribute to panels and industry events.

CSIC Events

Cybersecurity for Smart Infrastructure
CSIC's winter Partner Event brought focus to the challenges and opportunities of Cybersecurity for Smart Infrastructure and featured a number of presentations from leading experts, including a UK Government security advisor, Topcon, A Luck Associates, PA Consulting, Gleeds and Laing O'Rourke. The presentations and workshop considered the implications of cybersecurity, highlighted pressing issues and recommended the range of support available.

Observational Method Workshop
CSIC Investigator Dr Giovanna Biscontin led a Centre for Digital Built Britain (CDBB) and CSIC-sponsored workshop titled *The Observational Method (OM) for supported excavations: research challenges for removing barriers*, in March 2018. The aim of the one-day workshop was to bring together representatives from all the expertise and functions that interact on large excavation projects to identify barriers to the adoption of data-driven adaptive design in practice.

Digital Cities for Change Workshops
CSIC hosted a workshop *Emerging Connections: Tomorrow's Cities and their Infrastructure* in June 2017, as part of the The Ove Arup Foundation funded Digital Cities for Change (DC^2) project. DC^2 is a partnership with CSIC to create a four-year programme to identify how data and digital tools are impacting the mechanics of policy, governance and management of a city and infrastructure planning and design in practice. For 2018 the Emerging Connections workshop was incorporated into the two-day *Technology and Data in Future Cities Workshop*. The workshop explored the potential to improve city services through automation in the transport sector.

CSIC Distinguished Lecture
The CSIC Distinguished Lecture 2017 was presented by Dr W. Allen Marr, the founder and CEO of Geocomp Corporation, a leading US-based company providing geostructural design and performance monitoring services to clients across the United States and around the world. In his lecture titled *Managing Risks to Infrastructure with Real-Time Monitoring of Performance*, Dr Marr discussed the nature of risk to typical infrastructure facilities and how these can be mitigated by using sensors, computers and the internet to provide real-time data. Dr Marr's lecture can be viewed on CSIC's YouTube channel.

CSIC Partner Summer Party
CSIC's annual Partner Summer Party was held at Trinity Hall, University of Cambridge, in September. The event provides an opportunity for partners to learn about the latest CSIC research and projects through short, fast-paced presentations, project posters, and informal discussions with CSIC researchers. The presentations can be viewed on CSIC's YouTube channel.

CSIC Partner Strategy Day
The CSIC Partner Strategy Day is an annual event designed to inform partners on CSIC's current programme and to invite input from partners on our future strategy. Discussion sessions are designed to identify any gaps in our activity which could lead to future research opportunities and new collaborative proposals. The day also provides a valuable opportunity for CSIC to better understand the challenges faced by industry. Several common themes emerged from discussions at the 2017 Strategy Day which was organised over four sessions: (1) infrastructure design, assessment and construction; (2) asset management and operation; (3) cities; and (4) sensing and measurement. Discussion points and suggested opportunities for CSIC involvement for each theme informed the *CSIC Partner Strategy Day 2017 Key Outputs from Discussions* document which was made available to CSIC partners.

ICSIC 2019
Plans are underway for the International Conference on Smart Infrastructure and Construction (ICSIC 2019) which will take place from 8 to10 July 2019 at Churchill College Cambridge. The 2019 conference will bring together world-leading academics and practitioners from the fields of infrastructure planning and delivery, asset management and sensing. A Call for Papers has been issued with Abstracts due by mid-September 2018. More information can be found at www.icsic2019.eng.cam.ac.uk.

External events

As part of our role as an Innovation and Knowledge Centre (IKC) CSIC seeks to share its research outputs with a variety of audiences.

ISNGI 2017

CSIC and our UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC) colleagues contributed to the fifth in a series of symposia on next generation infrastructure. *The International Symposium for Next Generation Infrastructure 2017* (ISNGI2017) marked the official launch of UKCRIC, a major research programme that co-sponsored the 2017 event and of which CSIC is a partner. The event featured a keynote address presentation by Professor Lord Robert Mair, Head of CSIC and President of the Institution of Civil Engineers (ICE), and contributions from Dr Jennifer Schooling, Director of CSIC, and Dr Ajith Parlikad, CSIC Investigator.

Innovate 2017

CSIC was invited to be part of Innovate 2017, Innovate UK's flagship event. The conference addressed how UK innovation can tackle some of our biggest global challenges. CSIC Director Dr Jennifer Schooling was part of a panel discussion that considered 'How to Build a School where Children Achieve More'.

Institution of Civil Engineers Tunnel Engineering and Invisible Superheroes Exhibitions

CSIC contributed to the Tunnel Engineering Exhibition at the Institution of Civil Engineers (ICE), in London (May to November 2017). The exhibition featured a short film about CSIC's award-winning Smart Tunnel project. Two display cases presented innovative sensing devices including distributed fibre optic sensing (DFOS) and the multi award-winning miniature UtterBerry sensor. The display was so popular that CSIC was also invited to contribute to the Invisible Superheroes exhibition which is open throughout 2018.

Hosting visits to CSIC

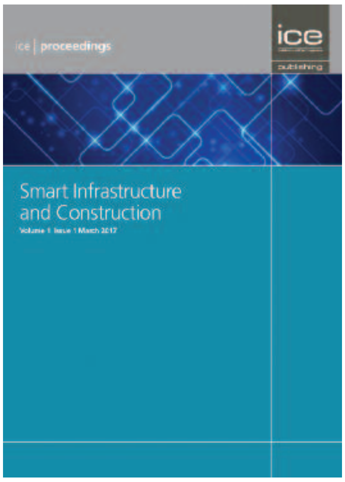
CSIC hosts visits by a range of organisations and individuals throughout the year. In the past year our visitors have included: Trustees from the Ove Arup Foundation; the Institution of Civil Engineers (ICE) Council; the Innovate UK Urban Systems team; a delegation from Hong Kong including the Permanent Secretary for Development (Works); and His Royal Highness The Duke of York, KG. These visits, which typically include presentations, lab demonstrations and informal discussions, provide an opportunity for CSIC researchers to share knowledge and promote the use of smart technologies and solutions.

Cambridge Science Festival

This year the Department of Engineering was a host venue for the University of Cambridge Science Festival. CSIC's event attracted much interest and included hands-on and family-friendly activities showcasing a range of smart technologies including: a fibre optic instrumented suspension bridge demonstrating dynamic strain; a CSIC-developed data acquisition system featuring acoustic emission sensors and accelerometer that displayed a real-time signal on contact with the sensor; a short film about the creation of CSIC's 'Smart Tunnel'; and a video showing some of the smart sensor technology embedded in the James Dyson Building that is home to CSIC.

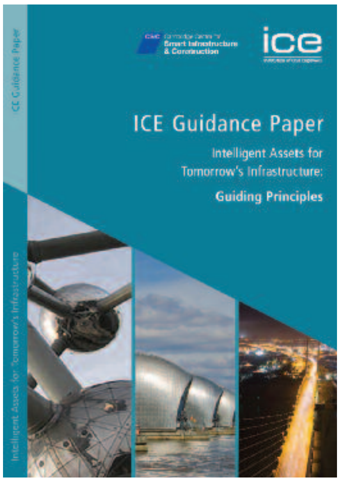
Research and guidance

Journal of Smart Infrastructure and Construction (SMIC)



Smart Infrastructure and Construction (SMIC) is a journal proceedings focused on developing a learned community around the opportunities and challenges presented by the global adoption of emerging digital technology in the design, construction and management of infrastructure assets. SMIC, which has completed its first year, is co-edited by Dr Jennifer Schooling, Director of CSIC, and Professor Kenichi Soga, Department of Civil and Environmental Engineering, University of California – Berkeley, USA. Learn more about Smart Infrastructure and Construction at: www.icevirtuallibrary.com/page/jsmic/new-authors.

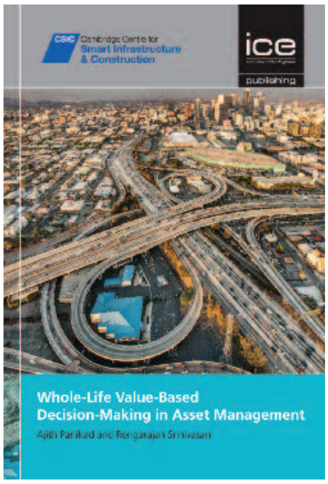
ICE Guidance Document – Intelligent Assets for Tomorrow's Infrastructure: Guiding Principles

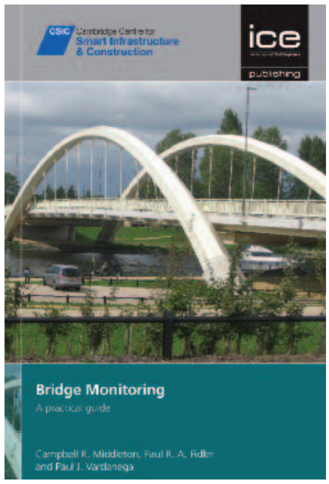


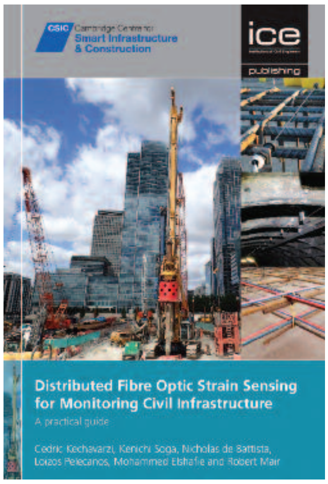
CSIC and the ICE Asset Management group produced a report which introduces the concept of smart infrastructure and intelligent assets. *Intelligent Assets for Tomorrow's Infrastructure: Guiding Principles*, which is written by CSIC Investigators Prof Duncan McFarlane and Dr Ajith Parlikad, CSIC Director Dr Jennifer Schooling, David Pocock (Jacobs), Simon Parsons (RealFoundations) and Charles Jensen (ICE), looks at how advances in sensing and data management have the potential to transform the way our key infrastructural assets perform throughout their lives, enabling them to identify and solve problems themselves. Download the document from the ICE website at www.ice.org.uk.

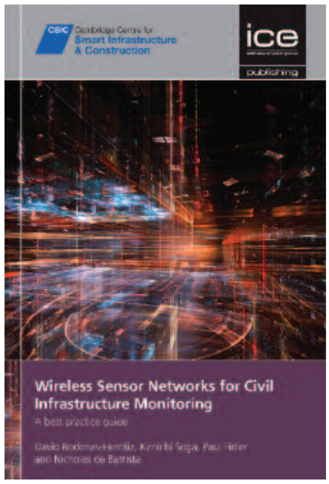
CSIC Best Practice Guides

The CSIC best practice and technology guides, published by ICE, are designed to support the construction industry, infrastructure owners and operators, and the manufacturing, electrical and information sectors. These best practice and practical guides provide information on the installation and operation of novel sensing technologies for asset monitoring and management. The titles include: *Whole-Life Value-Based Decision Making in Asset Management; Wireless Sensor Networks for Civil Infrastructure Monitoring: A Best Practice Guide; Distributed Fibre Optic Strain Sensing for Monitoring Civil Infrastructure: A Practical Guide*; and *Bridge Monitoring: A Practical Guide*. The guides are available from the ICE Bookshop.









Installing fibre optic monitoring at Mansion House

Leadership

Professor Lord Robert Mair CBE
Head of CSIC
President of the Institution of Civil Engineers (ICE)


Image courtesy of Paul Milsom on behalf of ICE

Lord Robert Mair is a Fellow of the Royal Academy of Engineering and a Fellow of the Royal Society. He was formerly Master of Jesus College, Head of Civil Engineering at the University of Cambridge and Senior Vice-President of the Royal Academy of Engineering. Lord Mair is an independent crossbencher in the House of Lords and is a member of its select committee on Science and Technology. His research at Cambridge specialises in the geotechnics of tunnelling and underground construction. He worked in industry for 27 years, and was a founding partner of the Geotechnical Consulting Group. He has advised on numerous tunnelling and major civil engineering projects in the UK and worldwide, including the Jubilee Line Extension, Crossrail, HS1 and HS2. He is Chairman of the Science Advisory Council of the Department for Transport and Engineering.

Dr Jennifer Schooling
Director of CSIC
Director of Research Bridgehead, Centre for Digital Built Britain (CDBB)

Dr Jennifer Schooling was appointed Director of CSIC in 2013. Dr Schooling has secured £7.6m in grant funding from EPSRC and Innovate UK for the Centre. She is a Fellow of Darwin College and founding Co-Editor-in-Chief of the Smart Infrastructure and Construction Proceedings journal (ICE). A member of ICE State of the Nation 2017 'Digital Transformation' Steering Group, Dr Schooling was also part of PAS185 Smart Cities security standard steering groups, the Tideway Innovation Forum and Tideway Academic Advisory Group and the UKCRIC standing committee. She worked in industry for Arup, leading the Research Business, and the Modern Built Environment Knowledge Transfer Network leading on the development of the agenda for the emerging Future Cities Catapult.

Executive Committee

Dr Giovanna Biscontin
Lecturer in Geotechnical Engineering
Dr Ruchi Choudhary
Reader in Architectural Engineering
Prof Daping Chu
Head of the Photonics and Sensors Group
Dr Matthew DeJong
Senior Lecturer in Structural Engineering
Dr Ying Jin
Reader in City Planning, Urban Design and Modelling
Dr Cedric Kechavarzi
Operations Manager
Prof Lord Robert Mair CBE
Emeritus Professor of Civil Engineering, Director of Research
Prof Campbell Middleton
Laing O'Rourke Professor of Construction Engineering
Dr John Orr
University Lecturer in Concrete Structures
Dr Ajith Parlikad
Senior Lecturer in Industrial Systems
Dr Jennifer Schooling
Director of CSIC
Prof Giulia Viggiani
Professor of Infrastructure Geotechnics

International Advisory Group

Prof Michael Batty
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Prof Yozo Fujino
Yokohama National University, Japan
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> "CSIC's leadership in smart infrastructure and the calibre of their work are making significant contributions to better designed, built and managed assets. Participating with CSIC is a tremendous opportunity for Jacobs to engage with academic experts and senior infrastructure managers, to guide development and deployment of solutions.

David Pocock, Director, Asset Management Advisory, Jacobs

Our people

Investigators

CSIC benefits from contributions made by a number of Investigators who are all experts in their specialist fields. Our Investigators work across a range of academic disciplines enabling a productive and effective synergy.

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The UK has the potential to lead one of the defining developments of the 21st century. The intelligent use of digital technologies will enable the country to maximise the whole-life value of our built assets and create a digital and smart economy that will bring benefits to all.

The key to securing this potential is collaboration between stakeholders in research, policy and practice. By working together we will all benefit.

Dr Jennifer Schooling, Director of CSIC

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