JRC CONFERENCE AND WORKSHOP REPORT

Indirect structural health monitoring (iSHM) of transport infrastructure in the digital age

MITICA (Monitoring Transport Infrastructures with Connected and Automated vehicles) workshop report

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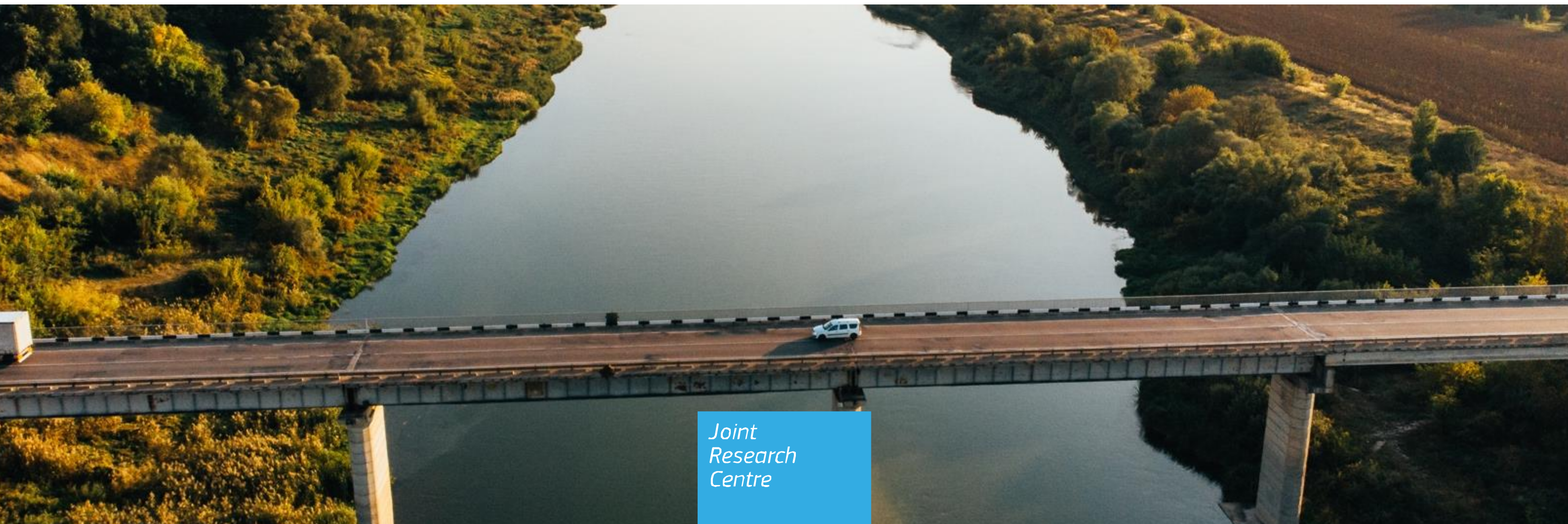

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Contents

Abstract

The existing European motorway infrastructure network is prone to ageing and subject to natural events (e.g. climate change) and hazards (e.g. earthquakes), necessitating immediate actions for its maintenance and safety. Within this context, the structural health monitoring (SHM) framework allows a quantitative assessment of the structural integrity, serviceability and performance, facilitating better-informed decisions for the management of the existing infrastructure. The European Commission Joint Research Centre (JRC) established the exploratory research project MITICA (Monitoring Transport Infrastructures with Connected and Automated vehicles) to investigate the opportunity to use novel methods for infrastructure motoring, aiming at the efficient maintenance of the European aging road infrastructure. This report summarizes the discussion and the outcomes of a workshop held at the JRC in Ispra (Italy) on June 6-7 2022, as part of the MITICA project. Considering the EU priority “A Europe fit for the digital age”, the workshop was dedicated to SHM and its application to civil infrastructure, focusing on innovative indirect structural health monitoring (iSHM) approaches that rely on the vehicle-bridge interaction and the deployment of sensor-equipped vehicles for the monitoring of the existing bridge infrastructure. The report aims to become a reference document in the area of iSHM using passing vehicles, for both scholars and policy makers.

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1 Introduction

The existing European urban and infrastructure network is prone to ageing and subject to natural events (e.g. climate change) and hazards (e.g. earthquakes), necessitating immediate actions for its maintenance and safety. Within this context, the structural health monitoring (SHM) framework allows a quantitative assessment of the structural integrity, serviceability, and performance, facilitating better-informed decisions for the management of the existing infrastructure.

In this framework, the European Commission Joint Research Centre (JRC) established the exploratory research project MITICA[1] (Monitoring Transport Infrastructures with Connected and Automated vehicles) to investigate the opportunities of innovative methods of motoring for the efficient maintenance of the European aging road infrastructure. MITICA addressed the future advantages of connected vehicles and the measurements from vehicles on-board sensors to infer bridges conditions possibly offering an alternative low-cost method of structural assessment. The workshop comes as a conclusion to the MITICA project that was carried out in the period 2020-2022.

Considering the EU priority "A Europe fit for the digital age"[2], this workshop aimed to showcase recent technological advances and developments in SHM and their application to civil infrastructure. Special focus was given to innovative indirect structural health monitoring (iSHM) approaches that rely on the vehicle-bridge interaction and the deployment of sensor-equipped vehicles for the monitoring of the existing bridge infrastructure, including results from the MITICA Project. The pros and cons of iSHM methods were compared against direct SHM approaches with a special emphasis on the challenges and lessons learned from real-life SHM implementations. Further, this workshop aimed to present the relevant European research and discuss the current state towards the SHM integration in technical standards at a European level.

In more details, the workshop aimed to:

1. discuss the state-of-the-art of iSHM based on the vehicle-bridge interaction;
2. present innovative SHM methods regarding advanced sensors and technologies, signal processing methods, artificial intelligence;
3. identify and analyse technical, legislative and operational challenges and opportunities (including data issues) for future large-scale implementation of iSHM;
4. explore synergies with ongoing R&I projects and other initiatives;
5. discuss the integration of SHM approaches to standards and codes of practice;
6. provide insights towards the way forward for future research and implementation.

This report summarizes the discussion and the outcomes of the workshop, aiming to become a reference document in the area of iSHM using passing vehicles, for both scholars and policy makers. The first can get an overview of the state of art, including the most up to date research techniques and methods. The latter can understand that iSHM using passing vehicles could be an option for future policy developments, especially when considering the further development and deployment of connected and automated vehicles in the next years.

The report structure follows closely the structure of the workshop program, developed over one and a half days under seven sessions, on top of the welcome address, an introductory and a concluding session.

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[1] https://trimis.ec.europa.eu/sites/default/files/documents/jrc122485_mitica_leaflet_final_0.pdf

[2] https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age_en

2 Welcome address.

Moderator: Maria Cristina Galassi, Sustainable, Smart and Safe Mobility Unit JRC[3]

The first day kicked off with a welcome address from the JRC hierarchy to the participants. Dr. Galassi who moderated the brief session, introduced the MITICA project to the participants, provided an overview of the inspiration for the project, explained the way the project was set-up and the challenges that were faced, considering also the overlapping with the Covid-19 pandemic.

2.1 Jutta Thielen - Del Pozo, Head of Scientific Development Unit, JRC

Dr. Thielen - Del Pozo provided an overview of the JRC and exploratory research programme, highlighting some interesting aspects. JRC exploratory research accounts for a very low fraction of JRC research (approximately 5%), and embraces research not directly linked to policy development. As such, it brings together research community that is not thematically bound, forging collaborations between people from different JRC Units, and helping them inspire each other.

2.2 Alois Krasenbrink, Head of Sustainable, Smart and Safe Mobility Unit, JRC

Dr. Krasenbrink emphasised the positive collaboration between the two main units working on the MITICA project, which helped bring together research areas linked to transport (including infrastructure) and safety. He also highlighted that the idea of the MITICA project came up after the Genova bridge collapsing. Unfortunately, as he stated, very often tragic events trigger interest from the community (people, scientists, policy makers and other stakeholders) but in short time they are forgotten. As a final remark, he highlighted that we (the community) should be proactive instead, and work towards preventing negative events.

2.3 Artur Pinto, Head of Safety and Security of Buildings Unit, JRC

Dr. Pinto, following up on the comments from Dr. Krasenbrink, stated that forgetting unfortunately is something that occurs in society but as researchers we have the role to maintain and give our contribution to societal needs. He highlighted the fact that the project started just before the pandemic, with obvious difficulties in designing and building an experimental facility, considering also that the project lasted only two years. In particular, the entire period from March to June 2020 (while the facility was put in place), there were serious difficulties even for the JRC personnel to access the site. This is an example of the determination shown from the JRC, also beyond the people involved directly in the project, and including the people responsible for the JRC Infrastructure. The difficulties were even higher since it was difficult for the people behind MITICA to get in touch directly. However, this led to increasing the connection and coherence of the group.

Finally, Dr. Pinto concluded with a remark about the role of the JRC to provide policy support to the European Commission to protect our society. Also, accidents like the one occurred in August 2018 (the Polcevera viaduct collapse), can and should be avoided, and the European Union (EU) with its future policies on the well-being and safety of people will contribute towards such goal.

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[3] Former Sustainable Transport Unit

3 Setting the context

This introductory session had as objective to set the context in which projects like MITICA and iSHM research in general are introduced. Focus was given on the European perspective of research and innovation (R&I) and the role of the JRC.

3.1 Introduction

Presenter: Maria Cristina Galassi (JRC)

Dr. Galassi introduced the workshop stating that the JRC established the exploratory research project MITICA (Monitoring Transport Infrastructures with Connected and Automated vehicles) to investigate the opportunities of novel methods of infrastructure motoring for the efficient maintenance of the European aging road infrastructure. MITICA addressed the future advantages of connected vehicles and the measurements from vehicles on-board sensors to infer bridges conditions possibly offering an alternative low-cost method of structural assessment. The present workshop comes as a conclusion to the MITICA project that was carried out in the period 2020-2022.

She highlighted that the EU motorway infrastructure network is ageing, with many bridges presenting structural deficiencies. While methods for assessing the actual condition of a structural systems are already in place, the primary bridge evaluation methods rely on visual inspections, which are subjective, often of difficult implementation (thus expensive) and affect the definition of the maintenance plan.

At the same time, only major and more recent bridges are equipped with fixed sensor networks, which are of difficult installation on existing infrastructures, of very expensive maintenance and can provide limited information, depending on the number and position of the installed sensors. Aging European transport infrastructure requires significant investments in maintenance or retrofitting, and careful monitoring for prioritizing interventions and prevent catastrophic failures. Novel solutions and technologies are urgently needed to cope with limited resources, urgency of interventions and the extent of the existing assets to overcome the limitations of existing solutions.

At the same time, while on the infrastructure side we observe a lack of data, on the transport side we have an unprecedented data availability from sensors on board connected and automated vehicles (CAVs) – that may be even more appealing than those available today. Thanks to their hardware and software equipment, automated vehicles are able to sense and evaluate the environment, and perform driving functions.

JRC is contributing to the development of the type approval framework for CAVs. We already had a United Nation (UN) regulation for SAE Level 3 automation (L3) traffic-jam pilot adopted in 2020 (UNECE 2020). This year we will have an extension of this regulation to approve more capable L3 highway chauffeur, and the new EU Regulation for the type approval of SAE Level 4 automation (L4) Automated Driving Systems (ADS) that will allow the market introduction of shuttles, robotaxis, Automated Valet Parking (AVP) and hub-to-hub commercial applications. And indeed, as clearly represented in the ERTRAC roadmap (ERTRAC 2020), many L3 and L4 applications are expected to be available on the market in the next few years.

There are high expectations for CAVs market penetration in the coming decade, and concerning their capability of providing real-time data. From here our research question in MITICA: can sensors on board CAVs contribute to monitoring the state of transport infrastructure?

In fact, mobile sensors on board CAVs can provide data with a denser spatial resolution respect to fixed sensors; this, combined with hundreds of millions of daily vehicles trajectories, could potentially provide frequent and comprehensive scan of road infrastructure.

Concluding, with the MITICA Exploratory Research (ER) we aimed at exploring possible synergies between CAVs and smart infrastructures for Indirect Health Monitoring of EU transport network.

3.2 Safety of Bridges

Presenter: Georgios Tsionis (JRC)

Dr. Tsionis presented an overview of the safety of bridges linked to the structural Eurocodes, highlighting that a set of 10 “European Norm” (EN) standards is applied in bridge design. These cover all types of bridges (road, railway and foot bridges).

JRC work on the topic originates on an Administrative Agreement (AA) between the JRC and the Directorate General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW). Nowadays, the Eurocodes are well established in EU countries, while there are also countries outside EU that are interested in adopting them.

DG GROW has issued a mandate for the next generation of Eurocodes, something that will amend existing Eurocodes and extend their scope. The mandate covers several bridge related issues, including: ease of use and technical consistency; assessment and retrofitting; load models and combination of actions; partial prestressing and crack control; bearings and expansion joints; integral bridges; fatigue; robustness; and, footbridge vibrations.

The JRC and Eurocodes experts developed a set of worked examples for bridge design that covers all the aspects: basis of design; actions; modelling and structural analysis; concrete bridge design; composite bridge design; geotechnical aspects; seismic issues. These examples can be downloaded from the Eurocodes website[4].

The JRC coordinates scientific networks, providing support to DG GROW, the European Committee for Standardization (CEN) and the National Standardization Bodies for what regards data, standardisation and research needs. Examples include adaptation of structural design to climate change, e.g. snow loads and corrosion that might be accelerated by climate change, and the design of underground structures.

On a different stream of action, the JRC opens its research infrastructures to the research community[5], providing users with infrastructure that they do not have in their countries, while a benefit for JRC is to enter new areas of research and maintain the excellence of our research infrastructure. In this case, the European Laboratory for Structural Assessment (ELSA) reaction wall[6] is relevant to bridge related research.

In the slides, some examples of experimental work carried out in the ELSA reaction wall are provided.

When it comes to the future, a new four-year project under the Horizon Europe Framework Programme just started. Under this project ERIES[7] (Engineering Research Infrastructures for European Synergies) the JRC is offering transnational access to the ELSA reaction wall.

3.3 Bridge Research and Innovation in Europe

Presenter: Konstantinos Gkoumas (JRC)

Dr. Gkoumas provided an overview of recent EU funded R&I projects. In doing so, he firstly introduced the activity of the European Commission's Transport Research and Innovation Monitoring and Information System (TRIMIS). TRIMIS among other things maintains a database of more than 9000 EU and Member States (MSs) funded projects and programmes that go back well before the Seventh Framework Programme (FP7). Based on this database, as well as on other sources of information TRIMIS analyses technology trends and R&I capacities in the European transport sector.

Based on TRIMIS work, a report was published in 2019 focusing on bridge maintenance, inspection and monitoring R&I in Europe in the last quarter of a century (Gkoumas et al., 2019). The report critically addresses issues and methods, and also highlights new technological developments and future-oriented approaches. The report is currently the most downloaded of the TRIMIS reports, with more than 1500 downloads only from the JRC publications repository.

On another stream of research, an effort was made to:

1. assess the state of play of policies on connected road mobility, bridge maintenance, and monitoring;
2. discuss the current direction of research within the iSHM paradigm by indicating the current state of the art of technologies and methods; and,
3. Provide pathways for the way forward for iSHM using CAVs.

To this aim, and as partial fulfilment of the MITICA work package on literature review, a scientific paper was published (Gkoumas et al., 2021).

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[4] https://eurocodes.jrc.ec.europa.eu/

[5] https://ec.europa.eu/jrc/en/research-facility/open-access

[6] https://joint-research-centre.ec.europa.eu/laboratories-and-facilities/european-laboratory-structural-assessment-reaction-wall-facility_en

[7] https://eries.eu

Getting back on EU funded research, highlights were shown and briefly discussed, based on TRIMIS research that assessed more than 70 projects on bridges R&I. The projects were clustered under five themes: Hazards; Materials and Components; Maintenance and Lifecycle; SHM, Visual Inspection and Sensors; and, Software tools. What emerges is that the highest budget was devoted to R&I on Hazards (either alone or in combination with one or more themes). The concentration of many projects on hazards in the early 2010s can be explained by the occurrence of seismic events in Europe around or before that time. In parallel, many projects starting after 2014 coincide with the emerging topic of disaster resilience. The research is consistent also on the theme of software tools, while, many new technologies were developed under H2020 (e.g. drones). For drones, it seems that the industry is keener to bring the technology to the market, and there are initiatives from the EU at a policy/legislative level (e.g. the U-Space[8], Drone Strategy 2.0[9]) that can facilitate implementation.

Concluding, some of the expectations and challenges from the R&I perspective that arise are reported below.

- New and emerging digital technologies can revolutionize the way bridges and transport infrastructures are designed, build and maintained. Examples: digital twins, Unmanned Aerial Vehicles (UAVs), Internet of Things (IoT), Artificial Intelligence (AI), machine learning, vision-based monitoring, iSHM.
- For new technologies, interdisciplinary teams are needed to break the silos. A linkage and transition between disciplines is necessary, especially for SHM.
- Standardisation, data interoperability and security are paramount.
- Digitalization provides different levers to enable the sustainability transition. A challenge exists for energy systems to satisfy the demand of data centres.
- Technologies should be supported by policy and implementation actions at several levels.

3.4 Open discussion

Dr. Galassi opened the floor for discussions.

Dr. Pinto mentioned to Dr. Tsionis that the focus of the MITICA project is on monitoring and maintenance and not linked to design and the relevant Eurocodes and Standards. Is there a **need for guidelines** or other actions in the form of methodologies to cover aspects beyond design? A second question to Dr. Gkoumas was linked to the presentation and the fact that budget linked to maintenance did not evolve in the past years, especially considering the collapse of the Polcevera viaduct (Morandi bridge) in 2018: one should expect that new projects would commence after that.

Dr. Tsionis commented that there are currently no widespread standards on maintenance but there is ongoing work (some also presented in the workshop). He added that as Dr. Gkoumas mentioned, there is a need for data standardisation. Beyond standards, what is necessary is to **link the data to decision parameters**, because we often find ourselves with nicely organised data that are not easily interpreted by experts to take decisions (e.g. on maintenance or closure of the bridge).

Dr. Gkoumas mentioned that several projects started after the Polcevera viaduct collapse in Genova, but their principal focus is not on maintenance but on new technologies for inspection and monitoring. He also mentioned four projects that were presented in a conference in Brussels on results from H2020 projects on transport infrastructure. Briefly: research started after the Genova events, but a lot more had been performed before, and thus it is interesting to understand how **research is pushed forward into implementation** after the R&I project finishes.

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[8] https://www.sesarju.eu/U-space

[9] https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7076

4 DAY 1 Session 1: Advances in SHM strategies and its applications to civil infrastructure

Chair: Elsa Caetano (University of Porto)

4.1 Monitoring and managing structure dynamic performance for resilience, sustainability and serviceability

Presenter: James Brownjohn (University of Exeter)

Prof. Brownjohn described technologies and their applications for measuring and managing civil structure full-scale performance. These are targeted at serviceability -in respect of vibrations, resilience-in respect of structural health monitoring and sustainability -in respect of optimised design.

The three targets are covered by three symbiotically linked organisations: University of Exeter Vibration Engineering Section -for original research informed by real-world experiences accessed by both funded research and consulting activities, Full Scale Dynamics Ltd (FSD) which applies research outcomes and technologies to prevent or mitigate serviceability problems and feed unique insights back to research, and FSD Active which delivers active control solutions for sustainable management of serviceability.

A few examples illustrate this:

- a major United Kingdom (UK) football stadium checked for code compliant dynamic performance using forced vibration (shaker) testing and experimental modal analysis;
- a tall building (Canary Wharf, London), a long span bridge (Jiangyin, China) evaluated dynamically to identify key wind-sensitive modal properties using advanced Bayesian operational modal analysis and novel wire-free synchronous acceleration loggers;
- a telecoms monopole tested for resilience and serviceability for fifth generation of telecommunication systems (5G) upgrade using these technologies;
- a power station chimney and a high-guyed broadcasting mast monitored for safety using online modal parameter estimation;
- a remote offshore Victorian lighthouse studied using modal testing and monitoring to back-calculate extreme breaking wave loads and assess resilience of similar safety-critical structures for another century.

Bridges, masts and wind turbines exist in populations with nominal similarities and there is potential via a new research program (ROSEHIPS[10]) to leverage performance measurements on subsets to inform resilient management of the wider populations

There is a strong and potentially conflicting relationship between serviceability and sustainability in building design, and UoE/FSD/FSD Active have technologies to optimise design solutions.

- VSimulators is a dual-site motion platform facility pitting humans at the centre of design to calibrate both generic design (via codes and standards) and specific design (people in the design loop). The facility is also being heavily used to study rehabilitation strategies for diseases such as Parkinson's that affect mobility.
- A compact and effective active mass damper now in commercial operation building on over a decade of research and consulting experience in floor vibration serviceability.

4.2 Structural Health Monitoring of critical infrastructure in seismic regions

Presenter: Anastasios Sextos (University of Bristol)

Prof. Sextos addressed the challenge of infrastructure resilience and the need for informed disaster risk mitigation and management of highway networks along with the quantification of resilience in a feasible, meaningful, and pragmatic manner. He presented a methodology coupled with applications of Structural Health Monitoring for the nearly-real time update of the scenario-based assessment of seismic loss, in case of an earthquake. The methodology is a multi-dimensional (i.e., structural, geotechnical, transportation and financial)

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[10] https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/W005816/1

framework that permits consideration of bridge damage, repair rates and downtime in the decision-making process for pre-earthquake retrofit (Kilanitis and Sextos 2019). Bridge fragility is assessed based on rigorous, frequency- and intensity dependent models for soil-pier (Lesgidis et al., 2017) and deck-abutment-embankment interaction (Zhang and Makris 2002), while regional seismic hazard is represented in the form of scenario-based spatially variable intensity measures. A set of novel, time-variant, resilience-based indicators which consider financial, environmental and social consequences are then used to identify the bridges that would have the maximum beneficial impact at a network level if strengthened prior to an earthquake event. Particular reference was made on the socio-behavioural aspects of network traffic given based on how drivers (i.e., independent network agents) respond when a natural disaster such as an earthquake interrupts the functionality of the system (Kilanitis and Sextos, 2018). This probabilistic risk management framework, as well as the corresponding GIS-based software, are deemed a useful tool for local/state or national stakeholders in prioritizing the pre-disaster strengthening schemes and accelerating the post-earthquake inspection and recovery measures, respectively. It was concluded that infrastructure resilience quantification is key for informed decision-making and that expert systems or AI technologies are needed to be able to maximize the applicability of the big data that can now be gathered with SHM and/or iSHM.

4.3 Advanced SHM techniques for civil structures and infrastructures

Presenter: Gian Paolo Cimellaro (Politecnico di Torino)

Prof. Cimellaro provided an overview of innovative and promising SHM techniques for civil structures and infrastructures. Civil structures and infrastructures are subject to degradation, cracking, and high loads and, in many cases, they have reached the end of their design life. For these reasons, community stakeholders are concerned about asset safety, unplanned maintenance, downtime and closures, escalating costs, unknown remaining asset life, asset replacement scheduling.

SHM technologies can monitor critical assets' defects combining innovative Non-destructive testing (NDT) and IoT by five steps: (1) pre-inspection, (2) sensor installation, (3) long-time/permanent monitoring, (4) secure data acquisition and sensor fusion, (5) analytics and client reporting. They represent an invaluable tool for infrastructure owners and community stakeholders as through data interpretation they can be used to assess defect criticality, extend asset life, reduce downtime through targeted maintenance, and minimize total costs of ownership.

Overall, the goal of SHM should be to improve the resilience of civil structures and infrastructures. As the number of applications increases, it will also be possible to use SHM data to reduce the uncertainty in design process and to perform more complex analyses involving multiple hazards. In the perspective of Smart Cities, SHM plays a key role also to save people during an emergency in a collapsing structure (social monitoring system). In case a proper SHM system is not in please, social monitoring could be achieved using mobile phones and wearable devices acting as nodes within a sensor network to identify the presence/position of people in the building.

Some of the traditional SHM technologies are piezoelectric impedance transducers, magnetoelastic stress sensors, and synthetic aperture radar. Traditional discrete monitoring sensors are still relevant in monitoring bridges at critical locations, where the development of cracks or large stresses are expected. Moreover, despite some of these technologies might be considered obsolete, modern iterations of the same devices might be found in the market offering high performances.

On the other hand, distributed sensing technologies, such as fibre optics and smart sensing materials, represents one of the latest evolutions in the SHM field. Although big companies have been a bit reluctant to use new technologies, fibre optics have many advantages such as geometric adaptability, possibility to be embedded in concrete, capability of measuring a variety of perturbations (e.g. strain, acceleration, temperature, etc.), high signal-to-noise ratio, resistance to harsh environments. They probably are the best option to monitor long structures like tunnels and some of the most recent sensors can be easily installed on existing structures with tape or glue.

Other recent innovations are related to non-contact sensing, which is particularly useful in situations where traditional human inspection operations are complex or unsafe. Examples are: (1) digital image correlation, where cameras are used to detect displacement, deformations and therefore stresses and crack propagation; (2) infrared, where the variation of the surface temperature of the material is used to identify phenomena such as delamination, detachment and cracks; (3) Light Detection and Ranging (LiDAR) sensors that can be mounted on vehicles or drones to scan the infrastructure even in low light conditions to identify deformations/displacements that may have occurred.

Some examples of experimental work carried out at the Politecnico di Torino Laboratory have been shown. Another project (MADI) which sees the Politecnico di Torino currently involved is about development of a wireless monitoring sensors system where the sensors are embedded in a case and laminated so that they can be glued directly on the surface of structures of different materials. The wireless architecture has been designed so that neighbour sensors can communicate between each other through a multi-hop approach. In this way the signal can travel for longer distances using only one or few gateways.

The last part of the presentation focused on techniques that can be used to identify the presence and the location of damage by processing the acceleration and deformation measurements recorded from SHM systems: (1) Modal Assurance Criterion with ambient vibration tests on bridges and viaducts from acceleration measurements; (2) neutral axis variation (statistical) from strain measures under simple flexural conditions; (3) dynamic curvature from strain measurements (non-symmetric responses with respect to structural scheme); (4) Interpolation Damage Detection Method (IDDM) with distributed low-noise accelerometers.

4.4 MITICA testing site and structural modal assessment

Presenter: Daniel Tirelli (JRC)

The MITICA project was led by staff inside the JRC from two fields of research, coming respectively from the "Sustainable, Smart and Safe Mobility" Unit and the "Safety and Security of Buildings" Unit, covering broad competences for the complexity of the project. Being an iSHM project financed by an exploratory research budget of the JRC, limitations were applied to the size of the two main components: the structure and the vehicle. A small yet real concrete bridge of 9.0 m length by 3.0 m width was designed and installed inside a road loop. The monitoring was performed using a nearly scaled instrumented vehicle, a Fiat Panda of about 1/14 of the total weight. To complete and help in the understanding of the system a numerical model was implemented.

The pandemic came at the beginning of the project causing delays and safety supplementary tasks. Tests were performed in real conditions and different seasons and time (also during the night), bringing a wide range of difficulties, and some unexpected behaviour. The more important detail in the design of the structure was in the supports of the two beams. Four (six for the future) supports were instrumented with a load cell in each. A system of prepositioning of the load cell on a steel plate were design to change the span of the bridge simulating in this way a damage of the structure. A fast change of the positions was eased by lifting the deck with a system of four hydraulic jacks.

Many issues were solved in the design phase, or in preliminary tests and equipment:

- the size of the circuit by preliminary tests of accelerations, gear changes, safety distances and braking;
- temperature control by thermocouples adequately installed to capture irradiation, inertia and conduction. Coupled to displacement sensors it revealed the skin effect of the deck;
- the elevation of the bridge was designed with the temperature variation to limit at the minimum the horizontal forces on the load cells;
- loading test to verify static mechanical properties;
- modal properties of the bridge were measured by the Fast Impact Hammer Testing method (FIHT) (Tirelli, 2011). Classical wire system and new wireless system were applied to compare the results and solve the issues of filtering, sampling, and data transmission.

Other issues appeared in the phase of iSHM tests. We observed that when a moving vehicle crossed the bridge there was a dispersion of the spectra and it becomes then difficult to process the data.

To capture the dynamic properties of the bridge we used the FIHT method, an Input-Output method where impact force and Frequency Response Functions (FRFs) are measured on a regular mesh on the deck, but not simultaneously. The reciprocity theorem of the FRFs, for this type of specimen, is used to obtain accurate results but remains limited to small and medium structures for the low level of input energy. Data are processed with an algorithm (DANBOX) (Tirelli et al., 2018) which belongs to Operational Modal Analysis (OMA) methods. It is well adapted for MITICA for the number of configurations of the bridge to be tested.

Map of the forces and of the coherences allows a fast control of the FRFs recorded. At this stage, the extraction of the peaks of all the FRFs is performed quickly by application of the algorithm specific to the DANBOX software. The modal parameters, frequency, damping and modes shapes, are extracted by a clustering process based on two experimental parameters: the standard deviation and the stability of the number of modes found.

As it is often the case in others modal analysis software, in this case no limit value of dispersion is taken a priori, and the frequency values are amplitude weighted, which gives to DANBOX a new experimental approach of modal analysis. The method already used in different project at the ELSA has shown very interesting aspects in the results, including e.g. automatic tables of results, spline interpolation of the modes shapes, modal shapes recorded in video format.

For the MITICA project, it provides the tables of comparison of the frequencies and damping of the main modes in different support conditions of the bridge. These data are the reference for the iSHM campaign described in a following presentation.

4.5 Open Discussion

Prof. Caetano provided the highlight of the session and opened the floor for discussions.

Mr. Tirelli was asked if the damage was simulated by changing the span, on the possible other damages that could be implemented in the bridge model, in addition to those stated in the presentation that focused on changing the boundary conditions, and if the bridge was in reinforced concrete. The reply was that the damage was simulated by changing the span, and that no other damages were simulated at this stage, but the intention was to simulate the damage of a pile by eliminating one of the four supports. He also confirmed that it is **difficult to observe very small damage** due to the presence of noise, hence, many sessions of campaigns are necessary to be sure that the damage detected is accurate.

Prof. Brownjohn was asked to elaborate on **walk by monitoring** and the associated challenges. He replied that it is more about an idea at this stage, but you can certainly do modal testing using one accelerometer placed on the back of the neck of the person and one on the bridge. Or you can use cheap sensors, take them out, synchronise them leave them for a period of time and then collect the data. On a question about the feasibility of energy harvesting using the dynamic excitation of the bridge, Prof. Brownjohn replied that it would not be very efficient.

Prof. Sextos replied on a question about how extensive should the monitoring system be, considering that in some countries it would be possible to have a minimum set of fixed instrumentation and use drive-by monitoring. His reply was that structural health monitoring is key, and if it is implicit even better. However, for practical applications iSHM should be (a) reliable (i.e., operative during the post-earthquake crisis period) and (b) low-cost in terms of development and maintenance to be applied at **large scale with reasonable cost**.

A second question was about the monitoring of the ground motion and if this is monitored in every bridge location or a model of propagation of the ground motion is used. His answer was that there are two ways to assess the seismic demand: (i) using Shake Maps of spectral acceleration and displacement spatial distribution appropriate agencies in each country (see USGS in the US, or EPPO/ITSAK in Greece; approximate way), or (ii) to have an instrument at the base of the structure and one at the free field (albeit the frequencies of a long bridge and those of the earthquake are very different, it is good to double check always since the one at the base can be influenced to some extend by the bridge vibration). This way we have earthquake record (input) and structural response (from sensors on the structure) through which the performance of the bridge can be assessed in almost real time. Both options offer the possibility to update the scenarios developed before the earthquake event as they remove one layer of uncertainly (i.e., seismic hazard becomes deterministic, while bridge fragility remains probabilistic associating exceedance of a limit state given an Intensity Measure, which in this case is known). Note that Shake Maps typically provide Peak Ground Acceleration (PGA), but SHM/iSHM can measure Spectral Acceleration which is a more reliable way to express bridge fragility.

A third question was on the structural assessment and if this takes place in real time (like a digital twin, supported by FEM and computer analytics). How much time is needed to have an input on where to intervene to restore vulnerable bridges in the network? The response was that if you aim for the input of Shake Maps, the delay is about 5 minutes, which is already quite short. If you rely on your own measurements is nearly real time, plus around 15 minutes to process data and obtain the estimate of structural performance. This is because the key aspects of the methodology (e.g. fragility curves) are pre-defined. Considering that for crisis management currently it takes days for the first level of post-earthquake rapid visual Inspection that can even take weeks for the case of a large portfolio of bridges, this method greatly accelerates the evaluation of the earthquake damage.

A question to Prof. Cimellaro was on the experience from involving users in situations of crisis, using their mobile phones. This is a challenge also for involving users in vehicle assisted iSHM (engaging with users and using data generated from them). Prof. Cimellaro specified that the context was different, and not focusing on a large scale system like for bridge monitoring. Nevertheless, software exists for mobile phones that allows to be tracked in case of emergency.

Dr. Limongelli added on the above question that it is difficult to engage people and an option was to set up a rewarding game. This is how they envision iSHM **using bikes and accelerometers from smart phones**: the reward would be extra time credits for rental bikes.

5 DAY 1 Session 2: Indirect Structural Health Monitoring (iSHM) using passing vehicles.

Part 1. Chair Flavio Bono (JRC)

5.1 MITICA experimental campaign at the JRC – indirect structural health monitoring challenges and lessons learned

Presenter: Kyriaki Gkoktsi (JRC)

The iSHM experimental campaign of the MITICA project (Gkoktsi et al., 2022) was presented by Dr. Gkoktsi, with special emphasis given on:

- the wireless sensor network;
- the dynamic characterisation of the vehicle and the bridge (de-coupled systems);
- the challenges and the lessons learned during the iSHM experimental campaign.

A short video introduced the motivation of this research work, highlighting the potential exploitation of evolving technologies in automated vehicles with embedded sensors to address the degradation of the existing European infrastructure due to ageing.

After briefly discussing the advantages and limitations of iSHM methods (e.g. the fast and mobile bridge monitoring versus the adverse effects of the road profile roughness and the vehicle speed), the adopted wireless sensor network was presented. The latter comprised five signal acquisition systems, two systems installed on the vehicle (i.e., system 1 collecting data from nine wireless accelerometers, and system 2 measuring data from one wireless inertial sensor), and three acquisition systems installed onto the bridge (i.e., system 3 acquiring data from nine wireless accelerometers, system 4 collecting data from two infrared sensors at the entrance/ exit of the bridge, and system 5 measuring data from up to six load cells and eight thermocouples on the bridge). Upon presenting the experimental modal analysis results obtained from the vehicle dynamic testing at a four-poster rig facility of the Council for Agricultural Research and Analysis of the Agricultural Economy (CREA) lab[11], in Treviglio (BG), a discussion followed on the main iSHM challenges identified during the MITICA experimental campaign. These challenges are:

- **Challenge 1**: inherent limitations in wireless sensor networks (e.g. bandwidth constraints at fast sampling rates, synchronisation of five acquisition systems).
- **Challenge 2**: the non-negligible vehicle mass with respect to the mass of the bridge (i.e., high vehicle/bridge mass ratio) that leads to a strong interaction between the two systems, as manifested with the increase of the bridge resonant frequencies – the “bridge stiffening” phenomenon which is in line with other findings in the literature (e.g. Cantero et al., 2017).
- **Challenge 3**: the vehicle’s low-pass filtering properties with cut-off frequencies at 40 Hz at the vehicle’s wheel level and 20 Hz above the suspension level. This suggests that the iSHM using sensor-equipped vehicles is mainly focused on the low-frequency range of the bridge dynamic response.
- **Challenge 4**: speed trade-offs associated with the bridge excitation, signal duration, and frequency resolution i.e., higher vehicle travelling speeds induce higher bridge vibration amplitudes (favourable), but this comes at the cost of shorter signal duration and coarser frequency resolution (unfavourable).
- **Challenge 5**: Vehicle-induced bridge vibration and its transmission back to the vehicle. The vehicle acceleration signals do not carry the information associated with the low-amplitude bridge vibration subject to the moving vehicle at the considered speed levels. The results are significantly improved under the use of a speed bump on the bridge, leading to higher bridge excitations which can be sufficiently transmitted to the vehicle’s wheels.

It was concluded that various conditions should be fulfilled for a reliable iSHM approach using sensors on vehicles. Further, it was appreciated that prior knowledge on the dynamic properties of both the vehicle and the bridge is required. Conclusions: challenges of the MITICA project.

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[11] https://www.crea.gov.it/home

5.2 Data-driven approaches for indirect bridge monitoring: numerical results and experimental validation using laboratory measurements

Presenter: Abdollah Malekjafarian (University College Dublin)

Dr. Malekjafarian presented recent works from his team on data-driven approaches for indirect bridge monitoring (Malekjafarian et al., 2022, Corbally and Malekjafarian 2022). He explained the pros and cons of indirect monitoring methods by comparing them to the traditional bridge structural health monitoring (direct approaches). It was disused that drive-by bridge monitoring in its current state, is still dealing with several challenges which need to be overcome in order to bring them into practice. The recent state-of-the-art from the most recent review paper in this field were also discussed, where the recent approaches are categorised into two main groups of (i) modal identification and (ii) bridge condition monitoring. This goes back to the different components available in the drive-by responses such as the driving frequency, the bridge frequency and the vehicle frequency. He also explained the current challenges from his perspective as:

- Short duration of signals
- Interference from the pavement-induced vibration
- Accounting for Environmental and Operational Influences
- Quantification of Damage
- Experimental Verification of Drive-by Concepts

It was discussed that there has been a trend towards using multiple vehicles in the field of drive-by bridge monitoring in recent years.

The results from a numerical study carried out at University College Dublin were presented. Data collected from multiple vehicles passes over a healthy bridge at different speeds were used to train an artificial neural network (ANN). The proposed ANN then was used for predicting the vehicle responses. The quality of the prediction is shown that could be a good indicator of the bridge condition. It is also shown the proposed ANN can be also trained using temperature data to account for environmental conditions. The results from different damage scenarios such as cracks, boundary conditions were discussed. The results from a laboratory scale vehicle bridge interaction (VBI) model were presented showing the capabilities of the proposed approach. It was concluded that further studies using field measurements need to be done in future for real-life verification of data-driven methods.

5.3 Good Vibrations: towards a crowdsensing approach for bridge structural health monitoring

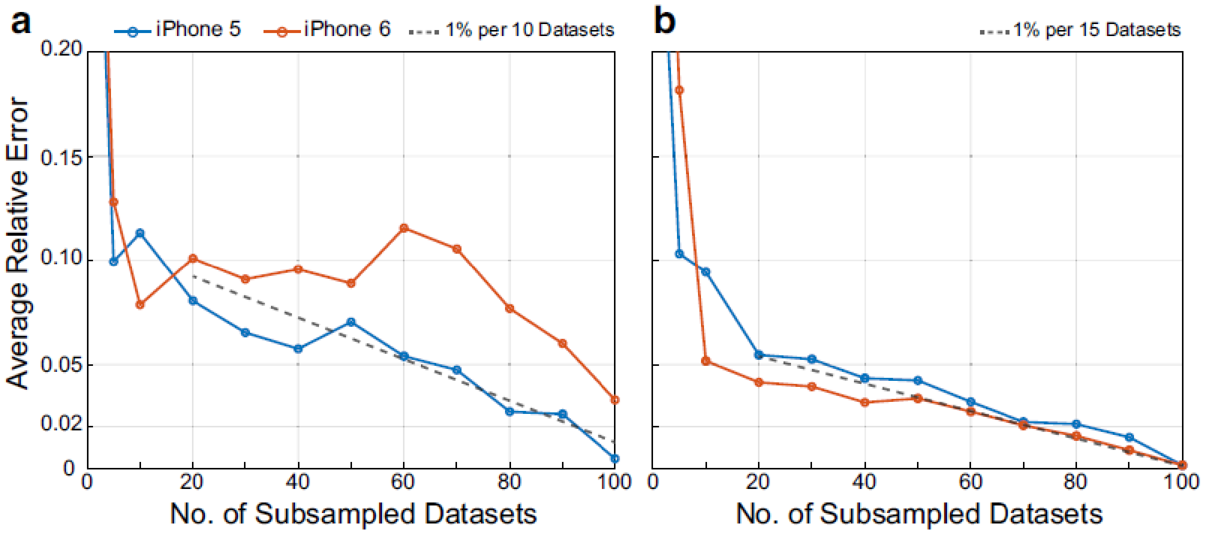
Presenters: Umberto Fugiglando & Lorenzo Benedetti (MIT)

“How can we use smartphones to measure our bridges’ health?” This is the question behind the Good Vibration project, aiming to implement a modal-based, indirect structural health monitoring of bridges through opportunistic data coming from smartphones placed into vehicles crossing the bridge. The project is being studied at the **MIT Senseable City Lab**, whose mission is to study interactions between the physical and the digital layer of cities, seeking opportunities that could bring benefits to communities.

The project presented at the MITICA workshop specifically focuses on bridge structural health monitoring, and on the possibility of applying the paradigm of crowdsensing to the monitoring of worldwide bridge infrastructures.

The research started with an experimental campaign on the Golden Gate Bridge in 2018, when researchers from the Senseable City Lab drove two cars across the bridge for 102 times, while two smartphones and one reference sensor placed on the dashboard registered bridge vibrations using their embedded accelerometers. The GPS position was recorded too, at a 1Hz sampling rate. The results were very promising: we managed to estimate the first three natural frequencies of the bridge with a maximum error lower than 3% (**Figure 1** Matarazzo et al., 2022). A similar campaign was then conducted on the Harvard bridge, next to MIT, comparing the results of the drive-by monitoring to a ground truth established thanks to an Ambient Vibration Test. Consequently, a partnership with Uber allowed us to explore the power of data crowdsourcing, with Uber drivers collecting data from daily trips on the two bridges. Uncontrolled data acquisition pointed out some issues, mainly related to GPS accuracy, sensor orientation, and data fidelity (**Figure 1**). On the left (**Figure 1a**) are reported Smartphone most probable modal frequencies (MPMF) errors for the first vertical frequency (m = 1). On the right (**Figure 1b**) Smartphone MPMF errors for the second vertical frequency (m = 2). Each line represents the mean error for a different smartphone.

Figure 1. Errors of the MPMFs as a function of the size of the data subset.



Source: Umberto Fugiglando & Lorenzo Benedetti

The research then focused on mode shapes estimation and semi-controlled data acquisition, realized within a three-years partnership with Anas S.p.A., the Italian national road maintenance and construction company. In particular, the methodology consists of transforming each time history into a space-frequency map. Such reshaping is realized applying the so-called *synchrosqueezed wavelet transform*, which guarantees better performances compared to other wavelets in terms of frequency smearing (Daubechies et al., 2011). Synchrosqueezing turns single bridge trips into maps containing bridge dynamics, vehicle dynamics, and noise. All the maps are then combined together to obtain a final average map. The averaging allows us to highlight the bridge structural behaviour, reducing the effects of noise and vehicle dynamics. All trips, indeed, share the same bridge dynamics content, while vehicle and noise are different for every single trip. Such a methodology explains the power of big data in this application: the more maps are averaged together, the less noisy the final map will be. After synchrosqueezing is applied, a Most Probable Modal Frequencies algorithm is exploited to estimate a bridge's natural frequencies, which appear on the space-frequency map under the form of statistical wavelet ridges. Mode shapes reconstruction is based on a similar concept: cutting the map in correspondence of the modal frequency, we look at the intensity of the statistical ridges, which represents the amplitude of the bridge motion at each spatial location. Since data acquisition is not synchronous, only absolute mode shapes can be estimated.

The app "Good Vibrations" has been developed within the partnership with Anas to perform semi-controlled data collection. The app, installed on smartphones of a pilot group of Anas road operators (the Italian Autonomous Roads Corporation), requires no interaction with the user and acquires data in an autonomous way. The minimization of battery consumption and data transmission has been achieved thanks to a geofencing algorithm, which densifies data collection when the smartphone is localized in the proximity of a bridge of interest. According to the data pipeline, Anas fleet collects data, transfer them to an Anas database, and then to MIT for processing.

The case studies currently involved in the campaign are all located in Italy, three near Rome, and one in the Dolomites, close to Cortina. The latter, called "Ponte Cadore", has been the object of further experiments. A 272 m single span bridge, built as a hyperstatic structure with two pins and two diagonal supports, in 2013 Anas performed a monitoring campaign that involved a dynamic testing. In 2021, we deployed another experimental campaign aimed at studying the impact of vehicle dynamics, sensor performances, and GPS accuracy on the effectiveness of drive-by monitoring. The campaign consisted of Ambient Vibration Testing (AVT), to verify the dynamic properties of the bridge, and a data collection performed via two e-scooters on which both a smartphone and a professional wireless accelerometer were installed. Such a rich dataset, combined with more than 1000 passages recorded through the app by Anas personnel in 2022, allowed us to test the performances of drive-by monitoring according to the choice of sensors diagnostic vehicles. The first analyses pointed out outstanding results from the e-scooters, able to identify more mode shapes than using cars. This outcome opens interesting horizons on the use of micro-mobility in urban environment for scanning the health of our bridge infrastructure.

5.4 Open discussion

Mr. Bono provided the highlight of the session, noting the remarkable work performed by the presenters and opened the floor for discussions, asking the presenters which is in their opinion the way forward for drive by iSHM. In particular, could the integration with inertial sensors or GPS provide advantages?

Mr. Bono stressed the different approaches and dimensions of the presented research. He also stressed the differences from working in simulation or in a controlled experimental setting, compared to crowd sourcing from vehicles with no control on their speed. **Crowd sourcing** and **artificial neural networks** (ANN) could help on the interpretation of data in terms of the bridge conditions. Focusing on AI, the problem is to identify the type of parameter to use for damage detection: frequency, wavelet transform or spectrum? This is the next question to answer: is it one parameter or one parameter per bridge type (different for short and long span bridges)? For example, the methods used in a long span bridge like the Golden Gate in San Francisco, will not fit a 20-meter-long bridge due to the huge difference in vibration characteristics.

Mr. Fugiglando mentioned that there are many challenges and many opportunities, and that they are also moving towards monitoring different typologies of bridges. As it has been mentioned, making it a **scalable process** should not be underestimated. He also stated that one of the biggest challenges they faced was to make sure that the developed app does not drain the battery. Only this aspect took months of development. And if you want to go towards production, or if you want to convince Uber to collect data, this is the kind of problem you need to solve.

Dr. Gkoktsi highlighted that now it is the perfect time for developing iSHM, since digital technologies are thriving. The **quality of data** is of paramount importance in developing concrete methodologies; emerging technologies can offer a promising tool towards increasing the quality of data. Also, such multi-disciplinary research works can be benefited from the collaboration of scientists with diverse backgrounds (e.g. civil, mechanical, electrical engineering), each focusing on their field of specialisation to identify the challenges on each sub-systems (e.g. structures/bridges, vehicles, wireless communications, etc.).

Mr. Bono identified two pathways: either have perfectly calibrated sensors in a fixed number of “patrolling” vehicles, which scan the network at night with little interference, or remove the variability through big data acquisition using many vehicles.

Mr. Benedetti along this line of thinking mentioned that there should be a trade-off **between quantity of data and quality of data**. And we should be careful since we are dealing with safety assessment. A discussion in the panel started with Dr. Malekjafarian stating that not all data are necessary and we should carefully decide beforehand what we need, and Mr. Fugiglando mentioned the option to do processing on the edge and transfer less data, but this implies access to privacy info and involvement of the user. Mr. Bono mentioned that the advantage of CCAM could be in the computational capability and the embedded sensors. He also emphasised the previously mentioned idea of having trust in data, for results to be reliable.

Dr. Gkoktsi replied to a question from the audience attending online: “based on current state of the art, in the context of civil engineering structures maintenance, what in your opinion are the three the most important data sets that should be collected and constantly monitored by the road operators?” The reply was along the line that it depends on the application under consideration. For the structural dynamic identification and damage detection, it is very typical to acquire acceleration signals, as considered in the MITICA experimental testing. , In the literature, there are also methodologies based on acquisition of displacement signals.

Dr. Limongelli on the same question added that the question is not “what data to gather” but “what decision to support”, e.g. to support decisions relevant to maintenance interventions for strength deterioration processes such as those due to corrosion, vibration-based monitoring would hardly provide useful information.

A discussion started with Mr. Bono supporting the use of automated monitoring methods that maybe cannot give a full picture of the structure health, but they give an indication. Which is better that having nothing. Along the same path, Mr. Fugiglando used an example from everyday life: people now use smart watches to monitor their temperature, heartbeat and blood pressure. If the find alarming values they go to the experts (doctors) for advice and further prescription of testing. Mr. Bono stated that there is a unique opportunity in using connected vehicles because they really monitor so many data nowadays (e.g. for maintenance purposes). Dr. Galassi confirmed this, stating that nowadays there are organisations collecting data to provide this kind of information to car manufacturers (for maintenance or safety purposes), but also to cities (e.g. to support decisions on the location of charging infrastructure). Dr. Malekjafarian supported also the possibility of drive by monitoring of railway bridges, since obtaining data is easier, and also considering that rail is an established transport mode in Europe. Mr. Benedetti highlighted the different challenges for rail bridge monitoring (the mass-to-bridge ratio is different, but at the same time, trains share similar characteristics among them), something that leads to adopting a tailored approach. Concluding, Mr. Tirelli, mentioned that the last presentation (from Mr. Fugiglando and Mr. Benedetti) and the research carried out in MITICA provide two extreme limits of drive-by monitoring. For long bridges, vibration frequencies are very low, and the time to record the signal is longer. An additional challenge for MITICA was that the power emitted by the wireless sensors in Europe is more restricted compared to the USA.

6 DAY 1 Session 3: Indirect Structural Health Monitoring (iSHM) using passing vehicles.

Part 2. Chair Kyriaki Gkoktsi (JRC)

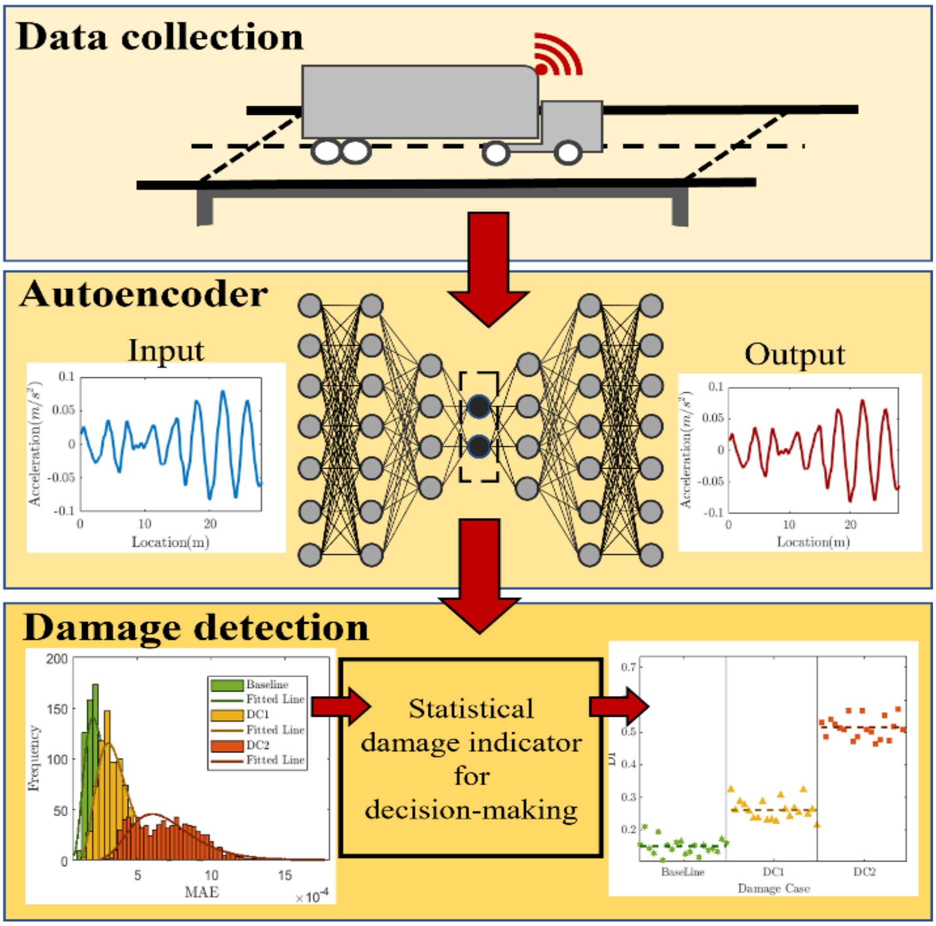
6.1 Deep autoencoder model for road bridge damage assessment using vehicle responses

Presenter: Daniel Cantero (NTNU)

Dr. Cantero presented the latest results produced in his group at the Norwegian University of Science and Technology (NTNU). Their work explores the possibilities of extending the use of intelligent transport communication (ITC) to support structural safety evaluation of bridges in a road network. Based on already existing Vehicle-to-Infrastructure (V2I) communication and on-board vehicle sensing technology, the goal is to develop structural damage detection procedures that use the recorded responses from passing vehicles. Past experiences have shown that it is possible to detect changes in structural behaviour indirectly by analysing the signals from built-in accelerometers on specialized vehicles traversing the bridge at low speeds. However, another possibility is to use vehicle responses from ordinary traffic under normal operational conditions. In that case, many more vehicle passages are required to obtain robust results. Machine learning (ML) techniques can be used to process these signals and identify important deviations in vehicle responses that might indicate serious damage processes of the infrastructure. Such a procedure could be implemented across the whole road network to support existing bridge maintenance strategies implemented by the road authorities.

In a recently published article (Sarwar and Cantero, 2021), these ideas have been evaluated under numerically simulated conditions. The idea is graphically summarized in **Figure 2**.

Figure 2. Graphical summary of the damage detection idea.



Source: Sarwar and Cantero, 2021

A deep-autoencoder ML model was suggested to process the signals from passing vehicles and derive a damage indicator, which permitted the detection of bridge damages. The database consisted of simulated vertical accelerations of 5-axle trucks traversing bridges with various simulated damages. In an effort to replicate real measurements, the simulations considered vehicle-bridge interaction, road profile irregularities, variability of vehicle mechanical properties, varying speed, the presence of multiple vehicles, signal noise and ambient temperature oscillations. The ML algorithm was trained to encode and then reconstruct the vehicle signals, while minimizing the residual (difference between reconstructed and original signal). A damage indicator was derived based on batches of vehicle crossing events and their associated distribution of reconstruction errors. Deviations of these distributions clearly indicated the presence of bridge damage, even for relatively small damage magnitudes.

The use of vehicle responses for structural condition evaluation supported by ML have shown promising results, indicating the big potential of utilizing drive-by information to support structural maintenance operations. However, many challenges remain that need to be addressed before these ideas can benefit infrastructure owners. Arguably, the most pressing need is to jump from theoretical, numerical, and small-scale laboratory testing to full scale normal traffic conditions studying existing bridges of the road network. Furthermore, future works should explore the integration of vehicle information into existing tools towards the development of digital twins.

6.2 Fleet Monitoring of Infrastructure - a Paradigm Change in Approach

Presenter: Eugene J. OBrien (University College Dublin)

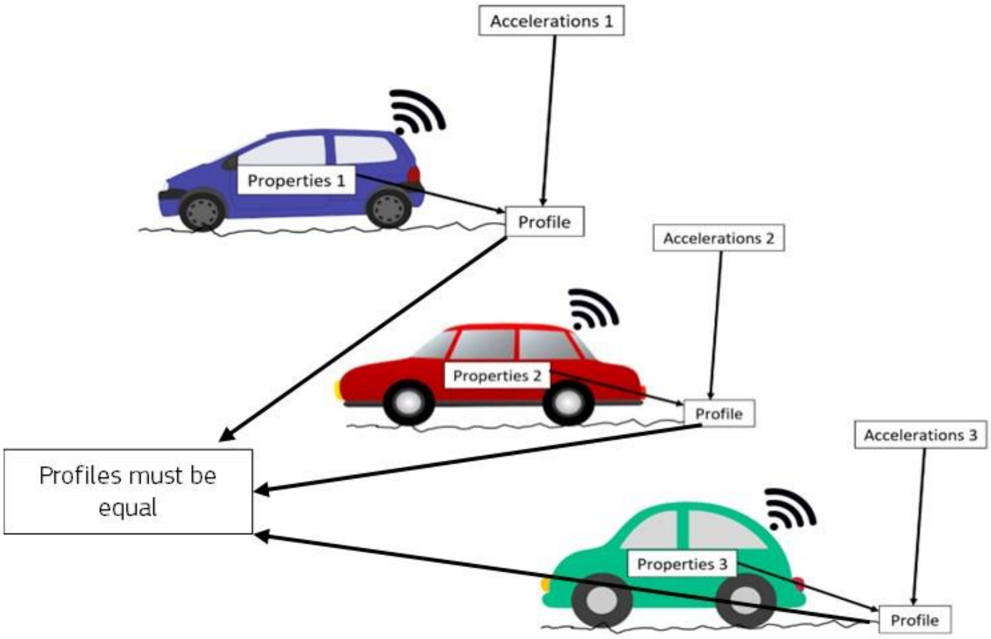
Prof. OBrien proposed that there is a compelling argument for a change towards indirect monitoring. This will be a paradigm shift, from the current situation where most monitoring is by human inspection, to the time when most monitoring will be indirect, with all the instrumentation in passing vehicles. He made three main points: (i) iSHM with a single vehicle is difficult; (ii) direct monitoring with a fleet of vehicles is feasible and (iii) iSHM, with a fleet of vehicles, is the future.

(i) iSHM is difficult: Prof. OBrien reported on a study of a railway bridge, simulated with a 3D Finite Element (brick) model (Quirke et al 2017). Local bridge strike damage was simulated by removal of one element on a beam flange, near the centre of the bridge. Assuming that the passing vehicle measurements could be processed to find deflections under the axles, he calculated these (moving reference) deflection signals due to a passing 4-axle railway carriage. The simulated measurements were repeated before-and-after damage. The maximum damage-induced change in deflection for this example was around 0.04 mm. Even a Traffic Speed deflectometer, the state-of-the-art in highway-speed deflection measurement, is only as accurate as its Laser Doppler Vibrometers, which have a resolution of about 0.02 mm. Thus, without a significant increase in accuracy, iSHM with a single vehicle pass, is unlikely to be sufficiently accurate for bridge health monitoring.

(ii) Direct monitoring with a fleet of vehicles is feasible: Prof. OBrien went on to describe another numerical study where damage in an instrumented bridge was monitored using direct rotation measurements from (simulated) sensors on the bridge (OBrien et al 2020). The damage indicator consisted of the monthly average vehicle tandem weights of passing trucks. This generally worked quite well, with low levels of damage being detected most of the time. However, it requires the instrumentation of the bridge which is generally considered infeasible for all bridges of a network.

(iii) iSHM with a fleet of vehicles is the future: For indirect monitoring, Prof. OBrien proposed the mining of data from a fleet of instrumented passing vehicles – **Figure 3**. He described a 3-step process, as follows: (a) Processing of accelerations measured on the vehicles using an inverse Newmark-beta method to determine moving reference deflections under vehicle axles (Keenahan et al 2020); (b) Using off-bridge deflection data to calibrate the vehicles of the fleet, exploiting the fact that they all pass over the same road profile (**Figure 3**); (c) Using on-bridge data to determine a moving-reference influence line, i.e., deflection at a (moving) point on the bridge due to a unit (moving) load. He showed, through simulations, that the moving reference influence line was damage-sensitive and was an effective way of aggregating data from a wide variety of uncontrolled passing vehicles from the general traffic. He concluded that a fleet-based approach has great potential to be an effective means of iSHM in the future. The next step is to prove the concept by instrumenting vehicles in full scale field trials.

Figure 3. Indirect monitoring using a fleet of vehicles to determine road surface profile.



Source: Eugene J. OBrien

6.3 Indirect Monitoring for Railway Infrastructure Assessment

Presenter: Charikleia Stoura[12]

Dr. Stoura presented an overview of the activities at the Chair of Structural Mechanics & Monitoring (SMM) at ETH Zürich on the theme of Indirect monitoring for road- and railway infrastructure assessment.

First, she presented the driving theme behind the motivation for adopting an on-board monitoring or indirect sensing paradigm, which draws from the increasing need to understand when, where and which type of intervention is needed for optimally managing railway infrastructure. While advanced non-destructive evaluation (NDE) techniques are already used in (outfitted and costly) diagnostic vehicles, such as ultrasonic, camera-based, and acoustic methods, these specify a higher-end monitoring solution, which typically can only be used at a finite frequency (e.g. twice annually). This motivates a shift towards low-cost vibration-based on-board monitoring applied on in-service trains, which provides a means for collecting data at higher frequencies and across longer infrastructure stretches (Hoelzl et al., 2022). This temporally and spatially more dense data collection scheme, combined with fusion techniques (data from different sensors, coupling with engineering models) can be used to support our decision assessment tools.

At the SMM Chair, particular weight is placed on data-driven and hybrid schemes; a hybrid approach is one that couples data with models that rely on first principles (physics/mechanics). Such a fused approach needs to capitalize on ML techniques for i) identifying & classifying events based on big data, as well as ii) complementing partial and incomplete knowledge of engineering models. A proof of concept is currently run on the potential of detecting flaws in welds based on axle box acceleration (ABA) data from on board monitoring (OBM) (project OMISM[13]). ABA measurements offer information on the growth of this damage over time, which is corroborated with optical information form the high-end diagnostic vehicle and also passed on for final assessment to the experts/engineers. This forms a collaboration with the Swiss Federal Railways authority (SBB).

Conclusion: on-board monitoring of railway infrastructure forms an important tool for minimizing costs and downtime linked to conventional monitoring. In-service monitoring trains further supply access to broader monitoring information, thus more efficiently supporting preventive maintenance schemes and measures in case of disruption. The SMM group activities further include projects with the use of Ground Penetrating Radar

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[12] Presentation prepared with Prof. Eleni Chatzi (ETH Zürich)

[13] https://www.ivt.ethz.ch/en/ts/projects/omism.html

systems for the assessment of ballast moisture (project REASSESS[14]), as well as sensing for condition assessment of the railway wheel shaft and catenary/pantograph system (project SENTINEL[15]).

6.4 Open Discussion

Dr. Gkoktsi opened the floor for questions.

Dr. Cutini posed a question on the **choice of the vehicle**, and if that choice can help the monitoring process. In particular, what would be desirable concerning tyres and suspensions. And conditions: tyres, suspension? Would it make sense to set up a special vehicle for this monitoring?

Prof. OBrien observed that this runs against the principle of indirect monitoring, and that the effort should be towards using every vehicle that is out there. If there was a choice, a **heavier vehicle** with a heavy group of axles would be more suitable, since it produces a bigger deflection that is easier to measure. In their experiment, they did not find the suspension system so relevant as the response of the bridge was largely pseudo-static. In their experiment, they filtered out two-axle vehicles because they are simpler, but it is also feasible to filter out 5-axle vehicles since they are common and repeatable.

Dr. Malekjafarian addressing Dr. Cantero asked on the machine learning (ML) algorithm they developed, observing that one of the challenges for **combining drive-by and ML** is how the acceleration data are input. So, the first question was if they used the whole acceleration input as a vector in the algorithm. The second question was on damage quantification and diagnosis, for which we need to perform unsupervised learning as he mentioned, then we have to build up a FEM model from drive-by, and then we have enough information for classification. How did you find that challenge?

Dr. Cantero answered that the signals were normalised, the length of the signals was made constant (and we are talking about 1500 samples), and also the trick was to normalise in terms of space. So, knowing the passing speed of the vehicle the important point is not to use different signals with different lengths in ML. Regarding the ML algorithm, with an unsupervised method you cannot really quantify the damage. The unsupervised method actually shows different damage indexes for different damage levels. But to quantify the damage you need supervised ML, a model of the bridge, and train the ML algorithm for different damage scenarios.

Dr. Gkoktsi asked if temperature variation was considered in the ML approach. Dr. Cantero acknowledged the importance of this parameter, and mentioned that it is an ongoing work. Implementing this should not be complicated, considering that temperature is given as input. Dr. Gkoktsi mentioned that this parameter was quite significant for the MITICA bridge-like test specimen, adding further that in some cases the **temperature variations** can mask the information about structural damage.

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[14] https://csfm.ethz.ch/en/research/projects/reassess.html

[15] https://csfm.ethz.ch/en/research/projects/sentinel.html

7 DAY 1 Session 4: Digital technologies and iSHM enablers

Chair: Sotirios Argyroudis (Brunel University London)

7.1 Digital Transformation of construction and infrastructure sectors

Presenter: Flavio Bono (JRC)

In the EU, the architecture, engineering, construction, and operation (AECO) sector is a significant industry. It contributes up to 9% of the EU's Gross domestic product (GDP) and 18 million direct jobs, i.e. more than 6% of all employment in Europe. However, this crucial sector for the global economy is lagging in the adoption of Information and Communication Technology (ICT) and digital transformation when compared to other industries like the telecoms or the manufacturing sector.

New IT technologies can help the AECO sector to catch up with the other sectors and the adoption of digital technologies can significantly improve effectiveness and efficiency. In particular, considering constructions operation and maintenance procedures, the implementation of automatic processes through sensors and monitoring systems, along with the development of algorithms for predictive maintenance and the identification of critical events, can greatly improve the performance in the sector contributing to the implementation of better maintenance and intervention strategies.

If, on the one hand, the digitisation of the construction industry can lead to significant improvements (including reduced waste and resources consumption, better design and project management), on the other hand embedding digital systems in structures and buildings raises challenges. In particular, the different lifespan of civil structures and IT technology needs to be addressed: buildings and infrastructures are designed to last decades, whereas digital technologies, like the mobile phones we use every day, last just a few years with fast obsolescence that conflicts with installations in the built environment.

If we consider that that the EU and the US transportation networks comprise ageing bridges that were built decades ago, it appears clear how the need to carefully assess the structural capacity has become a top priority in many administrative agendas.

For new constructions and buildings, the adoption of the latest technologies is now usually considered from the very beginning of the design phase. As an example, for the new bridge that has been built to replace the Polcevera viaduct in Genova, Italy, collapsed in 2018, many recent technologies have been used (e.g. digital twins, BIM 4D, weigh in motion (WIM) in tandem with surveillance cameras, autonomous inspection systems based on cognitive mechatronics). Data collected from automatic sensors and scanning systems can feed intelligent methods for the analysis of anomalies and damage detection and, consequently, trigger targeted inspections. This approach, compared to the previous difficult monitoring of the collapsed structure built in the 60s, is undoubtedly more efficient in ensuring continuous monitoring across the service lifespan of such bridge.

However, what about old bridges? How can new digital technologies be applied to existing structures?

With a number of ageing bridges in road transportation networks with possible structural deficiencies induced by fatigue, increased traffic loads and environmental weather conditions, there is the need for low-cost solutions that can be widely implemented. Such solutions could therefore contribute to the definition of maintenance programs and generate warnings in case of critical events.

However, the installation of new devices on existing structures requires complicated approaches, possibly with power autonomous devices wirelessly communicating to avoid cabling. In this case, iSHM methods can be a useful solution that, if proved fully effective in assessing structures, could offer an easily implementable approach to monitor large ageing transportation networks.

New technologies for the monitoring and assessment of structures usually comprise three layers: i) Hardware (sensors, IoT, automation system); ii) Communication systems and devices; iii) Software layer, where data are processed possibly with the adoption of recent the AI and machine learning algorithms. Moreover, the development of digital twins can replicate the response of structures based on real-time signals from sensors, possibly leading to more insights.

Enablers of iSHM are: vehicle communication, on-board sensing and computing, the management of big data, the integration with existing infrastructures monitoring (providing additional reference signals for better indirect assessment), and the implementation of advanced algorithms and machine learning data processing,

The calibration of sensors is crucial but also prior knowledge of the analysed structures is needed to both design the acquisition systems and identify the suitable monitoring vehicles.

Moreover, standardization of both hardware, communication protocols and data, just like in the other environments adopting new digital technologies (e.g. smart cities), can ensure the iSHM future development with effective integration and interoperability of components and processes from different developers.

Finally, the role of the public sector is strategic: infrastructural monitoring has to be put forward by authorities, also for minor infrastructures.

Data ownership should be well considered to ensure access to data by multiple stakeholders and define rules for dissemination of relevant information. As an example, warnings could be forwarded to Smart City system to allow the management of critical events and possibly allow multiple authorities to act promptly (e.g. to divert traffic and alert emergency departments).

Considering transportation infrastructures, these are part of complex networks, with interconnected components and strong dependencies; single structural components like bridges, tunnels and overpasses can be considered as part of a system of systems where failures can lead to critical cascading effects.

In the future, local monitoring systems will possibly be integrated into smart cities digital platforms. This would allow the interaction with smart infrastructures that collect and process physical measurements and data, and then transfer relevant information to centralized systems, contributing to the functioning of urban system as a whole.

7.2 Digital Twinning with innovative Monitoring Structural (MonStr) devices

Presenter: Guido Camata (Università degli Studi G. d'Annunzio Chieti e Pescara)

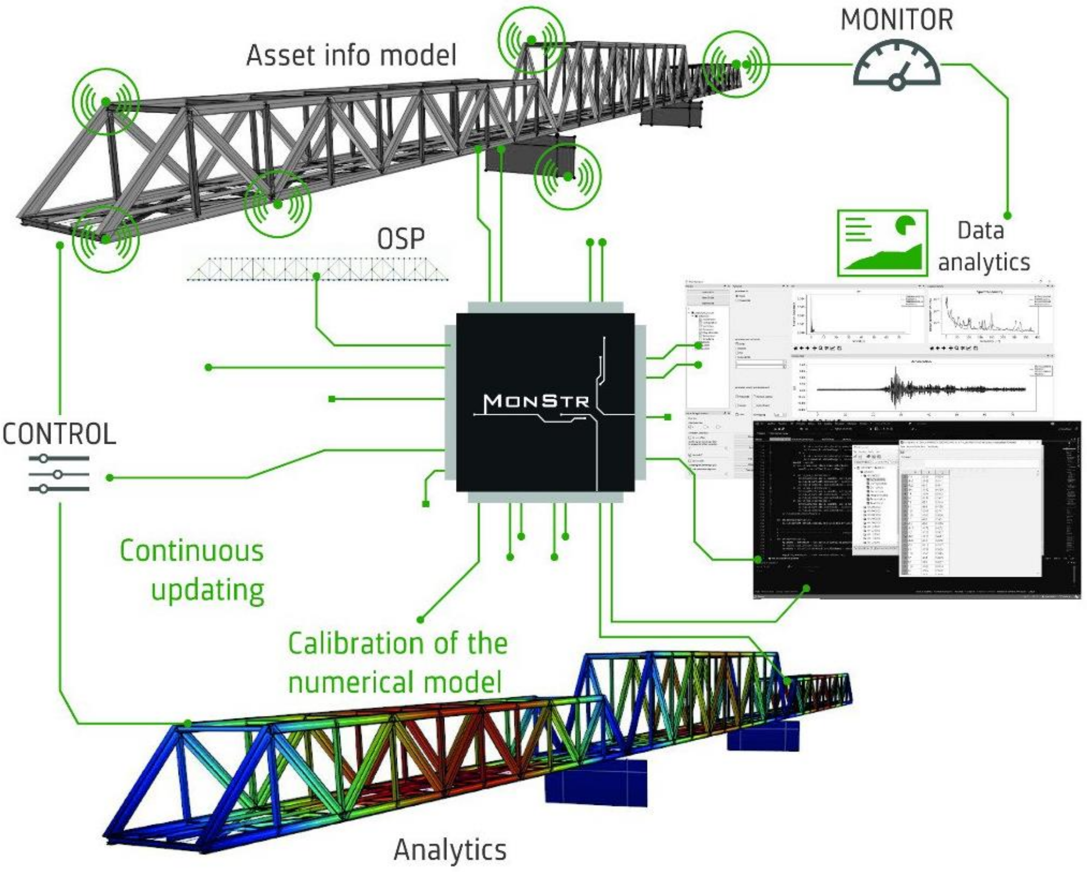
In his presentation, Dr. Camata focused on Asdea Hardware's proposal to establish a standard strategy for structural health monitoring (SHM), using the innovative MonStr device as the essential tool for accomplishing all operations involved. Typically, such tasks vary from anomaly detection in rough data collected in near-real time and model updating, i.e., the adoption of data flow to match the corresponding FEM model of the structure under examination. At present, there is still no truly comprehensive and broadly accepted method for assessing the true conditions of civil systems through dedicated algorithms for data analysis. This is due to the fact that the entire engineering community is still working to determine the best and most reliable approaches made possible only recently due to improvements in calculation technology.

Dr. Camata underlined how, no matter the workflow for the SHM process, it's essential that the algorithms be fed high-quality data to produce reliable predictions. Since data acquisition is itself a cornerstone for any detection machinery, the company placed special emphasis on the design of the hardware components responsible for signal capturing. In particular, Dr. Camata's presentation highlighted how MonStr devices match all the desired features for civil engineering purposes, including introducing major technical improvements compared to current devices commonly adopted for the task. Besides being equipped with triaxial accelerometers, gyroscopes, and inclinometers with high-frequency sampling (up to 4 kHz for the accelerometer), a magnetometer and a thermometer are also included for self-orientation and data compensation at the hardware level. Above all, each box is capable of performing custom univariate analyses on the acquired signals, meaning parallelization is used to speed up a large portion of the pre-processing computations. Consequently, instead of a large amount of unprocessed data, a compressed amount of pre-processed information is transmitted to the central node for further processing. Nevertheless, it was acknowledged that powerful devices alone do not guarantee good performance since a suitable number of optimally placed boxes composing the network must be installed to ensure complete monitoring. The modularity and scalability of the web are crucial, as the MonStr-based solution has no limits on the number of nodes, which are all synchronized automatically.

The novelties introduced on the hardware side are supported by advanced software dedicated to data analysis. A great effort was then put into the ideation of a well-established sequence of operations defining the hybrid approach to SHM known as "Digital Twinning." While the scientific community unanimously recommends the use of machine learning tools for data processing, with a predilection for deep learning models in the case of supervised training, there is no agreement yet on which physical observables are worth monitoring and, generally, on the definition of the workflow as a whole, including data selection and pre-processing. Moreover, in the practical realization of algorithms for digital twinning, data format incompatibilities arise due to the fact that a variety of different software programs designed by different manufacturers for different purposes are used, resulting in possible information loss during conversion. Even in the best-case scenario where no data is lost, this variety increases algorithm complexity and slows down the process.

The proposed solution overcomes such issues because all the products needed are designed by the same company so that every piece perfectly fits in the puzzle that depicts the process. A unique data format, the HDF5 format, is adopted for all I/O steps, and the software required for data analysis, spanning from pre-processing to damage detection, is embedded in the STKO program via its Python[16] interface. This way, the data flow is directly exploited to update the numerical model acting as the digital twin of the real structure, which can be used when needed to check possible alarms emitted by the data-driven algorithm by running FEM simulations, and to produce "what-if" analyses (**Figure 4**).

Figure 4. Proposed approach for the Digital Twinning.



Source: Guido Camata

7.3 Open Discussion

Dr. Argyroudis stated that it is clear that the future in the construction and infrastructure sector is digital. However, there are many challenges as this session showed (see also Argyroudis et al., 2022). Before opening the discussion, he brought in an argument for discussion, pointing out that nowadays we talk about the digital transformation and digital twins of individual infrastructure. However, in the future we could have digital twins (DT) of the entire critical infrastructure or even the entire city, what could be the consequences regarding **resources for data** elaboration, maintenance or storage, and in the end, how sustainable is this?

Mr. Bono observes that **Digital Twins for cities** are nowadays in very active development, aiming to capture urban dynamics (traffic, pollution etc), with the city of Helsinki being a good example, especially on urban planning. In the future we could see the convergence of the two different worlds: DT for specific buildings and DT for simulating wider areas. While today they run in parallel, in the future we could see them interact, with one feeding the other, accounting for the boundary conditions of a single building or infrastructure. Likewise,

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[16] https://www.python.org

Building Information Modelling (BIM) systems are nowadays evolving to have real time information about for example the material.

Dr. Camata mentions that obviously the idea is to connect everything in the network. Connecting everything (in an approach mentioned earlier in the presentation by Prof. Sextos) is doable, and not in the very far future. He also called to reflect on the concept of **cost-effective solution for new bridges for**, and that they are a fraction of the total building and maintenance costs.

Dr. Argyroudis reflected on the cost in terms of CO_2 emissions for maintaining a DT for many years at the level of system of systems. This cost maybe needs to be measured with the advantages the digital transformation is bringing.

Prof. Sextos reflected on the need of both local and global assessment, sustaining that both are necessary. An **expert system** is needed to elaborate on the findings from both local and global assessments to provide input on the state of the infrastructure and the maintenance needs.

Dr. Limongelli commented that: (i) regarding local and global, these could be relevant at **different scales**, local at the bridge scale, global at network scale; (ii) regarding the **amount of data** collected nowadays, it is huge, and we should reflect on what data are actually needed before collecting them; (iii) the use of DT is often downscaled to the updating of a FEM model: we need to consider DTs as a tool for optimising future management rather than a tool used to perform damage detection.

Dr. Camata, on the last point raised by Dr. Limongelli, confirmed that DT should be used first to assess the safety of the structure, but also to predict its evolution. Digital Twinning nowadays is more complex than model updating, possible only due to the extensive use of **non-linear data and AI**. What we do now is putting huge efforts on the calibration of the non-linear parameters. Finally, we need to combine local and global methods: results in terms of frequencies at global level can be misleading without local information.

8 Visit to the MITICA facility and the ELSA

Text curated by Dr. Kyriaki Gkoktsi, JRC

A visit to the MITICA testing facility took place on the 6th of June, 2022 (MITICA Workshop - Day 1). The members of the project's research team welcomed the workshop participants at the MITICA testing site, which is located at an external area of approximately 930.0 m^2, found in front of ELSA lab/building 48 at the JRC site in Ispra (**Figure 5** and **Figure 6**).

Dr. Gkoktsi, Dr. Bono, and Mr. Tirelli described the scientific concept linked with the development and design of the MITICA testing site, which comprises a bridge-like structural specimen, a two-lane road circuit and a control room. It was explained that a reinforced concrete slender bridge-like structure (9.0 m length by 3.0 m width) was selected as the testing specimen. The latter was prefabricated, transferred to the dedicated testing area, and placed over a box-like underground foundation that was specifically constructed for the needs of the MITICA project. In this respect, the top surface of the bridge was aligned with the ground level, enabling the straight travelling route of the vehicle at a speed up to 40 km/h.

It was further explained the importance of the bridge foundation system, which reflects a versatile support configuration for the bridge that allows the simulation of structural damage in the MITICA iSHM experimental campaign. Specifically, moveable supports are enabled at the two edges of the structural specimen and/or the potential activation of an additional support at the middle of the bridge, which are materialised through the shifting and/or adding of load cells – the intermediate components between the foundation and the soffit of the bridge.

The next topic was on the description of the employed wireless sensor network (WSN), which comprises an array of input sensors, wireless nodes, base-stations, and PCs. The WSN was installed onto both the bridge and the vehicle to measure motion and vibration data among others. The vehicle and the control room were next presented, opening the floor to the last part of this visit – the demonstration of an iSHM experimental test. Thus, the workshop participants had the chance to interact with the test specimens and discuss on the dynamic phenomena observed through the visualisation of the recorded data in real-time.

Figure 5. Workshop delegates over the bridge-like structure.

Source: Konstantinos Gkoumas

Figure 6. Workshop delegates at the MITICA testing site.

Source: Konstantinos Gkoumas

After the visit to the MITICA testing site, the workshop delegates visited the ELSA lab and the reaction wall facility (**Figure 7**). A presentation of the activity of the laboratory was provided by Dr. Armelle Anthoine, member of the MITICA team (**Figure 8**).

Figure 7. Workshop delegates at the ELSA.

Source: Konstantinos Gkoumas

Figure 8. Presentation of the ELSA activity.

Source: Konstantinos Gkoumas

9 DAY 2 Session 1: Policy perspective and integration with European research

Chair: Konstantinos Gkoumas (JRC)

9.1 Construction ecosystem & transport infrastructure

Presenter: Roman Horvath (DG GROW)

Mr. Horvath presented the activities of the Construction Unit of DG GROW. He stressed the importance of the construction ecosystem, one of the pillars of the EU economy, its contribution to the growth and jobs creation, but also its role of an enabler for various EU policies. Regarding competences in the construction, these are primarily at MS, the EU competences are limited. An initial Commission Construction Strategy, adopted in 2012, focused on five priority areas: topics: investments & innovations, skills, resource efficiency, Internal Market and globalisation.

There is no a specific focus on transport infrastructure, the area is from the investment perspective. In 2018-19 the Construction Unit prepared a discussion paper about this topic: State of infrastructure maintenance. Its annex provided an overview of H2020 & FP7 funded research on infrastructure maintenance.

Mr. Horvath explained that a lack of data on the construction ecosystem led in 2015 to the establishment of the European Construction Sector Observatory to gather data comparable across the EU, to analyse and interpret them, and to disseminate these data and their analyses. The Observatory publishes a short reports on national policies or interesting projects, which may serve as good practice examples.

There are also big analytical reports on a particular topic or a trend like skills, digitalisation, late payment, resource efficiency.

In 2021 the Commission published a Communication on New Industrial Strategy[17] (which updated the previous Strategy published in 2020) introducing the ecosystem approach encompassing not only construction activities but also other supporting activities to construction.

In 2021 the Construction Unit prepared scenarios for a construction transition pathway, to make the ecosystem more digital, resilient and greener. In 2022, these scenarios will be further consulted with stakeholders and finalised to a concrete roadmap.

Currently a new funding period of the Cohesion Funds 2021-27 is being finalised; also, additional resources from the Recovery and Resilience Facility are available until the end of 2026. The funding can be used also for the transport infrastructure. The construction ecosystem will serve as a principal enabler of these funds, as many activities will focus on construction of new or renovation of existing buildings and infrastructure. Contributions from H2020 projects to SHM of transport infrastructures.

9.2 Contributions from H2020 projects to SHM of transport infrastructures

Presenter: Sergio Escriba (CINEA)

Mr. Escriba presented the results of four research projects that, funded by the EU Horizon 2020 programme and managed by the European Climate, Environment and Infrastructure Executive Agency (CINEA), have a focus on increasing resilience of transport infrastructures.

CINEA is the successor organisation of INEA, and started its activities in April 2021. CINEA has become a key player in the implementation of the EU Green Deal[18].

The Agency is in charge of the implementation of 7 EU programmes that represent a budget of more than 55 billion euros for the period 2021-2027. Among these programmes, CINEA is responsible for the implementation of Horizon Europe Cluster 5 – Climate, Energy and Mobility, as well as the legacy H2020 projects in the field of Energy, Transport and Climate. Transport research in CINEA represents a portfolio of more than 400 projects and nearly three billion euros budget. In the field of transport infrastructures, CINEA managed and partly still manages in total 26 projects funded by Horizon 2020 with 100 million euros of EU funding.

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[17] https://single-market-economy.ec.europa.eu/industry/strategy_en

[18] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

Within the Horizon 2020 programme, the research topics have covered the whole life-cycle of maintenance in transport infrastructures, from monitoring and evaluation of the status of the infrastructure to planning and execution of maintenance tasks. The projects presented today, PANOPTIS, FORESEE, RESIST and SAFEWAY, were funded under topic H2020-MG-7.1-2017 which aimed at increasing the resilience of transport infrastructure to extreme weather and human-made events through innovative monitoring, data analytics and mitigation measures.

In line with the EU policies, we have observed a paradigm shift in the purpose of monitoring in EU funded projects: From ad-hoc monitoring of a few infrastructure assets, either critical, damaged or located in risky environments, to wide monitoring of the transport corridor, even the transport network, on a regular basis or after extreme events. The infrastructures can become more resilient thanks to the prediction of disruptive events and anticipation of their effects.

In practice, there are four main steps in any resilience strategy for transport infrastructures.

1. Prediction of disruptive events: Mainly natural hazards (floods, fog, earthquakes, landslides, etc.), but also man-made events (accidents, terrorism attacks, etc.).
2. Mitigation of effects of the disruptive events by design, through more robust materials and network layout.
3. Quick assessment of the network condition after the event.
4. Execution of maintenance works to restore the system's functionality.

The recently finished Horizon 2020 projects PANOPTIS, FORESEE, RESIST and SAFEWAY have made a significant contribution to the rapid and accurate assessment of the network condition after the event (step 3 in the previous list). They have developed innovative remote monitoring systems based on drones, laser, radar and satellite data, able to cover extensive areas very quickly and without the need to have physical access to the damaged zone. Given the enormous amount of data gathered by these systems, the projects have increased the computing capabilities in the measuring devices (processing on-the-fly) and developed automated real-time analysis tools to evaluate the status of the infrastructure assets.

While AI techniques can help with the analysis of monitoring data, they must be trained with existing data which used to be scarce when it comes to extreme events. To overcome this issue, the projects have also developed advanced models and simulations that can generate the initial set of data required by the AI algorithms.

Next, the highlights on infrastructure monitoring from the above mentioned H2020 projects on infrastructure resilience are presented:

PANOPTIS[19]: The project used hybrid UAVs that mix the benefits of Vertical Take-Off and Landing (VTOL) and fixed wings UAVs for road corridor surveying. It has a great potential for early survey after disaster event or accidents, as well as for regular inspection of slopes. PANOPTIS has also increased the on-board computing capabilities of drones, allowing to pre-identify defects (e.g. corrosion) in the surface of civil structures.

FORESEE[20]: With regards to remote monitoring, this project has developed a methodology to predict landslides along infrastructure corridors using EU satellite data (mainly Sentinel 1) and environmental variables collected in-situ. It is based on pore pressure modelling of the slopes and machine learning methods to predict ground motion.

RESIST[21]: This project was also working with drones but in a different way. It has developed genuine aerial robots for contact inspection of bridges and tunnels that are able to carry out ultrasonic testing, crack measurements and placing of vibration sensors on the structure. RESIST has also developed AI algorithms for visual inspection and crack detection in concrete surfaces, as well as corrosion detection on steel elements.

SAFEWAY[22]: The project has progressed the state of the art in mobile mapping of transport infrastructures. It has developed a methodology to extract asset data from a point cloud and to automatically feed the infrastructure model in standard Industry Foundation Class (IFC). Additionally, the project has created an

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[19] PANOPTIS Project, GA 769129, http://www.panoptis.eu/
[20] FORESEE Project, GA 769373, https://foreseeproject.eu/
[21] RESIST Project, GA 769066, https://www.resistproject.eu/
[22] SAFEWAY Project, GA 769255, https://www.safeway-project.eu/

innovative crowdsourcing concept able to identify potential infrastructure problems from aggregated human-generated data in social media.

9.3 Open Discussion

Dr. Gkoumas observed that EU research is fundamental for future proof transport infrastructure, and that decrease in maintenance funding has been observed in EU MS starting in 2006. Also, there is an open discussion if the Commission could do more to incentivise maintenance of transport infrastructures by MS.

Dr. Galassi asked Mr. Escriba on the limitations imposed by **regulations of using drones** for infrastructure monitoring. Mr. Escriba replied that indeed the projects followed different approaches depending on the country or region of operation, as well as on the specific context. For example, permission for flying a drone below the highway line (e.g. to inspect a bridge) would be rather easy to obtain, while in some cases flying a drone above the highway was impossible and it could only be done in a parallel line. On the same topic, while it is possible to inspect tunnels with drones (something done within the RESIST project), this cannot be done in presence of traffic.

Dr. Malekjafarian asked Mr. Escriba if there was any activity in the presented projects that could combine the use of drones with sensors for vibration measurement, to cover more infrastructure integrating vibration-based approaches. Mr. Escriba replied that the RESIST project was investigating **placing vibration sensors using drones**. Further use of drones to directly measure vibrations requires extra stability and is still a subject of research. Dr. Gkoumas added that there are indirect approaches aiming to capture vibration characteristics using e.g. high-speed cameras, but additional research is needed. This could be an area for EU R&I in the future.

A final question from Dr. Galassi to Mr. Horvath was on the possible policy gaps in the area of transport infrastructure monitoring that could be filled by the Commission in the future. Mr. Horvath acknowledged that this is a difficult question, since many of the **competences are in the hands of the MS**. Currently there is financial support also through the Connecting Europe Facility (CEF) programme and the Cohesion Funds, but there is not an exact obligation for the MS since they are using different approaches to address their specific circumstances. On the other hand, there are guidelines on climate proofing of infrastructure that needs to be taken into account for cohesion policy projects funded by the Commission in the period 2021-2027.

10 DAY 2 Session 2: Integration of SHM in standards and operational aspects

Chair: Francesco Petrini (Sapienza University of Rome)

10.1 Integration of SHM in standards: existing documents and research needs

Presenter: Maria Pina Limongelli (Politecnico di Milano)

Despite many successful applications and advancement of the research in this field, SHM is not extensively used for the performance assessment of civil structures. One of main issues behind this situation is the insufficient knowledge of these technologies on behalf of the users such asset owners and operators, practitioners, and designers, since SHM methods are rather new and their design requires expertise that is usually not available at a large scale. SHM is not usually included in the undergraduate university curricula and limited number courses are available at graduate level. This makes their design a task for experts, limiting their diffusion. This issue is particularly important for SHM of civil structures that are largely unique structures for which the 'one size fits all' concept does not apply. The design of an SHM system must thus be specific to each structure requiring a bespoke expertise. The standardization of the SHM process can facilitate the adoption of such systems, providing that the development of homogenous criteria in the design, deployment of state-of-art SHM systems is facilitated.

In the last 20 years several SHM guidelines have been issued in several countries worldwide. The complete list of documents can be found in Limongelli, 2022. Herein a short discussion of their content is reported. The first was published in 2001 in Canada. This document, is mainly focused on the use of SHM to support the diagnostic process but it does not address explicitly the use of monitoring information to support decisions. Five years later the EU project SAMCO (Structural Assessment Monitoring and Control) delivered the first European SHM guideline which is a more comprehensive document that thanks to the technological development that occurred meanwhile, also addresses continuous monitoring systems. However, the focus is still on the use of information to diagnose the structural state. As a novelty in SAMCO the qualification of test personnel, strictly related to the quality of data used for the diagnosis, is mentioned. In 2008 the standard RVS 13.03.01 was issued. The standard introduces for the first time the concept of performance modelling for lifetime management, even if no information is provided on how to perform the task. The first compulsory technical document outside Europe was published in China in 2014. The document addresses the basic technical requirements of an SHM system whose main purpose is still considered the acquisition of data to check structural condition and its compliance with design specifications. In 2016 the Long Term Bridge Performance (LTBP) program protocols were published. The interest of this document consists in the fact that this is the first document where the issue of management of data from bridge lifecycle management is addressed. This is carried out through the definition of protocols that guide the acquisition and storage of data. All the previous documents put emphasis on the acquisition and processing of data for diagnostic purposes. The first is a Circular published by the Transportation Research Board (TRB) that introduces prominently the concept of the benefit structural monitoring can provide as a decision support tool. The second is a set of three guidelines developed as deliverables of the European Cooperation in Science and Technology (COST) Action TU1402[23] that describe a framework to quantify the Value of Information (VoI) from SHM. Both the TRB and the COST documents are somehow complimentary to all the previous SHM guidelines since they deal mainly or exclusively with the use of SHM as a decision support tool.

The first document, to the best knowledge of the author, which extensively addresses all the phases of the SHM process – from data acquisition to their processing to extract information able to support decision making was published in 2016 by the Italian standardization body (UNI). The most recent technical documents on structural monitoring have been issued in Italy in 2020 and are specific for bridges. The first is a national guideline, issued by the Italian Ministry of Infrastructures and Transportation. In the document acquisition of information through monitoring systems is considered in the document one of the possible actions to manage bridge safety. In the Monitoring Regional (MoRe) guidelines (Limongelli et al., 2022) a change of glossary from SHM to Structural Monitoring (SM) is suggested to address the need to monitor not only parameters related to the health of the structure but also those related to the surrounding environment and that affect the management of the structural safety (e.g. temperature, humidity, loading, boundary conditions due hydrogeological parameters). SM

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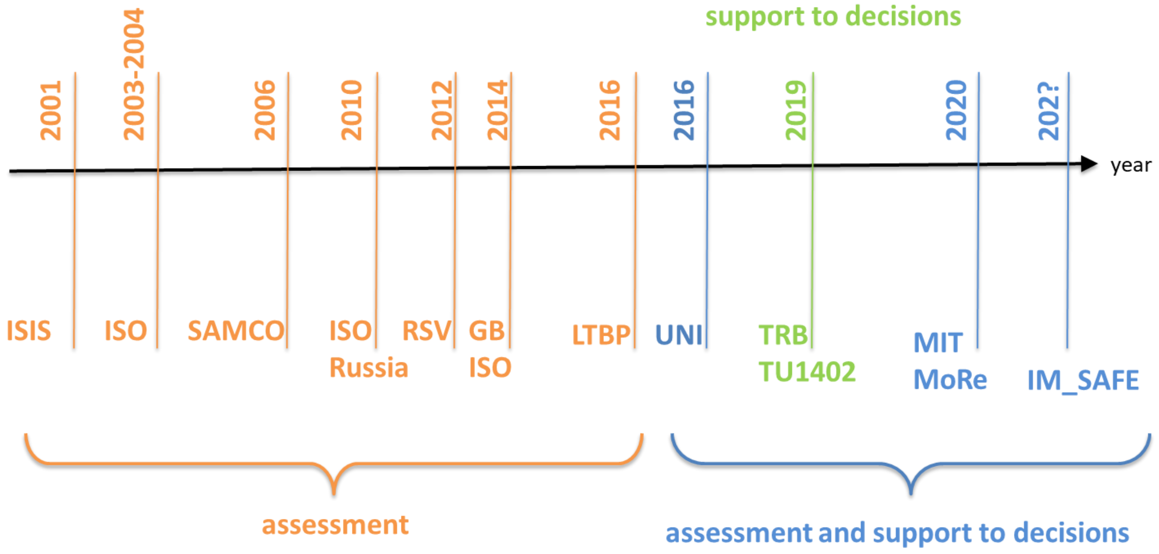
[23] https://www.cost-tu1402.eu

is clearly defined as a process in which monitoring information is managed to support management decision problems

Other documents, besides those summarized so far, have been published in several countries of the world. Furthermore, standardization bodies such as the International Organization for Standardization (ISO) have issued documents specific to the several phases of the SHM process: data acquisition, data processing, selection of parameters for condition monitoring.

The documents issued in the last 20 years and shortly described so far are reported in a time scale in **Figure 9** where the colours indicate the different perspectives of the documents.

Figure 9. SHM guidelines and standards.



Source: Limongelli, 2022

The older documents, issued between 2001 and 2006 (orange colour in the figure) consider SHM as a method to support the diagnosis of the structural condition. The two documents published in 2019 (green colour) consider monitoring only from the perspective of as a source of information to support decisions which correspond to the last step of the cycle in the figure. Recent guidelines (blues colour), starting from the UNI document of 2016, consider all the phases of the monitoring cycle and include both diagnosis and prognosis as decision problems that monitoring can support across the structure lifecycle.

The analysis of all the documents published between 2001 and 2020 reflects the shift occurred in the last 20 years in the perspective and objectives of SM. In the past, monitoring was meant to provide information to support condition assessment and to check the safety of the structure. Currently, the objective of monitoring is not only to assess the current condition but also to forecast the future performance to optimize in terms of cost-effectiveness the allocation of available resources.

To widen the use of SM, more research efforts are needed on the following aspects:

- A clear definition of protocols for the implementation of the individual phases is still missing. This is particularly important for the design phase that is seldom considered in the existing guidelines and documents. The LTBP documents can provide an interesting starting point for this endeavour.
- The design of a monitoring system must start considering the decision problem to support the monitoring information. In the MoRe guidelines (Limongelli et al., 2020) an initial proposal has been advanced.
- Established procedures for the assessment of the quality of the information used to support decisions are not currently available.
- The indicators proposed in the literature to perform the performance assessment based on SM information are seldom validated using data collected on real structures. Thereby indicators from SM lack the maturity level needed to achieve a wide industrial uptake.

- The reduction of uncertainty provided by the SM information is hardly accounted for in the design codes of new and existing structures. This does not enable to fully exploit the advantages SM could provide in terms of reduced use of resources and a sustainable approach to civil asset management.

Living SM laboratories, developed deploying extensive and multi-sensory SM systems with open access to data on diverse types of structures and asset management problems would be an important step forward for the rea world validation of methods, algorithms and approaches developed by researchers and to provide owners and managers demonstration of their effectiveness.

10.2 Towards effective standards for monitoring, data-informed safety assessment and maintenance of transport infrastructure

Presenter: Diego Allaix (TNO)

Dr. Allaix reported on the on-going activities of the H2020 Coordination and Support Action IM-SAFE EU-project[24], which supports the preparation of the mandate for CEN which aims at improving standardisation of the assessment of structural performance and of the proactive maintenance practices for the European transport infrastructure, in which optimal use is made of information from inspection, monitoring and testing. The project focuses on bridges, tunnels and other large infrastructures on the road and railway networks.

The rapid growth of large-scale civil infrastructures and increasing dependence of the society on the availability of transport networks has driven a political and societal pressure to keep transport infrastructure available, and to provide the required service level without unforeseen investments to maintain the desired performance. There is general consensus that effective and cost-optimal maintenance is only possible with the right policies and rational decisions. Such polices and decisions should consider and be effectively supported by timely available, meaningful and accurate information. In this respect, monitoring of structures is expected to become a key enabler of proactive maintenance strategies that are to be applied for ensuring the required safety of the transport infrastructure during its whole service life.

There is constantly growing number of examples where maintenance decisions are supported by reliable information about the condition of the assets obtained by monitoring of the structures. As an example, a data-informed service life prediction for fatigue in orthotropic steel bridge decks has been performed for the Van Brienenoordbrug, which is one of the busiest bridges in the Netherlands, with over 230,000 vehicles daily passing. By coupling fatigue crack growth monitoring, based on the acoustic emission technique, with advanced fracture mechanics-based models, accurate predictions have been made of the remaining service life. Such data-informed approach to diagnostics of structures, safety and service life assessment can very well serve in context of early warning system or real-time service life management. Next to diagnostics of structures based on the structure-specific direct or indirect-information, monitoring offers possibility to gathered information about actual hazards and actions on structures. In the Dutch field lab Moerdijk, road-WiM and bridge-WiM monitoring have been implemented and the monitoring data has been analyzed to improve understanding of the traffic loads on bridges. Benefits of this type of monitoring for design or assessment may range from deriving object-specific traffic load models from monitoring data, to the improvement of the traffic load models representative for the whole transport network. Ultimately, data-informed traffic load models may be used in-real time in full integration with digital twin models, with the aimed optimized use and maintenance of infrastructure assets. The IM-SAFE online-knowledge base contains huge number of examples in which data-informed approaches that involves monitoring of structures, have been implemented at the various stages of the maintenance decision-making[25].

Despite the availability of best practice examples, the current state-of-standardization in Europe for monitoring of structures and for the use of structure-specific information to support safety assessment and asset management of bridges and tunnels is scattered and fragmented. As an example, guidelines about structural monitoring have been recently published only in a limited number of European countries and largely differ in their refinement. In the last decade, several European countries have developed national standards and guidelines regarding the assessment and intervention of existing structures, however there is not a uniform consensus on how to differentiate safety requirements for new and existing structures. Hence, the major part of the standardization effort has been devoted to the improvement of the structural models for bridges but the development of a consistent reliability framework for new and existing structures is often lacking. Finally,

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[24] https://im-safe-project.eu

[25] https://imsafe.wikixl.nl

decisions on maintenance of bridges and tunnels are supported by guidelines drafted at the national or even by the infrastructure operators, leading to a variety of ad-hoc approaches not necessary supported but actual condition information. Even though the guidelines give attention to aging, damage and structural deterioration, and some of them implement simplified risk-based methodologies for prioritization of interventions, it appears that the standardization of quality control and the use of information from inspection, testing and monitoring in maintenance decision-making are far from being harmonized across Europe.

With digitalization recognized as an important enabling technology, the IM-SAFE project envisions a paradigm shift from the corrective maintenance towards preventive and condition-based maintenance strategies and risk-based maintenance management, through data-informed decision-making enabled by new and harmonized European standards. The outcome of the IM-SAFE project will be the input for the mandate for CEN for:

- **A new standard on structural monitoring**, addressing the principles of setting the objectives of structural monitoring, the principles and requirements for the design of monitoring systems and methodologies used for translating data into useful and meaningful information relevant for diagnostics of structures, safety assessment and maintenance approaches.
- **The further amendment to the existing EU standards on safety assessment taking into account inspections, monitoring and testing**, focussing on approaches to integrate monitoring and diagnostics of structures based on data from inspection, monitoring and testing with the evaluation of the structural condition and the assessment of the structural performance.
- **A new standard on maintenance of the transport infrastructure**, promoting the transition from corrective towards preventive and condition-based maintenance strategies and the implementation in the long term of risk-based maintenance management of infrastructure assets.

10.3 Open Discussion

Dr. Petrini opened the discussions providing the opinion that the management and maintenance of the monitoring system is important, considering that the **monitoring system lifespan** is different than the structure lifespan. Under this perspective, what are the actions to be taken after the end of life of the monitoring system? This aspect should be covered by standards, considering the number of sensors that could be placed in the bridge stock!

Dr. Limongelli agreed and provided the opinion that the cost of the monitoring system should be considered across the entire lifecycle of the structure, and should include its maintenance and replacement. At this point the **data processing cost** is also relevant. Dr. Allaix also agreed also that this aspect has to be considered in the management of the structure.

Prof. Brownjohn intervened saying that monitoring related aspects could be part of education modules (mentioning his personal experience **teaching modules** at MSc level) and could provide the right culture to future engineers to take decisions related to the different issues (e.g. lifecycle management).

Finally, Dr. Allaix mentioned that we cannot monitor structures for **all possible failure modes** (e.g. brittle failure modes). The actual needs for information-based monitoring should form the basis for designing a monitoring system.

11 Session 3: Vehicle-Infrastructure Interaction

Chair: Maria Cristina Galassi (JRC)

11.1 Test track and ground soil input characteristics determining agricultural tractor dynamics

Presenter: Maurizio Cutini (CREA-IT)

The Council for Agricultural Research and Analysis of the Agricultural Economy (CREA) is an Italian research organization dedicated to the agri-food supply chains. It's supervised by the Ministry of Agricultural, Food and Forestry Policies (MIPAAF). The CREA-IT department, Engineering and Agro-Food Processing, carries out activities in the field of biosystems engineering, agro-industrial and food processing, especially of fruit and vegetables, cereals and olives, for the sustainable management of the agro-ecosystems, agricultural, agro-food and agro-industrial sectors. The laboratory of vibration is in the research centre of Treviglio, Bergamo, Italy (**Figure 10**).

Figure 10. Layout of the "four poster" at the CREA-IT research centre.

Source: Maurizio Cutini

Whole body vibrations are among the risk factors of professional diseases in agricultural operators: terrain irregularity and forward speed are the most important sources of vibrations. One of the method for surface profile measurements consists in an iterative methodology based on signal acquisitions from tested vehicles followed by test bench replications: i.e. accelerations are acquired at specific parts of the vehicle (usually at the hubs) during the testing in operative conditions; afterwards the machine is placed on a test bench whose actuators are driven to create, by deconvolution method, the same input signals obtained in the former phase.

This study assessed agricultural surface unevenness and the relevant tractor response: tractor run on different tracks at different speeds, tire pressures and ballast settings, surface profiles were replicated at the four poster test bench (Cutini et al., 2016). Overall, twenty-nine operating conditions have been obtained.

The spectra of the replicated ground inputs showed a similar shape in terms of frequency pointing out that solicitations originating from different agricultural surfaces belonged to a specific range of frequencies (Cutini et al., 2017).

To discriminate as much differences as possible, the spectra of actuator plates displacements reproducing the test tracks (in frequency domain) were processed by means of principal component analysis (PCA).

No matter the surface, the highest variances were those associated with vibrations ranging from 0.2 Hz to 3.4 Hz pointing out that the outcome of the forces exchanged between soil profile and agricultural tires does not follow a random pattern. The value of the resonance frequency at 2.5-3 Hz, depended to tire stiffness, depending on the inflation pressure, and decreased with load (ballasted conditions). Other peaks were found at about 7-8 Hz: they indicated the resonance of the cab due to rubber mount supports.

Consequently, as solicitations originating from agricultural surfaces, no matter the surface profile, have been shown to belong to a specific range, a remarkable simplification and standardization of tractors' dynamics, comfort and materials resistance testing activity can be introduced.

The analysis showed the role of forwarding speed that, combined with surface profile, enhances the accelerations' amplitude the vehicle is subjected to; moreover, if it exceeds a threshold related to each tractor setting, excites tractor elastic components (i.e., tires, cab, rubber mountings, etc.) whose properties determine vehicle dynamics in terms of frequency. This effect is clear considering when a wheel runs over a cleat, the response of the hub acceleration to the effect of the cleat is to produce a sine function characterised by the same resonance frequency as that of the tyre, irrespective of the forward speed of the vehicle or the randomness of the track profile, and of amplitude characterised by the height of the cleat and by the vehicle's forward speed.

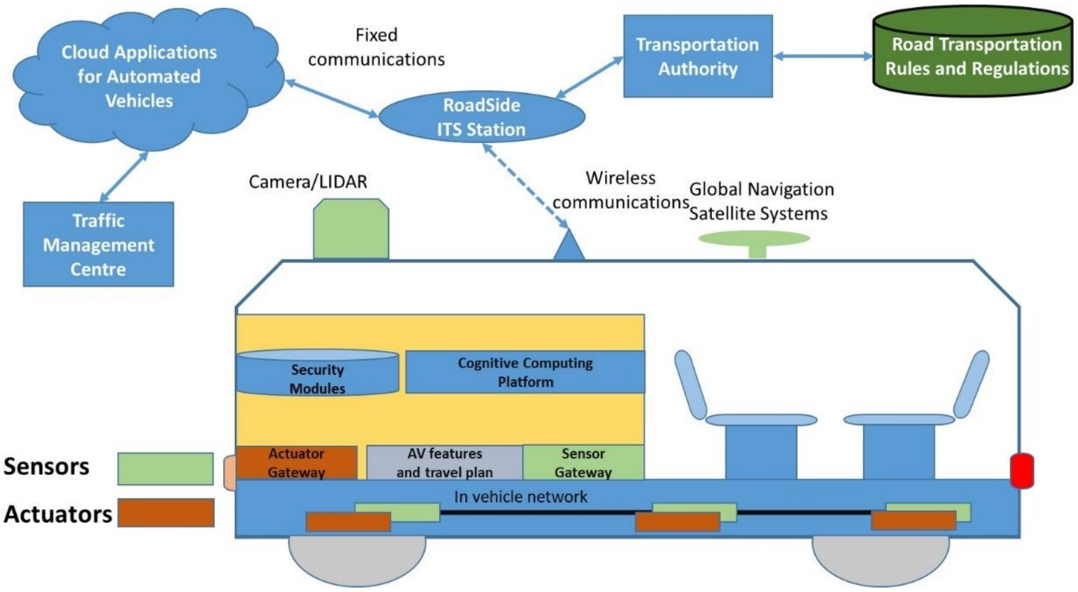
11.2 Connected and Automated Vehicles: opportunities and challenges for the future

Presenter: Gianmarco Baldini (JRC)

The concept of Cooperative, Connected and Automated Mobility (CCAM) or Cooperative and Automated Mobility (CAM) is related to the increasing level of connectivity and automation of modern vehicles to improve traffic management and safety on the road infrastructure. In recent years, EU countries, industry and the Commission collaborated to achieve the EU's ambitious vision for connected and automated mobility across the EU, taking into consideration public authorities, citizens, cities and industry interests. The terms cooperative and connected are distinct in CCAM because the first term refers to the communication among vehicles in the road without the support of the fixed communication infrastructure, while the connected is related to the connectivity to the fixed communication infrastructure and application systems (e.g. traffic management control centres). One potential issue is related to the possibility of implementing the cooperative and connected aspects using different wireless communication standards (e.g. DSRC ITS-G5 and LTEV2X) which are not interoperable and they may even compete for the use of the radio frequency spectrum. The duplication of communication systems may increase the deployment costs of the CCAM vehicles and the supporting fixed infrastructure.

In the context of automation, the information received through wireless communication means (either cooperative or connected) can be used by the cognitive automation engine in the automated vehicle to increase its situational awareness in the road and complement the information received by the sensors (**Figure 11**).

Figure 11. Conceptual setup of automated vehicle communication and sensing layout.



Source: Gianmarco Baldini

CCAM is a very promising set of technologies, but a number of things could go wrong in the evolution of CCAM considering the complexity of the automotive context and the safety aspects, which requires a very careful analysis by the regulators on the potential pitfalls. For example, cybersecurity aspects should not be neglected because connections can be exploited by malicious parties to take over the automated components of the vehicles in a similar way to ICT systems nowadays, which are often the target of cybersecurity attacks. Then, the evolution of CCAM should include an evolution of the regulatory frameworks (including type approval processes) in a similar way to what was done in the 70'/80' (e.g. Ralph Nader efforts for safer vehicles[26]). Another important aspect is related to the role of the Artificial Intelligence (AI) often implemented with machine learning and deep learning algorithms and models, which has to be trained to address many different traffic scenarios. This is challenging task for automated vehicles in particular for type approval because the number of potential driving scenarios is enormous. In this context, standardization is essential to ensure interoperability but also to ensure that adequate measures are in place in the standards themselves before deployment (e.g. security by design).

It should not be overlooked the impact of CCAM on current and future automotive regulations not strictly related to communications like electrification (e.g. the increased use of electric vehicles), vehicle emissions, commercial vehicle regulations (e.g. tachograph, weighing, dangerous goods) and others. The evolution of regulations can exploit the new technologies for improved efficiency and monitoring but it can also present pitfalls, which could weaken the regulations implementation once they become more digitized. For example, the possibility of tampering with regulations in sophisticated ways.

The JRC is working actively on these aspects to support a safe evolution of CCAM: from modelling and simulation of driving and testing scenarios, experimental activities for wireless communication, evaluations of cybersecurity aspects and foresight of the potential pitfalls in the adoption of AI for the automotive domain. To present a cohesive approach, the JRC should work as a single body to address all the different elements of this complex domain.

11.3 Open Discussion

Dr. Galassi opened the floor for questions.

Mr. Bono asked Dr. Cutini on the digitalisation and use of sensors in agriculture vehicles and Dr. Baldini on the perspective of transferring data with form vehicle to infrastructure using 5G, and where could the computation be performed.

Dr. Cutini mentioned the Agriculture 4.0 initiative (digital or precision agriculture). Nowadays tractors are very complex machines and their guidance is automated, for both navigation and positioning, can receive info on the seeds and the paths to follow directly in the onboard computer and can allow also transmit data to the site. In this way, the site agronomist can obtain direct real time info on the position and the performance of the tractor. What is important is that there is a protocol for **transmitting data from sensors** in the tractor to the site.

Dr. Baldini mentioned that Vehicle-to-Vehicle (V2V) and V2I can be based on very short exchange of communication messages, but connectivity (using for example 5G) can be used also for other operation like **transfer of data to the cloud**, or software updates. Therefore, connectivity can be used from two different points of view and therefore with different characteristics, so the two technologies might not be competing indeed, but be complementary. There are also aspects of technology maturity and deployment aspects, which should be taken in consideration. For example, for the cooperative aspects, DSRC ITS-G5 is a well-tested and mature technology, while the competing Long-Term Evolution Vehicle-to-Everything (LTE-V2X) technology does not have the same level of maturity and more testing in real scenarios should be performed. On the other side, cellular networks based on LTE and 5G will have a significant network deployment, which can be exploited by the automotive domain without the need to build a specific DSRC ITS-G5 infrastructure.

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[26] https://time.com/4124987/50-years-unsafe-at-any-speed

12 Session 4: Wrap up and way forward

Presenters: Konstantinos Gkoumas (JRC) & Kyriaki Gkoktsi (JRC)

This session focused on a short overview of what has been discussed in the two days of the workshop, including some quick takeaways.

- In the welcome address, the JRC Heads of the Units participating in MITICA emphasised the role of the JRC, from different perspectives: the safety and security, the sustainable transport and exploratory research. In particular, exploratory research inside the JRC focuses on research not linked to policies, like iSHM.
- Then, we set the context with the introduction of the MITICA project, the role of the JRC contributing to the safety of structures by means of the Eurocodes and the ELSA laboratory, the role of R&I in bridge safety, maintenance and monitoring.
- The main part of the workshop kicked-off with a session on the advances in SHM strategies. What is evident is that there is huge research in the past years both for what regards SHM at a global scale (focusing on structures, or structures at a network level, within a resilience approach) but also at a local level using appropriate sensors. The session participants showed very interesting examples and success stories from their research groups, and in the end the MITICA project was introduced from the JRC.
- The next session focused on iSHM, and started with a presentation of the MITICA experimental campaign. In the rest of the session, case studies and experiments were presented. What emerges is the interest from researchers to structures of different scale: from short span cantilever bridges to long span suspension bridges. It is clear that challenges are different.
- The session continued with a second part, focusing on applications aided by AI or a fleet of vehicles or with trains on rail bridges. The latter has some advantages considering the different vehicle-structure interaction and the absence of tyres, but also additional challenges.
- The first day concluded with a session on digital technologies and enablers. The characteristics and the challenges for the digital transformation of the construction sector were highlighted. Also, taking inspiration from a presentation of a device used for digital twinning, discussions took place on the definition of digital twins, and how they differ from traditional simulation models used for model updating.
- In the afternoon, participant to the workshop on-site, had the chance to see the MITICA testing facility, including a small demonstration, and the ELSA lab and reaction wall.
- Day two kicked-off with a session on the policy perspective and integration with European research. Relevant EU policies and funding schemes were presented. Also, contribution from four H2020 projects were presented, in which among else the use of drones for inspection was discussed.
- The next session on the integration of SHM on standards provided an overview of the developments in the past twenty years in the field and the future challenges.
- Finally, the session on vehicle-structure interaction focused on concrete examples from the agriculture sector and the way forward with the use of CAVs.

13 Conclusions

The discussions that took place during the workshop highlight the high interest within the academic and technical community to developing vehicle assisted iSHM. During the workshop, a special focus was given to innovative indirect structural health monitoring approaches. These rely on vehicle-bridge interactions and on the deployment of sensor-equipped vehicles to monitor existing bridge infrastructure: including results from the JRC MITICA Project.

The workshop delegates presented different applications and research (from theoretical and scaled experiments using a single vehicle, to full-scale applications by means of crowd-sensing campaigns), while the feasibility of monitoring foot bridges (with bikes) or rail bridges (using passing trains) was also highlighted.

The synergies mentioned above can exploit the dual functionality of a passing vehicle as it both excites the infrastructure and records its response. This offers a monitoring ability at the highest spatial resolution. These advantages were assessed at the JRC Ispra site with a full-scale experimental campaign on a bridge-like structure under laboratory-controlled conditions. It is expected that the developed methodology will be equally useful in monitoring existing roads and railways.

What emerged from the discussions is that significant ground work has been carried out, and it is expected that future research will focus on the accuracy of monitoring findings and the data collection and use. It is also estimated that the insertion of the bridge-like structure developed for MITICA in the latest call for expressions of interest on JRC Living Labs for smart city solutions focusing on Intelligent Mobility and Digital Energy[27], will contribute to the further development of in-vehicle systems for iSHM.

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[27] https://joint-research-centre.ec.europa.eu/pilot-living-labs-jrc_en

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List of abbreviations and definitions

5G	Fifth generation of telecommunication systems
AA	Administrative Agreement
ADS	Automated Driving Systems
AECO	Architecture, engineering, construction, and operation
AI	Artificial Intelligence
ANN	Artificial Neural Network
AVP	Automated Valet Parking
AVT	Ambient Vibration Testing
ABA	Axle box acceleration
BIM	Building Information Modelling
CAM	Cooperative and Automated Mobility
CAV	Connected and Automated Vehicle
CCAM	Cooperative, Connected and Automated Mobility
CEF	Connecting Europe Facility
CEN	European Committee for Standardization
CINEA	European Climate, Infrastructure and Environment Executive Agency
COST	European Cooperation in Science and Technology
CREA	Council for Agricultural Research and Analysis of the Agricultural Economy
DG GROW	Directorate General for Internal Market, Industry, Entrepreneurship and SMEs
DT	Digital Twin
ELSA	European Laboratory for Structural Assessment
EN	European Norm (Europäische Norm)
ERIES	Engineering Research Infrastructures for European Synergies
EU	European Union
FIHT	Fast Impact Hammer Testing
FP7	Seventh Framework Programme
FRF	Frequency Response Function
FSD	Full Scale Dynamics Ltd
GDP	Gross domestic product
H2020	Horizon 2020 Framework Programme
IDDM	Interpolation Damage Detection Method
IFC	Industry Foundation Class
IoT	Internet of Things
iSHM	Indirect Structural Health Monitoring
ISO	International Organization for Standardization
ITC	Intelligent Transport Communication
JRC	Joint Research Centre
L3	Level 3 automation

L4	Level 4 automation
LiDAR	Light Detection and Ranging
LTBP	Long Term Bridge Performance
LTE	Long-Term Evolution
MIPAAF	Ministry of Agricultural, Food and Forestry Policies
MITICA	Monitoring Transport Infrastructures with Connected and Automated vehicles
ML	Machine learning
MoRe	Monitoring Regional
MPMF	Most Probable Modal Frequencies
MS	Member State
NDE	Non-destructive evaluation
NDT	Non-destructive testing
NTNU	Norwegian University of Science and Technology
OMA	Operational Modal Analysis
OBM	On board monitoring
PCA	Principal Component Analysis
PGA	Peak Ground Acceleration
SAMCO	Structural Assessment Monitoring and Control
SBB	Swiss Federal Railways authority
SHM	Structural Health Monitoring
SM	Structural Monitoring
SMM	Structural Mechanics & Monitoring
TNO	Netherlands Organisation for Applied Scientific Research
TRB	Transportation Research Board
UAVs	Unmanned Aerial Vehicles
UK	United Kingdom
UN	United Nations
UNI	Italian standardization body
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VoI	Value of Information
VTOL	Vertical Take-Off and Landing
WIM	Weigh in motion
WSN	Wireless sensor network

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