# Special issue on emerging frontiers in automated inspection, sensing and control for civil infrastructure

## Preface

Sensing and automated inspections improve the accuracy of acquirable data and provide more opportunities for accurate structural evaluation, even during degradation. Their application in the modern world is increasingly widespread. Structures instrumented with sensors can communicate their current condition to a data acquisition system in the form of accelerations, displacements, strains, etc., depending on the sensor type. This information can be used in real-time to control and to evaluate structural performance during severe earthquake or wind loads or to assess rapidly the health of a structure on the basis of the acquired data after such events. Sensors can be jointly used with robotic solutions for inspection to evaluate structural degradation and to plan and act maintenance or retrofit works, and eventually to generate automatic alarms.

The present special issue expresses current progress in developing smart materials and structures and is witness to ever growing international synergies among researchers following the ANCRiSST 2019 Workshop and the Asia Pacific Euro Summer School held from July 15th to August 3rd at the historical Faculty of Civil and Industrial Engineering, Sapienza University of Rome, Italy.

Emerging frontiers in automated inspection, sensing and control of civil infrastructure have been presented and largely discussed during lectures in the Summer School and oral presentation at the Workshop. Contributions have been here collected in six areas such as system identification and modelling, advanced sensor technology, bridge inspection and monitoring, structural health monitoring of cultural heritage, damage detection, mechatronics and automated inspection.

After rigorous peer review, a total of 18 accepted papers are included, three for each area, in this special issue. The excerpts of these contributions follow.

In system identification and modelling, the paper “Dynamical models of a suspension bridge driven by vibration data” by Gattulli et al. proposes a methodology to furnish an analytical mechanical model of a suspension bridge in which the main parameters can be derived from vibration measurements. The pedestrian cable suspension Polvorines bridge (100 meters of span) is considered to demonstrate the procedure, due the test campaign conducted on March 2020. The paper “Amplitude-dependent model updating of masonry buildings undergoing demolition” by Martakis et al., deals with proper modelling masonry structures under high amplitude vibrations due to seismic event with material properties, inferred via data-driven model updating under appropriate conditions for predicting behavior under seismic actions. It is shown that relative amount of nonlinearity arising from structural behavior and soil-structure interaction can be determined if Bayesian model updating is carried out on field measurements that are representative of increasing levels of shaking, as for example the ones induced during demolition, on a pre-code masonry building. Furthermore, in modelling building-type structures, the paper “Structural identification of the dynamic behavior of floor diaphragms in existing buildings” by Sivori et al., introduces a discrete linear model of deformable diaphragm to analytically determine the modal properties governing the free undamped dynamics through a fully general perturbation technique (direct problem) and consequentially to assess the inertial and elastic properties of the deformable diaphragm (inverse problem), assuming the outcomes of experimental modal analyses as known input.

In advanced sensor technology, the paper “Non-contact monitoring of the tension in partially submerged, miter-gate diagonals” by Eick at al., uses a non-contact vision-based method for extracting the frequency of vibration by a proposed method of tension estimation for an in-service miter-gate diagonal that is also instrumented with load cells. Results for the proposed method show excellent agreement with load cell measurements. The paper “A new image-quality evaluating and enhancing methodology for bridge inspection using an unmanned aerial vehicle” by Lee et al. proposes a new methodology to address the image quality problem encountered as the use of an unmanned aerial vehicle in the field of bridge inspection increased. Image quality assessment based on local blur map and image quality enhancement using the variational Dirichlet kernel estimation is proposed as a solution to address the quality issues for this novel data acquisition technology. In addition, in the paper "Implementation of video motion magnification technique for non-contact operational modal analysis of light poles" by Thiyagarajan et al., the use of non-contact vision sensing for operational modal analysis of light pole on highway viaduct is explored. The phase-based video motion magnification method is implemented to obtain the light pole response in an ambient condition extracting, structural displacement using the image processing technique.

In bridge inspection and monitoring, the paper "Bridge weigh-in-motion through bidirectional Recurrent Neural Network with long short-term memory and attention mechanism" by Wang and Wang deals with dynamic bridge response measured during traffic and used to identify overloaded vehicles. The study investigates deep learning, specifically the recurrent neural network, toward bridge weigh-in-motion. The proposed method achieves high accuracy in estimating axle weights, in comparison with a conventional moving force identification method. The paper "Automated damage detection of bridge structures under unknown seismic excitations using support vector machine based on transmissibility function and wavelet packet energy" by Liu et al. evidences the needs to remove the effects of external excitation on the structural responses to retain only the structural information for structural damage identification. A data-driven algorithm is proposed for this purpose using the vector of wavelet packet energy obtained from the inverse Fourier transform of the transmissibility functions as the damage sensitive feature, which is taken as the input of support vector machine for damage location and damage level identification. Finally, for railway bridge monitoring the study titled "Response based track profile estimation using observable train models with numerical and experimental validations" by Thiyagarajan et al. has developed a practical inverse analysis scheme for the track profile evaluation by measuring in-service local train vehicle responses. Track profile estimation through in-service vehicle response measurements using smartphones potentially provides efficient and frequent measurement. Both numerical analyses and field experiments clarify the proposed track profile estimation capability using only one on-board sensing device with the target application of local railway network monitoring, especially for the vital wavelength range for rail maintenance and train running safety.

In structural health monitoring of cultural heritage, the paper "Structural analysis and health monitoring of twentieth-century cultural heritage: the Flaminio Stadium in Rome" by Di Re et al. deals with one of the iconic reinforced concrete sport facilities designed and built by Pier Luigi Nervi for the 1960 Olympic Games of Rome. In view of the foreseen SHM activity, it turns out that the main grandstand canopy plays a pivotal role in the Flaminio's structural response to seismic excitation; in addition, its state of conservation raises some concern. Therefore, the structural modeling and dynamic characterization of the canopy is deepened assessing its unusual features, such as geometry, material characteristics and dynamic interplay with the hosting main reinforced concrete frames. To validate the FE results, characterized by a high modal density, and investigate the response of the structure, dynamic tests carried out under operating conditions are presented. The relevant data management is framed in a heritage building information modeling context. Contextually, the paper "Monitoring an iconic heritage structure with OMA: the Main Spire of the Milan Cathedral" by Ruccolo et al. deals with one of the most remarkable structural elements characterizing the Milan Cathedral is its Main Spire, built in Candoglia marble and completed in 1769. The dynamic characteristics of the spire and their evolution during a time span of about 16 months is discussed evidencing that notwithstanding the remarkable effects exerted by the changing environment on the resonant frequencies, output-only removal of environmental effects and novelty analysis allow an effective monitoring of the structural condition. Historical structure deserves peculiar attention and the paper "Detecting and localizing anomalies on masonry towers from low-cost vibration monitoring" by Borlenghi et al. demonstrate that masonry towers can be monitored by installing few accelerometers at the top of the building. The development of a structural health monitoring procedure for the model-based damage assessment in masonry towers using frequency data is exemplified on the ancient Zuccaro tower in Mantua, Italy. Pseudo-experimental monitoring data were generated and employed to assess the reliability of the developed algorithm in identifying the damage location.

Specifically, in damage detection the paper "On the use of multivariate autoregressive models for vibration-based damage detection and localization" by Achilli et al. proposes a novel method suitable for vibration-based damage identification of civil structures and infrastructures under ambient excitation. The damage-sensitive feature employed in the presented algorithm consists of a vector of multivariate autoregressive parameters estimated from the vibration responses collected at different locations of the analyzed structure. In particular, the Mahalanobis distance between a set of reference and inspection parameters is evaluated. Thus, the Mahalanobis distance applied to vectors of multivariate autoregressive parameters has proven to be a robust indicator for damage detection and localization. Moreover, in the paper "Clump interpolation error for the identification of damage using decentralized sensor networks" by Quqa et al. an effective method for real-time modal identification is used together with a local approximation of a damage feature, the interpolation error, to detect and localize damage due to a loss of stiffness. The damage-sensitive features are evaluated using the responses recorded at small groups of sensors organized in a decentralized topology. Experimental tests conducted using real data confirm the robustness of the proposed method and the potential of its implementation on-board decentralized sensor networks. A description of damage in brittle material is presented in the paper "Experimental mechanical analysis of traditional in-service glass windows subjected to dynamic tests and hard body impact" by Figuli et al. This study aims at exploring the dynamic response and damage sensitivity of traditional glass window systems, based on the experimental derivation of few key material properties and mechanical parameters. To this aim the attention is focused on traditional, in-service windows that belongs to existing residential buildings and are typically sustained by timber frames, through a linear flexible connection. In doing so, major advantage is taken from experimental analysis, both in the static and dynamic field, for whole window assemblies of single components.

In mechatronics and automated inspection, the paper "Study of an optimal heating command law for structures with non-negligible thermal inertia in varying outdoor conditions" by Le Touz et al. addresses an optimal energetic control model applied to local heating sources to prevent black-ice occurrence at transport infrastructure surface is addressed. The heat transfer model developed is used to derive control laws with the objective of preventing ice formation while avoiding excessive energy consumption by taking also into account weather forecast information. Results obtained by numerical simulations for different operative conditions with various weather conditions are presented and discussed. In the paper "Addition of passive-carriage for increasing workspace of cable robots: automated inspection of surfaces of civil infrastructures" by Rubio-Gómez et al. cable-driven robots are studied due to their light-weight structure, high energy efficiency and ability to cover large workspaces since cables are easy to wind. The addition of a passive carriage in the top of the frame is proposed, allowing to achieve a much greater feasible workspace than the conventional one. Simulation and experimental results show that the feasible workspace can be notoriously increased while end-effector pose is controlled. This new architecture of cable-driven robot can be easily applied for automated inspection and monitoring of very large vertical surfaces of civil infrastructures, such as facades or dams. Finally, the paper "Closed loop cable robot for large horizontal workspaces" by Juárez-Pérez et al. proposes a non-invasive solution for inspecting horizontal surface such as bridge decks based on cable-driven robots which allow to inspect large surfaces maintaining a very low vertical occupancy in comparison to the conventional architecture of this kind of robot. Using closed cables loop instead of a set of cables, a device with low motorization power and very large workspace is designed and prototyped. As example of control an inverse dynamics technique is applied to control the end-effector where inspection tool is located, e.g. a vision system. Experimental results demonstrate that this novel device allows to inspect large horizontal surfaces, with low motorization and low vertical occupancy.

The guest editors expect this special issue will testify the emerging of novel approaches in facing the management of structures and infrastructures from modern engineering to cultural heritage. The publishing of this special issue could have not been possible without the effort of several young fellows and passionate researchers and personnel which have contributed to a successful starting during the Summer School and the Workshop in July 2019 in Rome, which were supported by the EU project DESDEMONA - Detection of steel defects by enhanced monitoring and automated procedure for self-inspection and maintenance (RFCS 2018 grant no. 800687). Furthermore, a special thanks is given to all the anonymous reviewers, who have reviewed submitted manuscripts and provided constructive comments on a very timely manner. Also, the guest editors would like to express special thanks to the Editors-in-Chief of Techno-Press, Prof. Hyung-Jo Jung for his support of the successful publication of the special issue. Last but not the least, many thanks to all the authors who contributed their precious works to the special issue.

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Prof. Yozo FUJINO
*Yosai University, Sakado, Japan*
*E-mail: fujino-yozo@josai.ac.jp*

Prof. Vincenzo GATTULLI
*Department of Structural and Geotechnical Engineering*
*SAPIENZA University of Rome, Rome, Italy*
*E-mail: vincenzo.gattulli@uniroma1.it*

Prof. Hui LI
*Department of Disaster and Prevention Engineering*
*Harbin Institute of Technology, Harbin, China*
*E-mail: lihui@hit.edu.cn*

Prof. Bill F. SPENCER
*Department of Civil and Environmental Engineering*
*University of Illinois, Urbana-Champaign, USA*
*E-mail: bfs@illinois.edu*


*Hoping we will be back soon so close*